UNDERSTANDING
ANESTHESIA EQUIPMENT

FIFTH EDITION

Jerry A. Dorsch • Susan E. Dorsch

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Dedication

This book is dedicated to the anesthesia educators who value the dissemination of equipment-related knowledge.

Preface

There have been many exciting changes in anesthesia equipment since the fourth edition was published. Once again we have updated equipment covered in previous editions. New chapters on latex allergy, suction equipment, double-lumen tubes, emergency airway devices, operating room fires, temperature control and the MRI environment have been added. Some of these were covered to some extent as parts of other chapters in previous editions but we felt they needed to be expanded into separate chapters because of the large amount of information available.

During the years since the last edition, anesthesia machines have undergone major changes. The anesthesia ventilator, which in the past was a separate entity, has been integrated with the machine and the breathing system. At the same time anesthesia ventilators have gained more features and now more closely resemble critical care ventilators. These chapters have been expanded.

One device that has had a great impact on anesthesia practice is the supraglottic airway. A number of new devices from different manufacturers have become available and the indications for these devices have continued to grow. This chapter has been greatly expanded.

Pressure- and flow-volume loops were discussed in the fourth edition. Many of the newer anesthesia machines and physiological monitors include them. We have expanded this section in the hope that this will make it easier to interpret them and appreciate their usefulness.

A problem that has drawn considerable attention since the last edition is the association of desiccated carbon dioxide absorbent and carbon monoxide formation. The mechanism of the desiccation has not yet been well elucidated. We have looked at

gas flows and how it would be possible for absorbent to become desiccated either from a continuous fresh gas flow or during an anesthetic in the chapter on circle systems. Hopefully this area will continue to be investigated.

We have followed our previous policy of not including equipment that is not currently manufactured or in use. Since the last edition, the Committee on Equipment and Facilities of the American Society of Anesthesiologists has published guidelines for anesthesia machine obsolescence. These are given in Chapter 5. We have excluded most equipment that would be considered obsolete by these criteria. For devices that have a short use span, we have tried to include only those that were available at the time this text was written.

We apologize that there are subjects that could rightfully have been included in this text but were not. The entire book was written by the two authors and it was not possible to include everything. Hopefully others will step up to the plate and produce texts covering subjects we did not include.

We sincerely hope that this text will be useful to experienced anesthesia providers as well as anesthesia residents and student nurse anesthetists. Hopefully they will experience some of the rewards that come from understanding and using both new and familiar equipment that we have enjoyed during the thirty seven years of writing this book.

Unfortunately this will be the last edition that we will personally write. We would like to challenge and encourage others to take up where we have left off. We would be happy to help future authors in any way we can. While it entails a tremendous amount of work, the rewards are priceless.

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Writing a text such as this requires help from many individuals and manufacturers. Without their help and the information that they supplied us, this book would be incomplete. Special mention must be made for the photographs and diagrams for various equipment which add immeasurably to understanding. When the manufacturer supplied photographs or diagrams the credit was supplied with the item.

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Chapter 1

Medical Gas Cylinders and Containers

Definitions

Psi, Psig, Psia

Psi stands for pounds per square inch. Psig stands for pounds per square inch gauge, which is the difference between the measured pressure and surrounding atmospheric pressure. Most gauges are constructed to read zero at atmospheric pressure. Psia stands for pounds per square inch absolute. Absolute pressure is based on a reference point of zero pressure for a perfect vacuum. Psia is psig plus the local atmospheric pressure. For example, at sea level, the atmospheric pressure is 0 psig but 14.7 psia.

Table 1.1 shows some units of expressing pressure and their conversion factors.

Nonliquefied Compressed Gas

A nonliquefied compressed gas is a gas that does not liquefy at ordinary ambient temperatures regardless of the pressure applied (1). Examples include oxygen, nitrogen, air, and helium. These gases do become liquids at very low temperatures, at which point they are referred to as cryogenic liquids.

TABLE 1.1 Units of Pressure

kPa	*Kilopascal*
cm H_2O	Centimeters of water
psi	Pounds per square inch
mbar	Millibar
mm Hg	Millimeters of mercury
100 kPa = 1000 mbar = 760 mm Hg = 1030 cm H_2O = 14.7 psi = 1 atmosphere	
Therefore,	
1 kPa = 10.3 cm H_2O	1 cm H_2O = 0.098 kPa
1 kPa = 0.147 psi	1 psi = 6.8 kPa
1 kPa = 7.6 mm Hg	1 mm Hg = 0.13 kPa

1 kPa = 10 mbar	1 mbar = 0.1 kPa
1 mbar = 1.03 cm H_2O	1 cm H_2O = 0.97 mbar
1 mbar = 0.76 mm Hg	1 mm Hg = 1.32 mbar
1 mbar = 0.0147 psi	1 psi = 68 mbar

Liquefied Compressed Gas

A liquefied compressed gas is one that becomes liquid to a large extent in containers at ambient temperature and at pressures from 25 to 1500 psig (172 to 10,340 kPa) (1). Examples include nitrous oxide and carbon dioxide.

Regulatory Agencies and Industry Standards

All those who produce, supply, transport, or use medical gases must comply with a variety of safety regulations promulgated and enforced by agencies at the federal, state, provincial, and local levels of government.

The purity of medical gases is specified in the United States Pharmacopoeia and is enforced by the Food and Drug Administration (FDA).

The Department of Transportation (DOT) and Transport Canada (TC) have published requirements for the manufacturing, marking, labeling, filling, qualification, transportation, storage, handling, maintenance, requalification, and disposition of medical gas cylinders and containers. U.S. states and Canadian provinces vary widely in their regulations for compressed gases (1). In addition, many local governments have regulations that apply to compressed gases.

The U.S. government regulates matters affecting the safety and health of employees in all industries through

the Department of Labor (DOL) and the Occupational Safety and Health Administration (OSHA).

The National Fire Protection Association (NFPA), the Compressed Gas Association (CGA), and the Canadian Standards Association (CSA) have published a number of standards. Although termed *voluntary*, many regulatory agencies have made adherence to these standards mandatory.

Medical Gas Cylinders

Components

Body (1,2)

Most medical gas cylinders (tanks) are constructed of steel, with various alloys added. In recent years, manufacturers have moved away from traditional steel cylinders toward steel carbon fiber cylinders. These can hold more gas than their older steel

counterparts and are lighter in weight. Cylinders made from aluminum are available. These are especially useful when anesthesia is administered in a magnetic resonance imaging (MRI) environment (Chapter 30). Cylinders that have a marking of Ĩ€3AAĨ€ are manufactured by using steel. The marking Ĩ€3ALĨ€ or Ĩ€3ALMĨ€ indicates that the cylinder is made from aluminum (3).

Cylinders have flat or concave bases. The other end may taper into a neck that is fitted with tapered screw threads that attach to the valve. In recent years, cylinders with integral pressure regulators and flow-metering devices as well as handles have become available (Fig. 1.1) (4). This eliminates the need for pressure regulator maintenance by the health care facility and simplifies use of the cylinder.

Valve

Cylinders are filled and discharged through a valve (spindle valve) attached to the neck (see Fig. 1.7). The valve, which is made of bronze or brass, is an integral part of the cylinder and should be removed only by the cylinder owner.

Port

The port is the point of exit for the gas. It should be protected in transit by a covering. When installing a small cylinder on an anesthesia machine, it is important not to mistake the port for the conical depression on the opposite side of the valve. The conical depression is designed to receive the retaining screw on the yoke. Screwing the retaining screw into the port may damage the port and/or index pins.

Stem

Each valve contains a stem, or shaft, that is rotated during valve opening or closing. To close the valve, the stem seals against the seat that is part of the valve body. When the valve is opened, the stem moves upward, allowing gas to flow to the port.

Figure 1.1 Cylinder with integral pressure regulator and flow-metering device.

Packed Valve

Most cylinder valves are of the packed type (Fig. 1.2). The stem is sealed by a resilient packing such as Teflon, which prevents leaks around the threads. This type of valve is also called *direct acting*, because turning the stem causes the seat to turn. In a large cylinder valve, the force is transmitted by means of a driver square (Fig. 1.2, right). This type of valve is capable of withstanding high pressures.

Diaphragm Valve

In a diaphragm valve (Fig. 1.3), closure between the cylinder interior and the atmosphere is accomplished by using a seal, usually metal-to-metal, and a bonnet nut that clamps one or more circular disks in place (1). These disks, or diaphragms, separate upper and lower stems, which may be permanently attached to the diaphragms. The upper stem is actuated by a manual or automatic means, and the lower stem shuts or

permits flow through the valve. This type of valve has the following advantages:

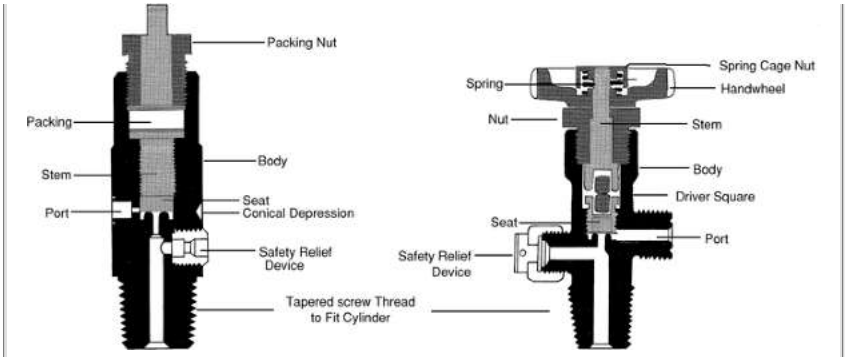

Figure 1.2 Small **(left)** and large **(right)** packed valves. The packing seals the stem and prevents leaks. Turning the stem on the large cylinder valve counterclockwise causes the seat to turn in its thread, opening the valve. (From drawings furnished by Puritan-Bennett Corp.)

1. It can be opened fully by using a one-half to three-quarters turn, whereas the packed valve requires two or three full turns.
2. The seat does not turn and is therefore less likely to leak.
3. No stem leakage can occur because of the diaphragm.

For these reasons, the diaphragm type is generally preferable when the pressures are relatively low and when no leaks can be allowed, such as with flammable gases. It is somewhat more expensive than the packed type.

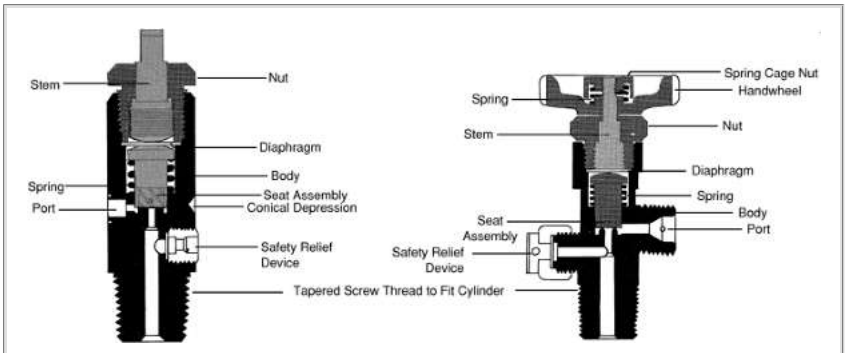

Figure 1.3 Small **(left)** and large **(right)** diaphragm valves. Turning the handle clockwise forces the diaphragm downward and closes the seat. Upon opening the valve, the upward force of the spring opens the seat. (From drawings furnished by Puritan-Bennett Corp.)

Handle or Handwheel

A handle or handwheel is used to open or close a cylinder valve. It is turned counterclockwise to open the valve and clockwise to close it. This causes the stem to turn.

A handle (cylinder wrench) is used to open a small cylinder

valve. Handles come in a variety of shapes (Fig. 1.4). Some handles, such as the one in the middle of Figure 1.4, have a hexagonal opening that fits the packing (gland) nut of the valve (Fig. 1.2). This handle may be used to tighten the packing nut if it becomes loose. A hazard associated with this handle is that a person unacquainted with cylinders could loosen the packing nut under the mistaken impression that he or she was opening the valve. This could cause the valve stem and retaining nut to come off the cylinder with great force (5).

Figure 1.4 Small cylinder valve handles. The hexagonal opening at the top of the middle handle can be used to tighten the packing nut on the cylinder valve. A ratchet handle is at the right. After a cylinder has been opened, this handle must be removed, inverted, and reapplied to close the cylinder valve.

A ratchet-type handle is supplied with some anesthesia machines (Fig. 1.4). After the cylinder is opened, the handle must be removed, inverted, and reapplied to close the cylinder (6).

A good practice is to attach a handle to each anesthesia machine or other apparatus for which it may be needed. It is also important to check that the cylinder can be opened before use. Cases where the valve could not be opened have been reported (7,8).

Each large cylinder valve has a permanently attached handwheel that uses a spring and nut to hold it firmly in place (Figs. 1.2, right, and 1.3, right).

Pressure Relief Device

Every cylinder is fitted with a pressure relief (safety relief, safety) (see Fig. 1.7) device whose purpose is to vent the cylinder's contents to atmosphere if the pressure of the enclosed gas increases to a dangerous level (1).

Rupture Disc

The rupture (frangible, burst) disc is a non-reclosing device with a disc held against an orifice (Fig. 1.5). When the predetermined

pressure is reached, the disc ruptures and allows the cylinder contents to be discharged. The pressure opening is the orifice against which the disc functions. The rated burst pressure is the pressure at which the disc is designed to burst. It is determined by the material, thickness, and shape of the disc as well as the diameter of the pressure opening. This device is used on some air, carbon dioxide, carbon dioxideโ€“oxygen, helium, nitrous oxide, helium-oxygen, nitrogen, and oxygen cylinders. It protects against excess pressure as a result of high temperature or overfilling.

Fusible Plug

The fusible plug is a thermally operated, non-reclosing pressure-relief device with the plug held against the discharge channel. It offers protection from excessive pressure caused by a high temperature but not from overfilling. The yield temperature is the temperature at which the fusible material becomes sufficiently soft to extrude from its holder so that cylinder contents are discharged. A fusible plug with a yield temperature of 212ยฐF is sometimes used on certain nitrogen and air cylinders.

Combination Rupture Disc/Fusible Plug

A combination rupture disc/fusible plug can be used to prevent bursting at a predetermined pressure unless the temperature is high enough to cause the fusible material to yield. Devices with a yield temperature of 165ยฐF may be found on cylinders of air, oxygen, nitrogen, nitrous oxide, helium, helium-oxygen mixtures, carbon dioxide, and carbon dioxideโ€“oxygen mixtures. Because these devices function only in the presence of both excessive heat and excessive pressure, they do not offer protection from high pressure due to overfilling.

Pressure Relief Valve

The pressure relief valve (Fig. 1.6) is a spring-loaded device designed to reclose and prevent

cylinder contents from being discharged after a normal pressure has been restored. The set pressure, at which it will start to discharge, is marked on the valve. A pressure relief valve may be found on air, helium, oxygen, nitrogen, helium-oxygen mixture, carbon dioxide, and carbon dioxideโ€“oxygen mixture cylinders with up to 500 psig charging pressure. Pressure relief valves are generally more susceptible to leaks than rupture discs or fusible plugs (1).

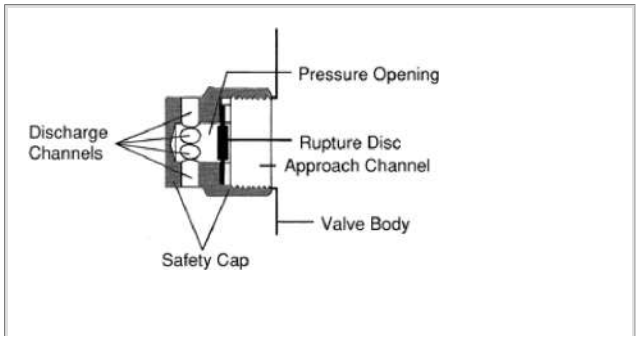

Figure 1.5 Rupture disc device. When the rated burst pressure is exceeded, the disc ruptures and gas flows from the approach channel into the pressure opening and to atmosphere through the discharge channels. (Redrawn from Frangible disc safety device assembly. Pamphlet S-3. New York: Compressed Gas Society, 4.)

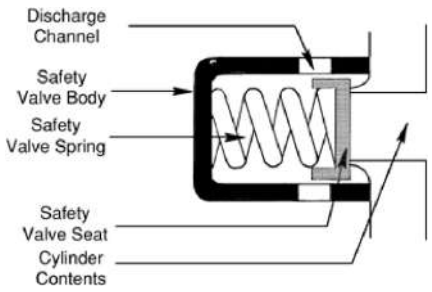

Figure 1.6 Pressure relief valve. When the set pressure is exceeded, the pressure in the cylinder forces the spring to the left, and gas flows around the safety valve seat to the discharge channel. (From a drawing furnished by Ohmeda, a division of the BOC Group, Inc.)

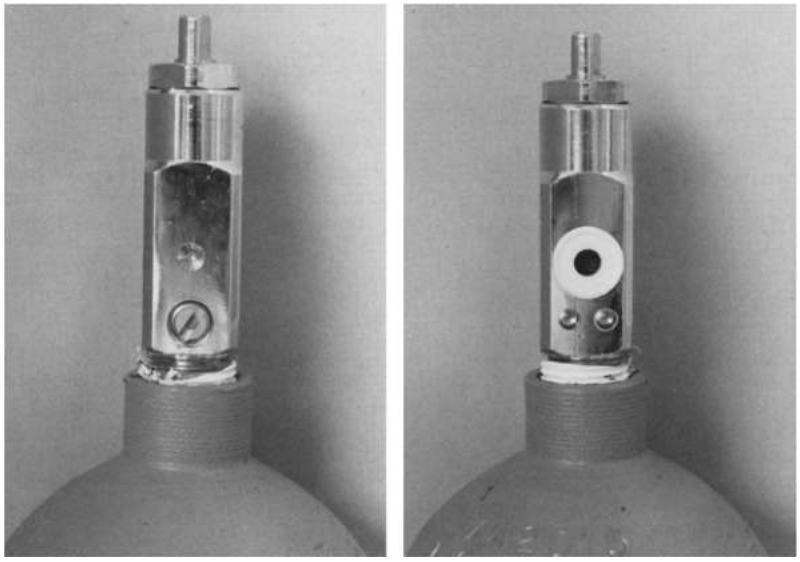

Figure 1.7 Small cylinder valves. **Left:** The conical depression is above the pressure relief device. **Right:** The port is above the Pin Index Safety System holes. A washer is over the port.

Conical Depression

Above the safety relief device on small cylinders is the conical depression that receives the retaining screw of the yoke (Figs. 1.2, 1.3, 1.7). It must be distinguished from the safety relief device. If the retaining screw is tightened into the safety relief device, the device may be damaged and the cylinder contents escape (9).

Noninterchangeable Safety Systems

With widespread use of cylinders containing different gases, a potential hazard is connection of a cylinder to equipment intended for a different gas (1,10). To help solve this problem, color coding was developed; however, this did not give complete protection against human error. Through the cooperation of the CGA and others, two noninterchangeable systems were developed. Both of these systems are located between the cylinder valve and the pressure regulator and should not be confused with the Diameter Index Safety System (DISS) or proprietary quick connects that are on the intermediate (pipeline) pressure side of the pressure regulator, which will be discussed in Chapter 5.

Pin Index Safety System

The Pin Index Safety System consists of holes on the cylinder valve positioned in an arc below the outlet port (Figs. 1.7, 1.8). Pins on the yoke or pressure regulator are positioned to fit into these holes. Pins assigned to gases or gas mixtures used in

anesthesia are shown in Table 1.2. Unless the pins and holes are aligned, the port will not seat. It is possible for a yoke or pressure regulator without pins to receive any cylinder valve, but ordinarily it is not possible for an undrilled cylinder valve to be placed in a yoke or pressure regulator containing pins.

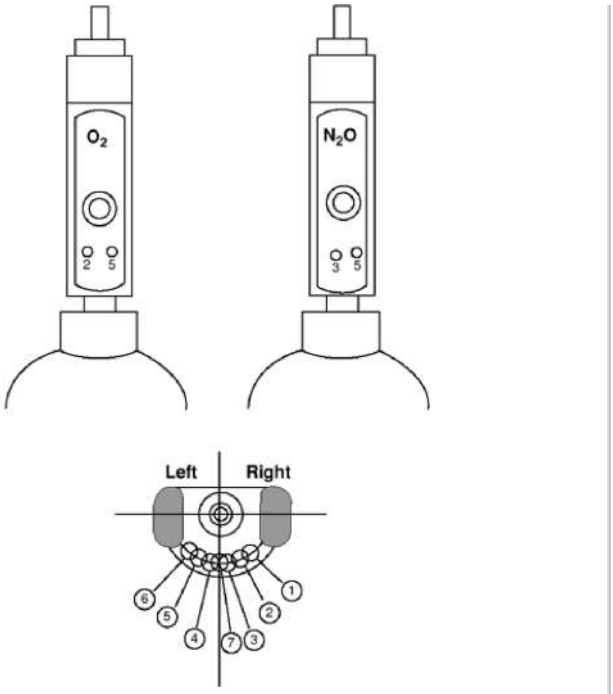

Figure 1.8 Pin Index Safety System. The bottom figure shows the six positions for pins on the yoke. The pins are 4 mm in diameter and 6 mm long, except for pin 7, which is slightly thicker. The seven hole positions are on the circumference of a circle of 9/16 inch radius centered on the port.

While the pin index system works well for the common gases used in anesthesia, there are problems when specialized gas mixtures are used. As an example, a 5% CO_2 mixture with oxygen has a different pin index than 100% carbon dioxide. Carbon dioxide mixtures of 7% or greater CO_2 would be fitted with the pin index of 100% CO_2 (11).

Valve Outlet Connections for Large Cylinders

Larger cylinder valves have threaded outlet (bull nose) connections (Fig. 1.9) (12). When the threads of this outlet mesh with those of the nut, the nut may be tightened, causing the nipple to seat against the valve outlet. In this way, the gas channel of the valve is aligned with the channel of the nipple. The outlets and connections are indexed by diameter, thread size, right- and left-handed threading, external and internal threading, and nipple seat design.

TABLE 1.2 Pin Index System

Gas	*Index Pins*
Oxygen	2, 5

Nitrous oxide	3, 5
Cyclopropane	3, 6
O_2-CO_2 (CO_2 < 7.5%)	2, 6
O_2-CO_2 (CO_2 > 7.5%)	1, 6
O_2-He (He > 80.5%)	4, 6
O_2-He (He < 80.5%)	2, 4
Air	1, 5
Nitrogen	1, 4
N_2O-O_2 (N_2O 47.5%Ì€“52.5%)	7

Sizes

Gas suppliers classify cylinders by using a letter code, with A being the smallest. Table 1.3 gives the approximate dimensions and capacities for some commonly used cylinders. The volume and pressure of gas in a particular size cylinder vary (13). Oxygen and air are similar in volumes and pressures. The same is true for carbon dioxide and nitrous oxide.

Size E is the cylinder most commonly used on anesthesia machines and for patient transport and resuscitation. Size D cylinders are used for limited supplies of gases where size and weight considerations are important. Aluminum cylinders were originally longer than steel cylinders with the same outside diameter (14). Ones manufactured more recently have the same or a shorter length and a larger outer diameter than steel cylinders.

Contents and Pressure

As illustrated in Figure 1.10, in a cylinder containing a nonliquefied gas, the pressure declines steadily as the contents are withdrawn. Therefore, the pressure can be used to measure the cylinder contents.

In a cylinder containing a liquefied gas, the pressure depends on the vapor pressure of the liquid and is not an indication of the amount of gas remaining in the cylinder as long as the contents are partly in the liquid phase. The pressure remains nearly constant (with constant temperature) until all the liquid has evaporated, after which the pressure declines until the cylinder is exhausted. Weight can be used to determine the amount of liquid in these cylinders. In practice, weighing cylinders is awkward and rarely performed.

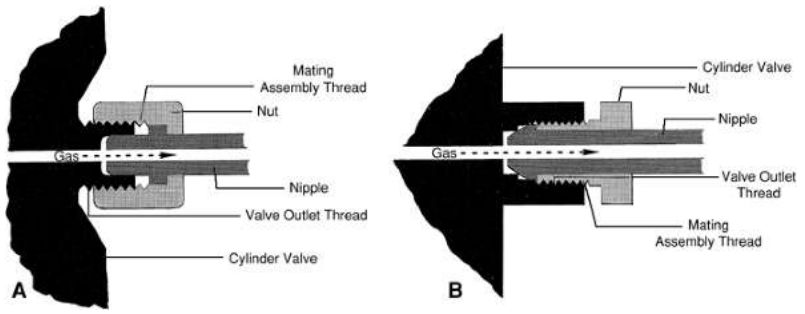

Figure 1.9 Valve outlet connections for large cylinders. **A:** The valve outlet thread is external, i.e., the threads are on the outside of the cylinder valve outlet and the nut screws over the valve outlet. **B:** The valve outlet thread is internal so that the nut screws into the outlet. The specification for cylinder connections are often shown as in the following example for oxygen: 0.903-14-RH EXT. The first number is the diameter in inches of the cylinder outlet. The next number gives the number of threads per inch. The letters following this indicate whether the threads are right hand or left hand and external or internal. (Redrawn courtesy of the Compressed Gas Association.)

During use, the temperature is not likely to remain constant. Evaporation of the liquid and expansion of a gas requires energy in the form of heat, which is supplied mainly by liquid in the cylinder. This results in cooling. If the outer surface of a cylinder that contains liquefied gas becomes cold as gas is discharged, this indicates that residual liquid remains in the cylinder (15). As the temperature falls, the vapor pressure of the liquid also falls so that a progressive fall in pressure accompanies the release of gas from the cylinder (15). If liquid remains when withdrawal stops, cylinder pressure will slowly increase to its original level as the temperature rises.

TABLE 1.3 Typical Medical Gas Cylinders, Volumes, Weights, and Pressures

Cylinder Size	*Cylinder Dimensions (O.D. × Length in Inches)*	*Empty Cylinder Weight (lb)*	*Capacities and Pressures (at 70°F)*	*Air*	*Carbon Dioxide*	*Helium*	*Nitrous Oxide*	*Oxygen*	*Nitrogen*	*Helium-Oxygen Mixturesa*	*Carbon Dioxide–Oxygen Mixturesa*
B	$3^1/_2$ × 13	5	L		370			200			
			psig		838			1,900			
D	$4^1/_2$ × 17	11	L	375	940	300	940	400	370	300	400
			psig	1,900	838	1,600	745	1,900	1,900	+	+
E	$4^1/_4$ × 26	14	L	625	1,590	500	1,590b	660	610	500	600

			psig	1,900	838	1,600	745b	1,900	1,900	+	+
M	7 ⅜— 43	63	L	2,850	7,570	2,260	7,570	3,450	3,200	2,260	3,000
			psig	1,900	838	1,600	745	2,200	2,200	+	+
G	$8^1/_2$ ⅜— 51	97	L	5,050	12,300	4,000	13,800			4,000	5,300
			psig	1,900	838	1,600	745			+	+
H	$9^1/_4$ ⅜— 51	119	L	6,550		6,000	15,800	6,900c	6,400c		
			psig	2,200		2,200	745	2,200c	2,200c		

[a]The + indicates that the pressures of these mixed gases will vary according to the composition of the mixture.
[b]An E-size cylinder of nitrous oxide contains approximately 250 L when the pressure begins to decrease below 745 psig.
[c]7,800-L cylinders at 2,490 psig are available.

Testing

A cylinder must be inspected and tested at least every 5 years or, with a special permit, up to every 10 years.

The test date (month and year) must be permanently stamped on the cylinder (1).

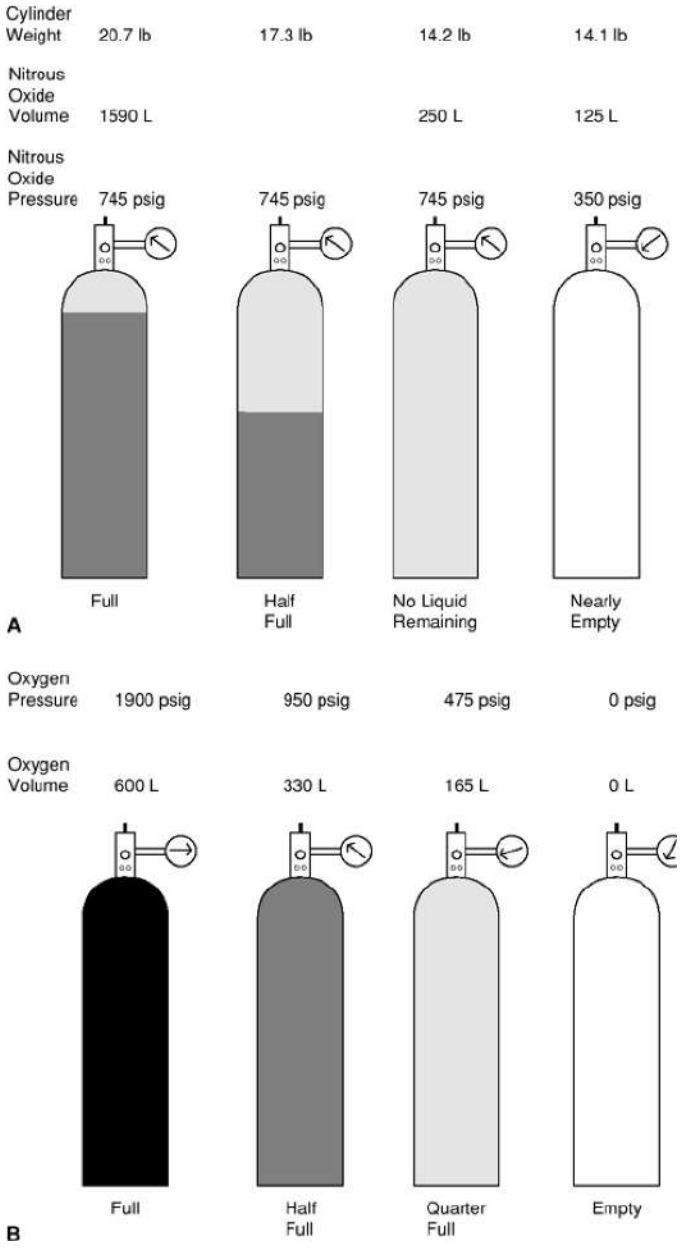

Figure 1.10 The relationship between cylinder weight, pressure, and contents. **A:** A gas stored partially in liquid form, such as nitrous oxide, will show a constant pressure (assuming constant temperature) until all the liquid has evaporated, at which time the pressure will drop in direct proportion to the rate at which gas is withdrawn. **B:** A nonliquefied gas such as oxygen will show a steady decline in pressure until the cylinder is evacuated. Each cylinder, however, will show a steady decline in weight as gas is discharged.

Each cylinder must pass an internal and external visual check for

corrosion and evidence of physical impact or distortion. Cylinders are checked for leaks and retention of structural strength by testing to a minimum of 1.66 (1.50 in Canada) times their service pressures. The service pressure is the maximum pressure to which the cylinder may be filled at 70ยฐF. Table 1.3 gives the service pressures for gases commonly used in anesthesia.

Filling

If a cylinder containing gas under a safe pressure at normal temperature is subjected to higher temperatures, the pressure may increase to a dangerous level (1). To prevent this, the DOT has drawn up regulations limiting the amount of gas a cylinder may contain.

1. The pressure in a filled cylinder at 70ยฐF may not exceed the service pressure marked on the cylinder except for some nonliquefied, nonflammable gases such as oxygen, helium, carbon dioxideโ€“oxygen mixtures and helium-oxygen mixtures, which may be allowed an additional 10%.
2. For gases other than nitrous oxide and carbon dioxide, the pressure in the cylinder at 130ยฐF may not exceed 1.25 times the maximum permitted filling pressure at 70ยฐF.
3. As illustrated in Figure 1.10, in a cylinder containing a liquefied gas, the pressure will remain nearly constant as long as there is liquid in the cylinder. Thus, if only the pressure were limited, these cylinders could be filled with any amount of liquid. To prevent a cylinder containing a liquefied gas from being overfilled, the maximum amount of gas allowed is defined by a filling density (filling or fill ratio) for each gas. The filling density is the percent ratio of the weight of gas in a cylinder to the weight of water that the cylinder would hold at 60ยฐF (1). The filling densities of gases commonly used in anesthesia are shown in Table 1.4.

The filling density is not the same as the volume of the full cylinder occupied by the liquid phase. For example, in a full nitrous oxide cylinder, the liquid phase typically occupies 90% to 95% of cylinder volume, whereas the filling density is 68%.

TABLE 1.4 Medical Gases

Gas	*Formula*	*United States*	*International*	*State in Cylinder*	*Filling Density*
Oxygen	O_2	Green	White	Gasa	
Carbon dioxide	CO_2	Grayb	Gray	Gas + Liquid (below 88ยฐF)	68%
Nitrous oxide	N_2O	Blue	Blue	Gas + Liquid (below	68%

				98ยฐF)	
Helium	He	Brownc	Brown	Gas	
Nitrogen	N_2	Black	Black	Gas	
Air		Yellowd	White & black	Gas	

[a]Special containers for liquid oxygen are discussed later in this chapter.
[b]In carbon dioxideโ€“oxygen mixtures in which the CO_2 is greater than 7%, the cylinder is predominantly gray and the balance is green. If the CO_2 is less than 7%, the predominant color is green.
[c]If helium is greater than 80% in a helium-oxygen mixture, the predominant color is brown and the balance is green.
[d]Air, including oxygen-nitrogen mixtures containing 19.5%โ€“23.5% oxygen, is color coded yellow. Cylinders with nitrogen-oxygen mixtures other than those containing 19.5%โ€“23.5% oxygen are colored black and green.

Color

Accidental confusion of cylinders has been a significant cause of mortality. Color can be used to help identify gases. The color code used in the United States is shown in Table 1.4. The top and shoulder (the part sloping up to the neck) of each cylinder are painted the color assigned to the gas it contains or the entire cylinder may be covered by using a nonfading, durable, water-insoluble paint. In the case of a cylinder containing more than one gas, the colors must be applied in a way that will permit each color to be seen when viewed from the top. In some countries, the body of the cylinder is painted with the color of the major gas and the shoulder the color of the minor gas (11). In this situation, a 14% mixture of CO_2 in O_2 might look more like an oxygen cylinder than a CO_2 cylinder but would fit a CO_2 pin indexed yoke.

Color coding is commonly used on valve protection caps, hoses, connectors, knobs, and gauges on medical equipment.

An international color code (Table 1.4) has been adopted by several countries, including Canada (16). This system differs from the one used in the United States in that oxygen's color is white and air is black and white rather than yellow. A number of countries besides the United States use a color code that differs from the international code (17). When people trained in one country work in another country that has a different color code, confusion frequently results.

Color standardization is not applicable in areas where specialty gases, such as those used for calibration, are used (18). It is important that the label be read carefully when these gases are used.

Because of variations in color tones, chemical changes in paint

pigments, lighting effects, and differences in color perception by personnel, color should be not be used as the primary means for identification of

cylinder contents. Cylinder labels are the best method to identify cylinder contents. However, color is useful to identify the contents of a cylinder from a distance and for sorting purposes and provides a useful check on labeling accuracy.

Markings

DOT and TC regulations require specific markings on each cylinder (1,19). These are permanently stamped, usually onto the shoulder of the cylinder. The markings of a typical cylinder might be arranged as follows:

DOT-3A2015

8642

XYZ

JCN

In this example, the DOT specification is 3A, the service pressure is 2015 psig at 70ยฐF, the serial number is 8642, the manufacturer is XYZ, and the owner's symbol is JCN. These same markings could be arranged in a horizontal line around the shoulder.

The initial qualifying test date (month and year) with an identifying mark for the testing facility between the month and year is required. If a cylinder has been retested, the retest date and testing facility must appear below the original qualifying date. A five-pointed star stamped after the most recent test date indicates that the cylinder may be retested every 10 instead of every 5 years. If a plus (+) sign appears immediately after the test date marking on a cylinder, it means that the cylinder is authorized to be charged up to 10% in excess of the marked service pressure. The word SPUN must be stamped on cylinders that have the bottom end closure produced by spinning or the word PLUG when the bottom closure has been produced by spinning, drilling, and plugging.

Figure 1.11 Cylinder label, showing the basic CGA marking system. The diamond-shaped figure denotes the hazard class of the contained gas (NONFLAMMABLE). To the left is a white panel with the name of contained gas (NITROGEN). The signal word (CAUTION) is to the right, followed by a statement of hazards and measures to be taken to avoid injury.

Labeling

Each cylinder must bear a label or decal on the side or, when space permits, the shoulder of the cylinder (but it may not cover any permanent markings) (1).

Figure 1.11 shows a typical cylinder label. It has a diamond-shaped figure denoting the hazard class of the contained gas and a white panel with the name of the contained gas to the left. The diamond indicates whether the contents contain an oxidizer, a nonflammable gas, or a flammable gas. A signal word (DANGER, WARNING, or CAUTION, depending on whether the release of gas would create an immediate, less than immediate, or no immediate hazard to health or property) is present. Following the signal word is the statement of hazard, which gives the dangers with customary or reasonably anticipated handling or use of the gas. A brief precautionary statement giving measures to be taken to avoid injury or damage is usually present.

The label should contain the name and address of the cylinder manufacturer or distributor and a statement about its content, usually the volume in liters at 70ยจF. Other information such as the cylinder weight when empty and full may also be present.

The expiratory date for the contents may also be present. It should be possible to read the expiratory date while the cylinder is connected to the anesthesia machine (20).

DOT regulations permit the use of a combination label-tag, one side of which contains the prescribed wording of the DOT label, while the other side is used as a shipping tag with space for the names and addresses

of the shipper and consignee. Medical gas manufacturers usually

use these on large cylinders, attached to the cylinder cap. The tag is perforated so that when the cylinder is empty, part of the tag may be torn off at the perforation, obliterating the label wording. The part of the tag that remains attached to the cylinder contains the return address of the supplier.

Tags

A typical tag is shown in Figure 1.12. It has three sections labeled FULL, IN USE, and EMPTY connected by perforations. When a cylinder is put into service, the FULL portion of the tag should be detached. When the cylinder is empty, the IN USE portion should be removed, leaving the EMPTY label. The tag sometimes contains a washer (seal) that fits between the small cylinder valve and the yoke or regulator. Tags normally bear the same color as the cylinder. The tag is primarily a means of denoting the amount of cylinder contents, not an identification device.

Rules for Safe Use of Cylinders

General

1. Cylinders should be handled only by personnel who have been trained in safe practices (21,22). Frequently, personnel involved in the transport, storage, and use of cylinders do not receive adequate instructions regarding their safe handling (23). Even those who do receive adequate training may become complacent.
2. Cylinder valves, pressure regulators, gauges, or fittings should never be permitted to come into contact with oils, greases, organic lubricants, rubber, or other combustible substances. Cylinders or valves should not be handled with hands, rags, or gloves contaminated with oil or grease. Polishing or cleaning agents should not be applied to the valve, as they may contain combustible chemicals.

Figure 1.12 Cylinder tag. When the cylinder is first opened, the FULL portion of the tag should be removed. When the cylinder is empty, the IN USE portion should be removed.

3. No part of any cylinder should ever be subjected to a

temperature above 54ยฐC (130ยฐF) or below -7ยฐC (20ยฐF) (22). A flame, torch, or sparks from any source should never be permitted to come in contact with any part of a cylinder. A cylinder should not be supported by or placed in proximity to a radiator, steam pipe, or heat duct. If a cylinder is exposed to a high temperature, it should be returned to the manufacturer for testing. Exposure to extremes of cold should also be avoided. If ice or snow accumulate on a cylinder, it should be thawed at room temperature or with water at a temperature not exceeding 54ยฐC (130ยฐF).

4. Connections to piping, pressure regulators, and other equipment should always be kept tight to prevent leaks. If a hose is used, it should be in good condition.
5. The discharge port of a pressure relief device or the valve outlet must not be obstructed.
6. Regulators, hoses, gauges, or other apparatus designed for use with one gas should never be used with cylinders containing other gases.
7. Adapters to change the outlet size of a cylinder valve should not be used, as this defeats the purpose of standardizing valve outlets.
8. The valve should be kept closed at all times except when the cylinder is in use. It should be turned OFF by using no more force than necessary to prevent damage to the seat.
9. The valve is the most easily damaged part of the cylinder. Valve protection caps (metal caps that screw over the valve on large cylinders [Fig. 1.13]) protect the valve in case the cylinder topples over and should be kept in place and hand tightened, except when the cylinder is connected for use.
10. No part of the cylinder or its valve should be tampered with, painted, altered, repaired, or modified by the user. Cylinders should be repainted only by the supplier.
11. Markings, labels, decals, or tags must not be defaced, altered, or removed.
12. A cylinder should not be used as a roller, support, or for any other purpose other than that for which it was intended, even if it is believed to be empty.
13. Care must be taken to prevent the cylinder from being damaged by an electric arc. This requires that cylinders not be placed or used in a manner where they can become part of an electrical circuit.
14. Cylinders should not be dropped, dragged, slid, or rolled, even for short distances. Cylinders should be

transported by using a cart or carrier made especially for that purpose (Figs. 1.14, 1.15). They should not be moved or lifted by the valve or valve protection cap.

Figure 1.13 Large cylinder valve protection cap. This cap should be kept in place at all times, except when the cylinder is connected for use.

15. Cylinders should be properly secured at all times to prevent them from falling or being knocked over (Fig. 1.16). They should not be dropped or permitted to violently strike each other or other surfaces. They should not be chained to movable apparatus such as a bed.

Figure 1.14 This cart is designed to store and transport E cylinders in an upright position.

Figure 1.15 Special baskets on transport beds are available to hold the cylinder during transport.

16. Cylinders should never be used where they could become contaminated by other gases or foreign material.
17. The owner of the cylinder must be notified if any damage that might impair its safety is noticed or if any condition that might permit a foreign substance to enter the cylinder or valve has occurred.
18. Disposition of unserviceable cylinders is potentially dangerous and should be done only by qualified personnel.

Storage

1. A definite area should be designated for storing cylinders. They should not be stored in an operating room.

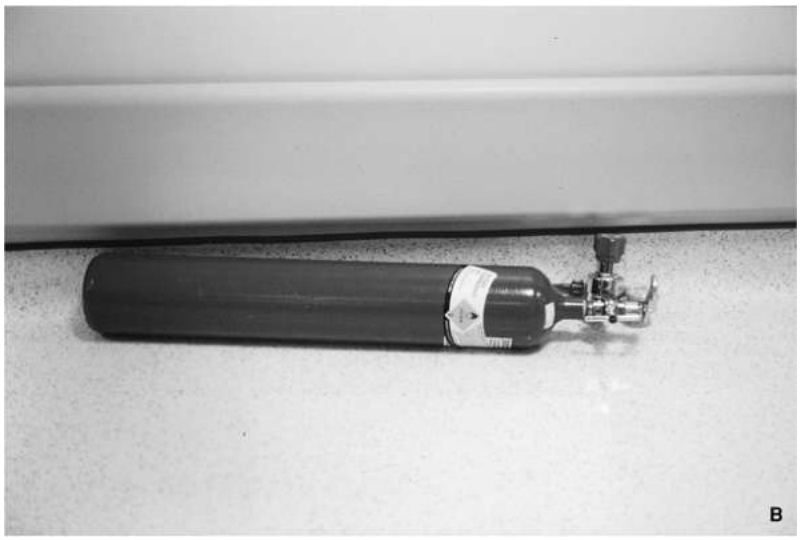

Figure 1.16 A: An unsafe practice. Cylinders should not be allowed to be upright and unsecured. **B:** If there is no means to secure a cylinder upright, it is safer to have it on its side. However, personnel may trip over it or damage it.

2. The storage area should be in a cool, clean area that is constructed of fire-resistant materials. Conductive flooring must be present where flammable gases are stored but is not required where only nonflammable gases are kept. Adequate ventilation should be provided so that if there is a leak in a cylinder, gas will not accumulate in the room.

Easily visible signs with texts such as Ỉ€GAS CYLINDERS. REMOVE TO A SAFE PLACE IN THE EVENT OF FIREỈ€ and Ỉ€OFF LIMITS TO UNAUTHORIZED PERSONNELỈ€ should be hung outside the storage area. Signs reading Ỉ €NO SMOKING,Ỉ€ Ỉ€NO OPEN FLAMES OR SPARKS,Ỉ€ Ỉ €NO OIL OR GREASE,Ỉ€ and Ỉ€NO COMBUSTIBLE MATERIALSỈ€ should be posted inside the room and on the door.

3. Cylinders may be stored in the open but should be protected against extremes of weather and from the ground beneath. During winter, stored cylinders must be protected from accumulations of ice and snow. The temperature should not be allowed to fall below 10ยฐC where Entonox cylinders are stored. In summer, cylinders must be protected from continuous exposure to direct rays of the sun in localities where high temperatures prevail.
4. Cylinders should be stored in a secure area, with removal only by authorized personnel. Cylinders in public areas should be protected from tampering.
5. Cylinders of nitrous oxide should be stored where the opportunity for theft and/or indiscriminate use is minimized. There should be a system for detecting unusually heavy use or loss of nitrous oxide. Thefts should be reported promptly to the police and the supplier.
6. Cylinders containing flammable gases should not be stored in an enclosure containing oxidizing gases (nitrous oxide, oxygen, or compressed air). Nonflammable (inert) medical gases may be stored in the same enclosure as oxidizing gases.
7. Combustible materials should not be kept near cylinders containing oxygen or nitrous oxide. An exception to this may be made in the case of cylinder shipping cartons or crates (5). Cylinder storage racks may be made of wood.
8. Sources of heat in storage locations must be protected or located so that cylinders are not heated to the point where integral safety devices are activated. In no case shall the temperature of the cylinder exceed 125ยฐF.
9. Smoking or open flames should be prohibited in storage areas.
10. Cylinders should not be exposed to continuous dampness, corrosive chemicals, or fumes, as these may damage the cylinders and/or cause valve protection caps to stick.
11. Cylinders should be protected from mechanical shock. They should not be stored where heavy moving objects may strike or fall on them.
12. Small cylinders are best stored upright or horizontally in bins or racks constructed of a nonflammable material that will not damage the cylinder surface when it is moved (Fig. 1.14). Large cylinders should be stored upright against a wall and chained in place.
13. Wrappings should be removed from cylinders before storage. Their presence in the storage area is undesirable

because they are frequently dirty, provide a combustible medium, and conceal the cylinder labels.

14. A cylinder should not be draped with any material. A combustible mixture may accumulate under the drape, and its removal could cause a spark.
15. When different types of gases are stored in the same location, containers should be grouped by contents and sizes (if different sizes are present). Full cylinders should be stored so that they are used in the order they were received from the supplier. Empty cylinders should be marked as such and segregated from full cylinders to avoid confusion and delay.
16. There should be a system of inventory for both empty and full cylinders.

Use

1. Before use, the contents of the cylinder should be identified by reading the label (24,25,26). The color of a cylinder should not be relied on for identification. If the label is missing, illegible, or altered or if the cylinder color and label do not correspond, the cylinder should be returned to the manufacturer unused. The user should read the precautionary information on the label and follow the recommendations.
2. Only cylinders with the letters DOT or ICC (Interstate Commerce Commission) should be used. In Canada, equivalent cylinders are marked BTC (Board of Transport Commissioners) or CTC (Canadian Transport Commission). A cylinder that does not show evidence of inspection within the required period should not be used. The cylinder valve, especially the pressure relief device, outlet, and pin index holes, should be checked for defects. The valve outlet should be clean and pin indexed or have a proper large valve outlet connection.
3. The release of high-pressure gas from a cylinder can be hazardous unless adequate means are provided for reducing the gas pressure to usable levels and for controlling the gas flow. Accordingly, a pressure regulator should always be used when withdrawing the contents of a cylinder. For small cylinders attached to an anesthesia machine, the regulator inside the machine performs this function. When connected to

a pipeline system, the regulator is part of that system (Chapter 2).

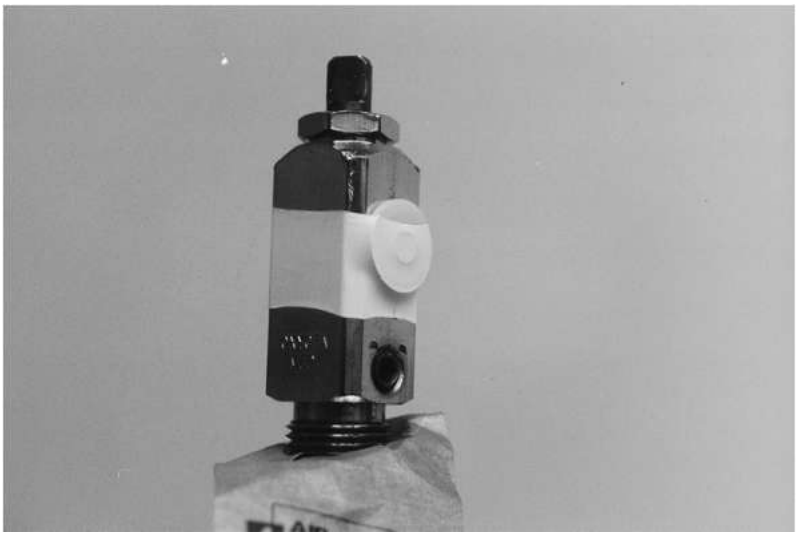

Figure 1.17 Protective cover over small cylinder valve outlet.

4. Full cylinders are usually supplied with a tamper-evident seal (Fig. 1.17). The seal usually is shrink-wrapped around the valve or is in the form of a tear off. This seal should be removed immediately before fitting the cylinder to the dispensing equipment.
5. The valve protection cap on large cylinders should be removed just before connecting the cylinder for use.
6. Before a regulator is connected to a cylinder, it should be inspected for signs of damage and to make certain that it is free of foreign materials. Regulators should be kept in good condition and stored in plastic bags to avoid contamination.
7. Before any fitting is applied to the cylinder valve, particles of dust, metal shavings, and other foreign matter should be cleared from the outlet by removing the protective cap or seal and slowly and briefly opening (‘€cracking‘€) the valve with the port pointed away from the user and any other persons (27). This reduces the possibility of a flash fire or explosion when the valve is later opened with the fittings in place; also, the dust will not be blown into the anesthesia machine or other equipment where it could clog filters or interfere with the internal workings.
8. A sealing washer (gasket) in good condition should always be used with a small cylinder valve. It fits over the port (Fig. 1.7). Only one washer should be used. If more than one washer is used, the pins on the yoke or regulator may not extend far enough to engage the mating holes, and the Pin Index Safety System may be bypassed or a leak may occur (28,29,30).
9. The threads on the regulator-to-cylinder valve connection and the pins on the yoke-to-cylinder valve connections should mate properly. Connectors that do not fit should never be forced.

10. Only wrenches or other tools provided or recommended by the manufacturer should be used to tighten outlets and connections. Wrenches with misaligned jaws should not be used because they may damage the equipment or slip and injure personnel. Excessive force should not be used. The handwheel should never be hammered in an attempt to open or close the valve.

11. The cylinder valve should be opened before bringing the apparatus to the patient or the patient to the apparatus. If a Bourdon gaugeÎ€“type regulator (Chapter 5) is being used, the low-pressure adjustment screw on the regulator should be turned counterclockwise until it turns freely before the cylinder valve is opened. If the cylinder is attached to the yoke on an anesthesia machine or a regulator/flowmeter, the flow control valve for that gas should be closed before the cylinder valve is opened.

12. The person opening a cylinder valve should be positioned so that the valve outlet and/or the face of the pressure gauge points away from all persons. The

user should stand to the side rather than in front or in back. Using goggles or a face mask is also recommended.

13. A cylinder valve should always be opened SLOWLY. If gas passes quickly into the space between the valve and the yoke or regulator, the rapid recompression in this space will generate large amounts of heat. Because there is little time for this heat to dissipate, this constitutes an adiabatic process (one in which heat is neither lost nor gained from the environment). Particles of dust, grease, and such in this space may be ignited by the heat, causing a flash fire or explosion. Opening the valve slowly prolongs the time of recompression and permits some of the heat to dissipate. The cylinder valve should continue to be opened slowly until the pressure on the gauge stabilizes and then fully opened.

14. After the cylinder valve is opened, the pressure should be checked. A cylinder with a pressure substantially greater than the service pressure should not be used but instead should be marked as defective and returned to the supplier. A cylinder arriving with a pressure substantially below the service pressure should be checked for leaks.

15. If a cylinder valve is open but no pressure is registered on the gauge or no gas flows, the cylinder valve should be closed and the cylinder should be disconnected from the dispensing apparatus, marked defective, and returned to the supplier with a note indicating the problem.

16. If a hissing sound is heard when the valve is opened, this indicates that a large leak exists and the connection should be tightened. If the sound does not disappear, the sealing washer should be replaced (in the case of a small cylinder valve). Under no circumstances should more than one washer be used. If the hissing sound persists, soapy water, a commercial leak detection fluid, or other suitable solution should be applied to all parts. Bubbles will appear at the site(s) of the leak(s). A flame should never be used for this

purpose. Should a leak be found in the cylinder valve itself, it may be possible to tighten the packing nut by turning it slightly in a clockwise direction (see special handle in Fig. 1.4) unless the manufacturer recommends otherwise. If the leak cannot be remedied by tightening connections without using excessive force, the valve should be closed, and the cylinder should be marked defective and returned to the supplier with a note indicating the fault.

17. Even if no hissing sound is audible when the valve is opened, a slow leak may be present and should be suspected if there is loss of pressure when no gas is being used. These leaks should be located and corrected.
18. When in use, a cylinder must be secured to a cylinder stand or to apparatus of sufficient size to render the entire assembly stable.
19. Cylinders in service or storage at user locations must be secured to prevent falling.
20. The valve should always be fully open when a cylinder is in use. Marginal opening may result in failure to deliver adequate gas flow.

After Use

1. At any time an extended period of nonuse is anticipated, the cylinder valve should be closed completely and all pressure vented (bled) from the system.
2. An empty or near-empty cylinder should not be left on an anesthesia machine. A defective check valve in the yoke could result in accidental filling if the valve is left open. In addition, the presence of an empty cylinder may create a false sense of security. A yoke should not remain empty after a cylinder is removed. If a full cylinder is not available, a yoke (blanking) plug (Chapter 5) should be in place. Some gas suppliers prefer that cylinders be returned with enough pressure (e.g., 25 psig) remaining to maintain the integrity of the cylinder.
3. Before removing a cylinder from a regulator or yoke, the valve should be closed and all downstream pressure released.
4. When a cylinder is empty, the lower part of the tag should be removed. A DOT green, yellow, or red label should be covered with an Ţ€Emptyţ€ label, or if the cylinder is provided with a combination label-tag, the lower portion should be removed.
5. Valves should be completely closed on all empty cylinders. Often, cylinders are not completely empty, and accidents have resulted from release of gas from a supposedly empty cylinder. If the valve remains open on an empty cylinder, debris and contaminants could be sucked into it when the temperature changes.
6. Where provided, valve outlet caps or plugs should be securely affixed to the valve outlet prior to transportation.

Transfilling

Transfilling should not be performed by unskilled, untrained persons (5). It is best performed by a gas manufacturer or distributor. If performed by a user, it should be in accordance with suggested procedures and not in a patient care area. There are several hazards.

1. Transferring medical gas from one cylinder to another may adversely affect purity.
2. When a small cylinder is transfilled from a large cylinder containing gas at high pressure, rapid recompression of the gas in the small cylinder may cause the

   temperature to rise sufficiently to ignite combustible materials and oxidize metals.
3. The hazard of overfilling small cylinders is always present (31). Filling capacities may vary for cylinders even though their sizes appear to be the same. Overfilling may result in damage to the cylinder or dispensing equipment.
4. Cylinders used for one gas may accidentally be charged with a gas other than that originally contained in the cylinder, resulting in a dangerous mixture (32,33). If an oxygen cylinder were filled with a gas other than oxygen, hypoxia would likely occur with use.
5. Safety relief devices and other parts must be inspected at frequent intervals to ensure safe operation and repairs and to ensure that replacements are made when defects are found. If transfilling is performed by users, this may not be done.

Hazards

Incorrect Cylinder

Despite almost universal use of the Pin Index Safety System and other systems to prevent an incorrect cylinder from being attached to an apparatus, reports of incorrect tanks being connected to yokes or regulators continue to appear (25,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50). Yokes or regulators may be incorrectly built or altered. Pins can be bent, broken, removed, or forced into the yoke or regulator; pin index holes may become worn; and more than one washer may be used. Some lasers have yokes that lack pins (39). In one reported case, the index system had been altered to accept Entonox (a mixture of oxygen and nitrous oxide) (51). The hole for the pin had been drilled through the valve. When a nitrous oxide cylinder was put on the yoke and tightened, the pin was pushed through the hole, and an incorrect cylinder could have been attached.

Incorrect Contents

A cylinder may not contain the gas for which it is indexed and labeled (32,33,34,52,53,54,55). In a cylinder with a mixture, the gases may not be properly mixed (56).

Incorrect Valve

A cylinder may be correctly labeled for the gas contained but have a valve for another gas (52,57,58,59). This usually will prevent its attachment to the correct dispensing apparatus. Industrial rather than medical gas cylinders are sometimes used to power surgical tools. These may have connections that fit equipment designed for other gases (60).

Incorrect Color

Cylinders may be painted with other than their standard color (57,61).

Incorrect Labeling

A cylinder with the correct color and valve may have an incorrect label (52,62).

Inoperable Valve

A cylinder may be delivered with an inoperable or blocked valve (7,57,63,64).

Damaged Valve

If the retaining screw on the yoke is screwed into the safety relief device instead of the conical depression, the valve will be damaged. This may result in a leak of cylinder contents (9). A pressure relief device may prematurely release gas (65).

Asphyxia

Sudden discharge of large quantities of gas other than oxygen from a cylinder into a closed space could displace the air from that space, creating a dangerous condition. If an oxygen-deficient atmosphere is suspected, the space should be checked with an oxygen monitor. A number of deaths due to nitrous oxide inhalation have been reported (66,67).

Fires

If an oxidizing gas is present, fires are likely to occur if a source of ignition and flammable material(s) are also there. Both oxygen and nitrous oxide are oxidizing gases, and their presence should be considered a source of risk. Materials that burn in air will burn much more vigorously and at a higher temperature in oxygen at normal pressure and explosively in oxygen under pressure. Some materials that do not burn in air will burn in an oxygen-enriched atmosphere, particularly under pressure. Materials that can be ignited in air have lower ignition energies in oxygen.

Many materials may be ignited by friction at a valve seat or stem packing or by adiabatic compression produced when gas at high pressure is rapidly introduced into a system initially at low pressure. If oxygen equipment is contaminated with dirt, grease, oil, hand cream, paraffin, or other combustible substances, explosive rupture and burning of components may occur (27,68). Oxygen regulators and cylinders contaminated with oil have been sold (69,70,71).

Fires have been reported when the incorrect gas was used to

inflate the abdomen during laparoscopy (50,72,73). Chapter 32 discusses additional information on fires.

Explosion

A cylinder that has been incorrectly filled may explode if the valve does not have the proper pressure relief device (74).

Projectile Damage

If a cylinder is improperly secured and falls over, the valve may break off. Because gas in cylinders is under pressure, rapid escape of cylinder contents can cause the cylinder to shoot like a rocket or to spin out of control (34,74,75,76,77). This could cause serious damage to equipment and personnel.

Improper handling or storage of cylinders can cause them to fall over. If a valve protection cap is not present, the valve could snap off. If the packing nut rather than the stem is loosened, the stem may be ejected when the valve is opened. Cylinders with defective valves may be manufactured (78,79,80,81).

If a steel cylinder is taken into the MRI environment, it can be drawn into the magnet (3). This will occur with such force that the magnet will be damaged or a patient or health care personnel in the room could be seriously injured or killed. Equipment for use in the MRI environment is discussed in Chapter 30.

Contaminated Cylinder Contents

Gases in cylinders may contain contaminants (57,81,82,83,84). Medical-grade oxygen is required to be 99% pure (81,85,86). Of the remaining 1% (10,000 ppm), not more than 300 ppm of carbon dioxide, 10 ppm of carbon monoxide, or 5 ppm of oxides of nitrogen can be present. No other contaminants are specifically excluded from the other 9,685 ppm. Thus, the possibility exists that oxygen or other gases may contain potentially dangerous amounts of other compounds and not be in violation of existing standards. An industrial-grade gas may not have the same requirements for purity as a medical-grade gas and may contain relatively large amounts of impurities (60). Accidental use of such gas could cause significant problems. Cases of poisoning due to contamination of nitrous oxide cylinders with higher oxides of nitrogen have been reported (82,87).

A cylinder should not be used if the gas has an odor. The cylinder should be sequestered and the appropriate authorities contacted.

Moisture may contaminate a cylinder and flow into the dispensing equipment if the cylinder is inverted (83). Adiabatic gas expansion as gas is released causes cooling, and the moisture could form ice and jam the regulator or yoke. In the past, this has been a significant problem with nitrous oxide cylinders.

Nitrous Oxide Theft

Nitrous oxide theft for substance abuse purposes can be a serious problem, and deaths have been reported (67,88,89).

Overfilled Cylinders

An overfilled cylinder may be delivered (52,57,90,91).

Thermal Injury

Frostbite injury from nitrous oxide has been reported in people who use the drug recreationally and in anesthesia providers and others who handle it occupationally (6,92,93,94,95).

Blocked Flowmeter

If a flow-metering device that is integral with a cylinder does not have a continuous scale but has fixed flow rates, then no oxygen may be delivered between flow rate settings (4).

Liquid Oxygen Containers

Small, specially designed containers filled with liquid oxygen have become popular, especially for patient transfer. Another use is when anesthesia is administered outside a health care facility, such as by armed forces. Advantages include low pressure, compactness, low weight, and simplicity.

Equipment

A stationary unit (reservoir, supply container) is kept in a suitable area and is refilled by the gas supplier as needed (Fig. 1.18). The smaller, portable (receiving) units are filled from the stationary unit. They are broader and shorter than cylinders. The portable unit has a means of regulating oxygen flow. The amount of gas contained can be determined by its weight.

Each container must have a pressure relief device and a means to limit the amount of liquid oxygen contained. When not in use, the pressure in the container is controlled by venting excess gas to atmosphere. This limits the time that oxygen can be stored in the portable unit (96).

Liquid gas containers are manufactured, maintained, filled, and transported in accordance with DOT regulations. Required markings include the specification number, service pressure for which the container is designed, an identifying mark of the original container owner, and a serial number. The date of original manufacture and a symbol identifying the inspector are also present.

An international standard covers these devices (97).

Rules for Safe Use

1. If liquid oxygen is spilled, a considerable time must be allowed for the oxygen to dissipate.
2. Contact between the skin and liquid oxygen must be avoided.

Figure 1.18 Liquid oxygen containers. **Left:** The stationary unit, which is refilled by the gas supplier as needed. Note the pressure relief valve at right front. **Right:** The portable unit is attached to the stationary unit for transfilling.

3. Liquid oxygen equipment must be kept clean of organic or combustible materials. These materials can react violently with liquid oxygen.
4. Cryogenic transfilling devices must be kept free of moisture to prevent accumulation of frost on valves or couplings that may cause them to freeze open or shut.
5. Containers should not be subjected to extremes of heat or cold.
6. Containers should be handled in a manner to avoid physical damage.
7. Markings and labels on containers must be legible and must not be altered.
8. Under no circumstances should any attempt be made to loosen, tighten, or otherwise tamper with the pressure relief device.

Storage

1. Both the stationary and portable units should be kept in open, cool, well-ventilated areas. Containers should not be stored in a closed space such as a closet.
2. Liquid oxygen containers should be stored away from any heat source.
3. Containers should be protected from corrosive atmospheres.
4. Containers should be stored in an upright position.

Transfilling

Liquid oxygen may be transferred by means of a cryogenic flexible hose assembly or the manufacturer's noninterchangeable direct connection. If a flexible hose assembly is used, its end connectors must conform to CGA regulations (1) or the manufacturer's noninterchangeable connectors and must have a pressure relief device.

Transfilling must be performed in a well-ventilated location that is remote from patient care areas, has no sources of ignition, and is posted with Ĩ€NO SMOKINGĨ€ signs.

Hazards

Fires

If liquid oxygen equipment becomes contaminated with hydrocarbons such as oil or grease or other combustible materials, ignition may occur. Vaporized spilled liquid oxygen will result in an oxygen-enriched atmosphere, increasing the fire hazard. Fires are discussed in detail in Chapter 32.

High Pressure

The large volume of gaseous oxygen resulting from vaporization of liquid oxygen has the potential, if trapped in a closed space that is not protected by adequate

pressure relief devices, to generate pressures high enough to cause danger to life, limb, and property.

Burns

Contact with cold liquid or frosted valves or couplings may cause cryogenic burns. Physical damage to or failure of liquid oxygen equipment can result in liquid spilling or spraying in an uncontrolled manner (98,99). A pressure relief valve on a portable container may open prematurely and vent liquid oxygen during or immediately after filling (100).

Equipment Freezing

Valves or couplings may freeze shut if they are not kept free of moisture.

Inaccurate Flows

One study showed that a high percentage of portable liquid oxygen devices had flows that differed substantially from those set (101).

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Questions

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. if D is correct

E. if A, B, C, and D are correct.

1. Liquefied compressed gases at room temperature include the following:

A. Carbon dioxide

B. Air

C. Nitrous oxide

D. Oxygen

View Answer

2. A typical cylinder label includes

A. A statement of hazard

B. The name of the gas in the cylinder

C. A signal word

D. The manufacturer or distributor

View Answer

3. Adiabatic compression

A. Refers to compression of a gas in a small space

B. Occurs downstream of a regulator

C. Can cause a fire

D. Occurs when a cylinder valve is opened slowly

View Answer

4. The likelihood of a fire is reduced by the following measures:

A. Cracking the cylinder valve before use

B. Opening the cylinder valve slowly

C. Storing pressure regulators in plastic bags

D. Keeping the cylinder draped during storage

View Answer

5. Hazards of transfilling the cylinder include the following:

A. Flash fires

B. Overfilling

C. Contamination of gases

D. Filling with the wrong gas

View Answer

6. The filling density is

A. The ratio of the weight of gas in a container to the weight of water that container would hold

B. The percentage of a cylinder volume occupied by liquefied gas

C. A means to limit the amount of a liquefied gas in a cylinder

D. Proportional to the density of the gas in the cylinder

View Answer

7. Cracking a cylinder valve

A. Is momentarily opening it to blow away foreign matter from the outlet

B. Should be performed before attachment of a dispensing device

C. Reduces the likelihood of flash fires

D. Refers to a fracture of the stem of the valve

View Answer

8. Noninterchangeable systems that prevent a large or small cylinder from being connected to the incorrect piping system include

A. The Pin Index Safety System

B. Manufacturer-specific quick-connect systems

C. Outlet valves with special threaded connections

D. The Diameter Index Safety System

View Answer

For the following questions, select the correct answer.

9. The government agency responsible for regulating medical gas cylinders and containers in the United States is the

A. Food and Drug Administration

B. Department of Health and Human Services

C. Department of the Interior

D. Department of Transportation

E. Department of Labor

View Answer

10. An E cylinder of oxygen contains approximately how many liters?

A. 500

B. 650

C. 750

D. 900

E. 1200

View Answer

11. All of the following are required permanent makings on a cylinder except

A. The service pressure

B. The serial number

C. The name of the contained gas

D. The test date

E. The symbol of the producer, user, or manufacturer

View Answer

12. The best means for identifying the contents of a cylinder is the

A. Color

B. Label

C. Tag

D. Markings on the cylinder shoulder

E. Pin index holes

View Answer

13. The cylinder size most commonly used on anesthesia machines and for patient transport is

A. Size A

B. Size B

C. Size C

D. Size D

E. Size E

View Answer

14. If an empty oxygen cylinder is found on an anesthesia machine, the best action to take is to

A. Remove the empty cylinder and leave the yoke empty

B. Remove the cylinder and replace it with a yoke plug

C. Mark the cylinder empty and leave it in place

D. Remove the empty cylinder and replace it with a full cylinder

E. Open the adjacent cylinder valve fully

View Answer

15. 1 kPa is approximately equivalent to

A. 10 cm H_2O

B. 14.7 psi

C. 0.76 mm Hg

D. 100 mbar

E. 1.47 psi

View Answer

Chapter 2
Medical Gas Pipeline Systems

Health care facilities use pipeline systems to deliver nonflammable gases such as oxygen, nitrous oxide, air, carbon dioxide, and nitrogen to anesthetizing locations and other patient care areas. Central piping systems are installed by mechanical contractors and are maintained by the engineering or maintenance department of the health care facility, usually with little input from anesthesia providers. This not only neglects a potentially valuable contribution but also leaves those who use the gases uninformed as to how the systems work. Because the systems are mostly out of sight and as a rule function well, they often do not attract attention until a problem occurs. A survey by the Anesthesia Patient Safety Foundation (APSF) determined that there is a significant knowledge deficit among anesthesia practitioners related to the pipeline systems (1).

When a new facility or addition is being planned, anesthesia personnel should play a key role in designing the piping systems. Their input is important to help properly size the systems and to locate outlets (including those in remote parts of the facility where patients are taken for diagnostic studies or various types of therapy). Careful planning may avoid expensive and inconvenient alterations at a later date.

Standards and Sources of Information

The National Fire Protection Association (NFPA), the Compressed Gas Association (CGA), the Canadian Standards Association (CSA), and the International Standards Organization (ISO) have published numerous documents related to piping systems (2,3,4,5,6). Many of their provisions are incorporated into law. There are also many state and local codes that supersede these standards. Compliance with these standards is one of the bases for accreditation by the Joint Commission on the Accreditation of Healthcare Organizations (JCAHO). These organizations do not approve, inspect, or certify any installations, procedures, equipment, or materials. In most cases,

compliance with standards is the responsibility of the individual gas supplier and facility. Although most medical gas pipeline systems in the United States and Canada are designed to conform to NFPA recommendations, failure to adhere to existing regulations is widespread (7).

Components

A medical gas distribution system includes a central supply, piping extending to locations where the gas may be required, and terminal units at each use point. Hoses that extend from terminal units to the anesthesia machine or other equipment, although not part of the piped system, are included here because they are important to anesthesia.

Supply Sources

A central supply system may be located outdoors (with the control panel protected from the weather) in an enclosure used only for this purpose or in a room or enclosure within a building. Access to the central supply area should be restricted to individuals familiar with and responsible for the system.

A common type of central supply for a small facility is shown in Figure 2.1. Two cylinder banks (units) are present (Fig. 2.2). Each bank must contain at least an average day's supply with a minimum of two cylinders. Larger amounts may be necessary in areas remote from suppliers. The cylinders are connected to a common manifold (header) that converts them into one continuous supply. A check (nonreturn) valve is placed between each cylinder lead and the header to prevent loss of gas from the manifolded cylinders if there is a leak in an individual cylinder or lead. The primary (duty, running) supply is the portion supplying the system at any time, while the other bank is the secondary (standby) supply. When the primary supply is unable to supply the system, the secondary supply automatically becomes the primary supply.

A reserve supply is often added, as shown in Figure 2.3. The reserve is used for emergencies or when maintenance or repair is needed. The reserve system size depends on the rate at which gas is used. A precaution against gas supply disruption is to place the reserve supply in a different area from the primary and secondary supplies and for the reserve supply to enter the

facility by a different route (8,9,10). Further safety may be achieved by separating the primary and secondary supplies so that the secondary supply can be accessed if the primary supply fails (10).

A pressure-reducing (operating) regulator is installed in the main supply line upstream of the pressure relief valve. The pressures at which gases are piped vary, depending on the country. In the United States, gases other than nitrogen and instrument

air are normally piped at 345 to 380 kPa (50 to 55 psi). Nitrogen and instrument air are usually delivered at 1100 kPa (160 psi). The NFPA now permits pressures up to 2068 kPa (300 psi) (2). All final line regulators must be duplexed with suitable valving to permit service without completely shutting down the piped gas system.

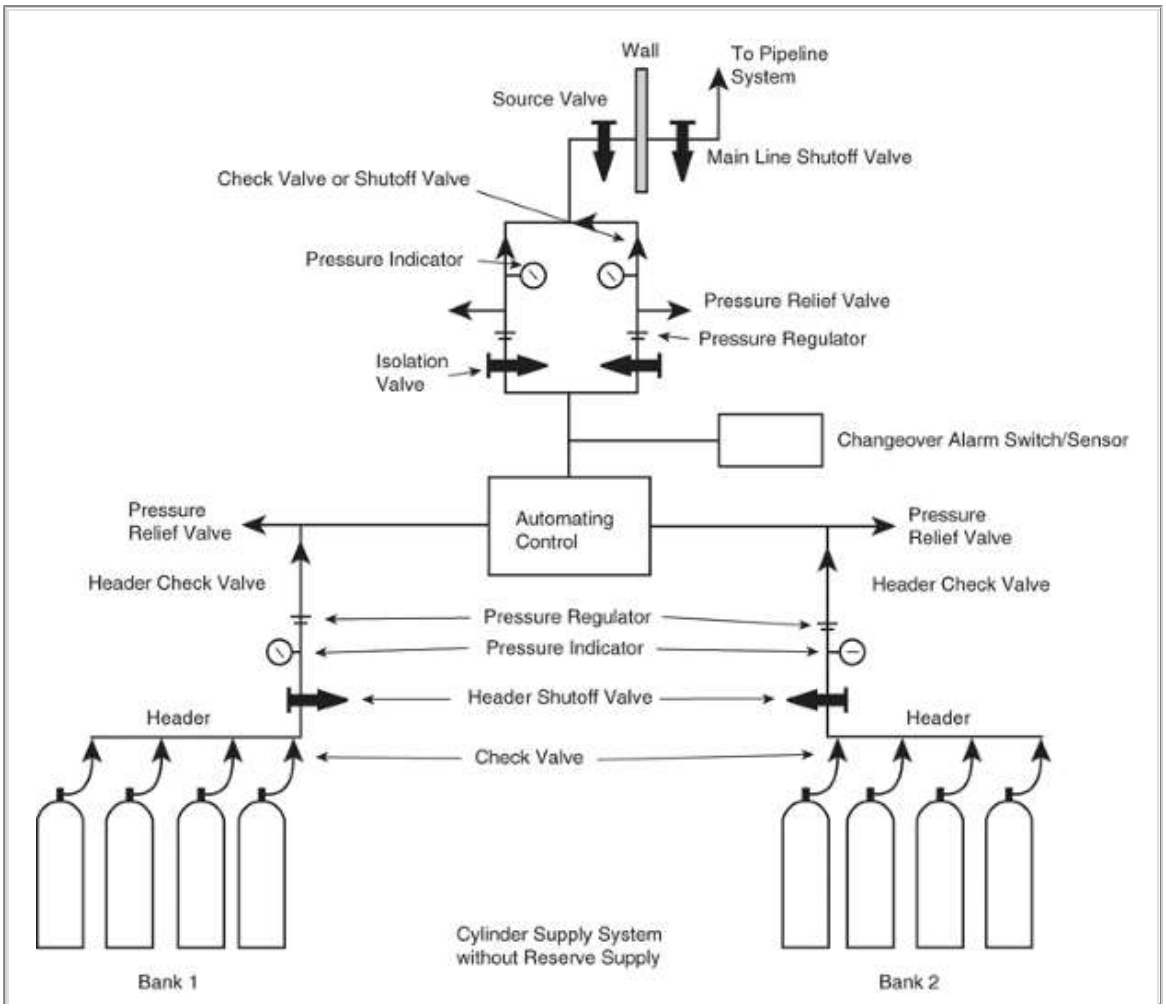

Figure 2.1 Cylinder supply system without reserve supply. This is known as an alternating supply system. The manual shutoff valves permit isolation of either bank of cylinders. Fluctuations in the distribution pressure can be decreased by reducing the pressure in two stages, so a pressure regulator is installed in the outgoing pipe. A manual shutoff valve must be located upstream of and a shutoff or check valve downstream of each pressure regulator. This makes it possible to service the regulator without shutting down the entire system. (Redrawn from a figure in National Fire Protection Association. Standard for health care facilities [NFPA 99]. Quincy, MA: Author, 2005.)

Oxygen

Oxygen may be stored either as a cryogenic liquid at low pressures or as compressed gas in cylinders.

Gaseous Supply

Oxygen may be supplied from compressed gas cylinders (usually G and H cylinders) (Chapter 1) that are transported between the distributor and the central supply area or from cylinders that are fixed at the site and refilled by the distributor.

Liquid Supply

When large amounts of oxygen are required, it is less expensive and more convenient to store it as a liquid. Most frequently, liquid oxygen containers are refilled from supply trucks without interrupting service. Alternatively, filled liquid containers may be transported between the supplier and the facility.

Liquid oxygen containers are installed at ground level so that they are readily accessible to supply trucks (Fig. 2.4). The containers should be located where exposure to potential ignition sources is minimal. NFPA

standards specify how far the container must be from sidewalks, parked vehicles, and other objects.

Figure 2.2 Cylinder supply system. This shows both the primary and secondary supplies with switching mechanism. Note the header and cylinder leads.

To prevent the liquid from evaporating, it must be kept at or below its boiling point (-297ยฐF) by keeping it in special insulated vessels. These containers vary in size and shape. They are constructed like Thermos bottles with outer and inner metal jackets separated by insulation and a layer that is near vacuum to retard heat transfer from the exterior. Each container should have a contents indicator and low liquid level alarm. Gaseous oxygen is drawn off as required and passed through a heater to bring it up to ambient temperature and raise its pressure.

Although the tank is well insulated, a small amount of heat will be continuously absorbed from the surroundings, causing the liquefied gas to evaporate. The amount of this uncontrolled evaporation is normally less than the demand for the piped system. If there is no flow from the container to the pipeline system, the pressure in the container will slowly increase until the safety relief valve opens and oxygen is vented to atmosphere. If a liquid system is left standing unused for a long period of time, a significant amount of oxygen will be lost. Using liquid containers is economical only when there is a fairly constant demand. Having the proper size container will minimize oxygen loss from venting.

Most of the time, the oxygen is kept cold by the latent heat of

vaporization as gaseous oxygen is removed and the temperature falls. As the temperature falls, the pressure within the tank also falls. To maintain pressure, liquid oxygen must be removed from the tank and passed through a vaporizer (evaporator, vaporizing column, gasifier), which supplies heat. This consists of a coil, tube, or mesh that is heated by using electricity or hot water.

Oxygen Concentrator

A third possible oxygen source to feed the oxygen pipeline is a supply system with oxygen concentrators (11). These are discussed in Chapter 9. An international standard covering these systems has been published (12).

Nitrous Oxide

Most facilities use manifolded cylinders to supply nitrous oxide to the pipeline system. One problem with nitrous oxide cylinders is that the regulator may become so cold that it freezes. Nitrous oxide may also be stored as a liquid at low pressure in special insulated vessels similar to those used for oxygen.

Warning signs should be posted around areas where nitrous oxide tanks are located to caution that nitrous oxide is an asphyxiant and that if there is a leak, a hypoxic mixture may be produced.

Medical Air

Medical air (air for breathing) is defined by the NFPA as air, regardless of its source, that meets U.S. Pharmacopoeia (USP) quality standards. Air may be supplied from manifolded cylinders, a proportioning device that

mixes gas from oxygen and nitrogen cylinders, or motor-driven compressors.

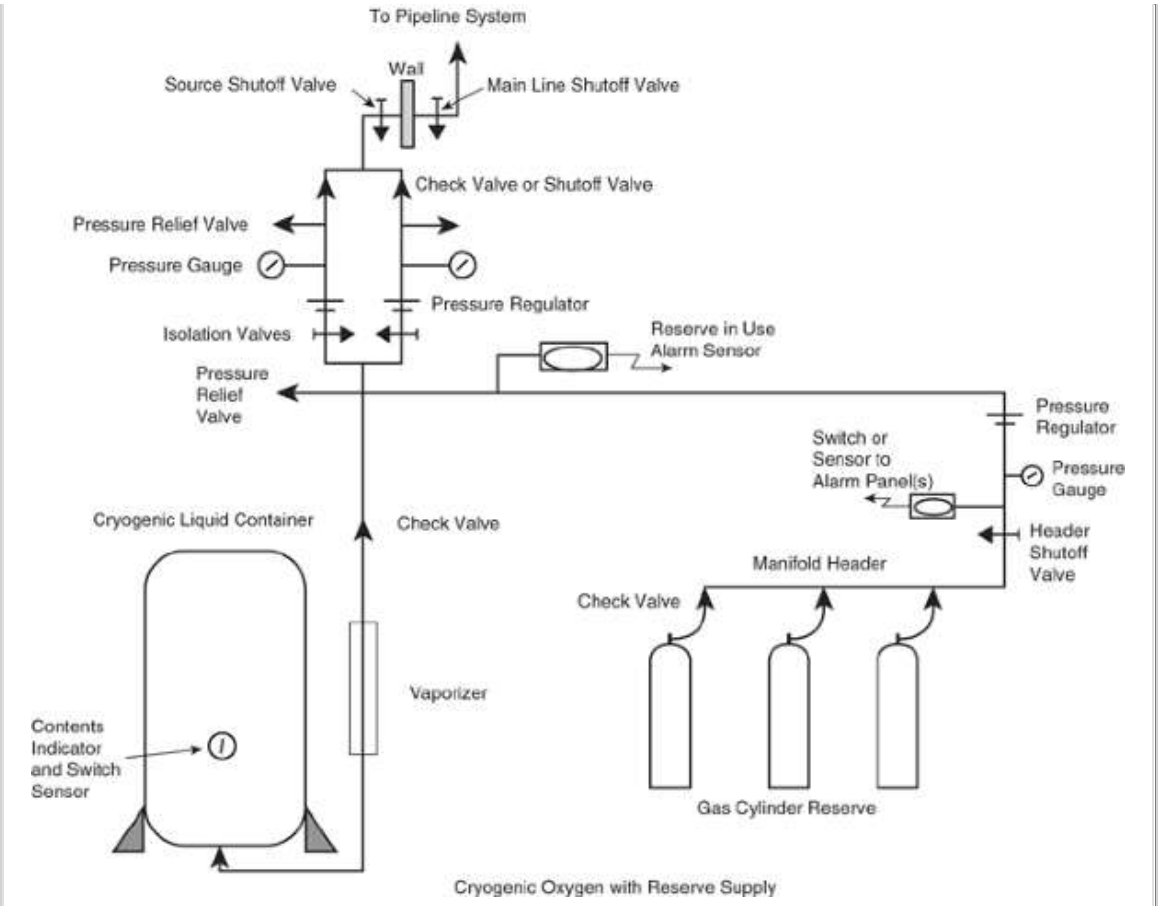

Figure 2.3 Cryogenic oxygen supply system with reserve supply. A liquid oxygen container serves as the operating supply with cylinders in the reserve supply. Operation of the reserve should activate the reserve-in-use alarm. This is known as a continuous-type system because under normal operating conditions, one primary source (which is refilled periodically) always supplies the system. (Redrawn from a figure in National Fire Protection Association. Standard for health care facilities [NFPA 99]. Quincy, MA: Author, 2005.)

The vast majority of piped air systems employ two or more compressors that operate alternately or simultaneously, depending on demand. A typical system is shown in Figure 2.5. Most components must be duplexed and equipped with upstream and downstream shutoff valves that allow both isolation and continued system operation if a component fails.

Each compressor takes in ambient air, compresses it to above the working pressure, and supplies it to one or more receivers

(accumulators, reservoir tanks, storage receivers, reservoirs, holding tanks, receiver tanks) from which air can be withdrawn as needed. The receiver must be equipped with a pressure relief valve, automatic drain, sight glass to permit visual checking that the drains are operating properly, and a pressure gauge.

The intake location is important to ensure that the air will be as free of contaminants as possible. It should be located where it will take in air that is, as much as possible, free of dirt, fumes, and odors. The intake is usually located outside but may be within the building if a source that is equal to or better than outside air is available. It should not be close to or downwind of vacuum or other exhausts, loading docks, or other sources of polluted air. Ambient air taken from a location free from exhausts or other sources of pollution is normally well within the limits required for compressed air by the USP and NFPA for medical air (13).

Figure 2.4 Liquid oxygen storage tank. Behind the large tank is a smaller liquid oxygen tank. To the left of this are two vaporizers.

The air at the intake should be checked periodically. Air quality varies and may exceed the contaminant limits of USP air for unacceptably long periods (13). There are cases where an intake

became improperly located as the environment around the intake changed due to changes in the facility (14).

To render the air suitable for medical use, its water content must be reduced. An aftercooler in which the air is cooled and the condensed moisture removed is usually installed downstream of each compressor. More water may condense in the receiver. Additional water may be removed by running the air through a dryer.

Air downstream of the dryers and upstream of the piping system must be monitored for carbon monoxide and dew point and, with certain types of compressors, for gaseous and liquid hydrocarbons.

Valves, pressure regulators, and alarms analogous to those in oxygen supply systems are needed. The reserve supply may be manifolded cylinders or a separate compressor system.

Instrument Air

A pipeline system that uses air for powering surgical tools and other equipment may be provided. The air provided by this system does not have to meet the requirements for medical air. It is piped at higher pressure than medical air.

Nitrogen

Central nitrogen supplies may include high-pressure cylinders or cryogenic liquid containers.

Carbon Dioxide

Carbon dioxide is being piped more frequently because it is used for laparoscopic surgery. The source is high-pressure cylinders.

Nitric Oxide

A pipeline installation for nitric oxide has been described (15). This gas is usually supplied in cylinders connected to the dispensing device.

Piped Distribution System

There are three general classes of piping:

1. *Main lines*โ€”Pipes connecting the source to risers or branch lines or both.
2. *Risers*โ€”Vertical pipes connecting the main line with branch lines on various levels of the facility.
3. *Branch (lateral) lines*โ€”The sections of the piping system that service a room or group of rooms on the same level of the facility.

Piped system layouts vary considerably. A typical piped system is shown in Figure 2.6. Pipes are made of copper. Generally, oxygen is installed in 1/2-inch outer diameter (OD) and other gases in 3/8-inch OD pipes. Pipes must be identified at least every 20 feet and at least once in every room and story traversed by the piping system to ensure that those installing and maintaining the pipeline are aware of its content. The name and pressure of the gas inside the pipe and its flow direction must be displayed.

Flexible hoses are restricted to exposed areas where they can be inspected and maintained. They cannot penetrate or be concealed in walls, floors, ceilings, or partitions (2).

Pressure Relief Valves

Each central supply system must have a pressure relief valve set at 50% above normal line pressure downstream of the line regulator(s) and upstream of any shutoff valve. This relief valve prevents pressure buildup if a shutoff valve is closed. The valve should close automatically when the excess pressure has been relieved.

Shutoff Valves

Shutoff (ON-OFF, isolating, section, zone) valves permit specific areas of the piping system to be isolated in the event of a problem as well as for maintenance, repair, testing, or expansion without the whole system being

turned OFF. There are two types of shutoff valves: Manual and service. Manual shutoff valves must be installed where they are visible and accessible at all times. Service shutoff valves are designed to be used only by authorized personnel. They are in

locked cases or have their handles secured and tagged to prevent accidental closing.

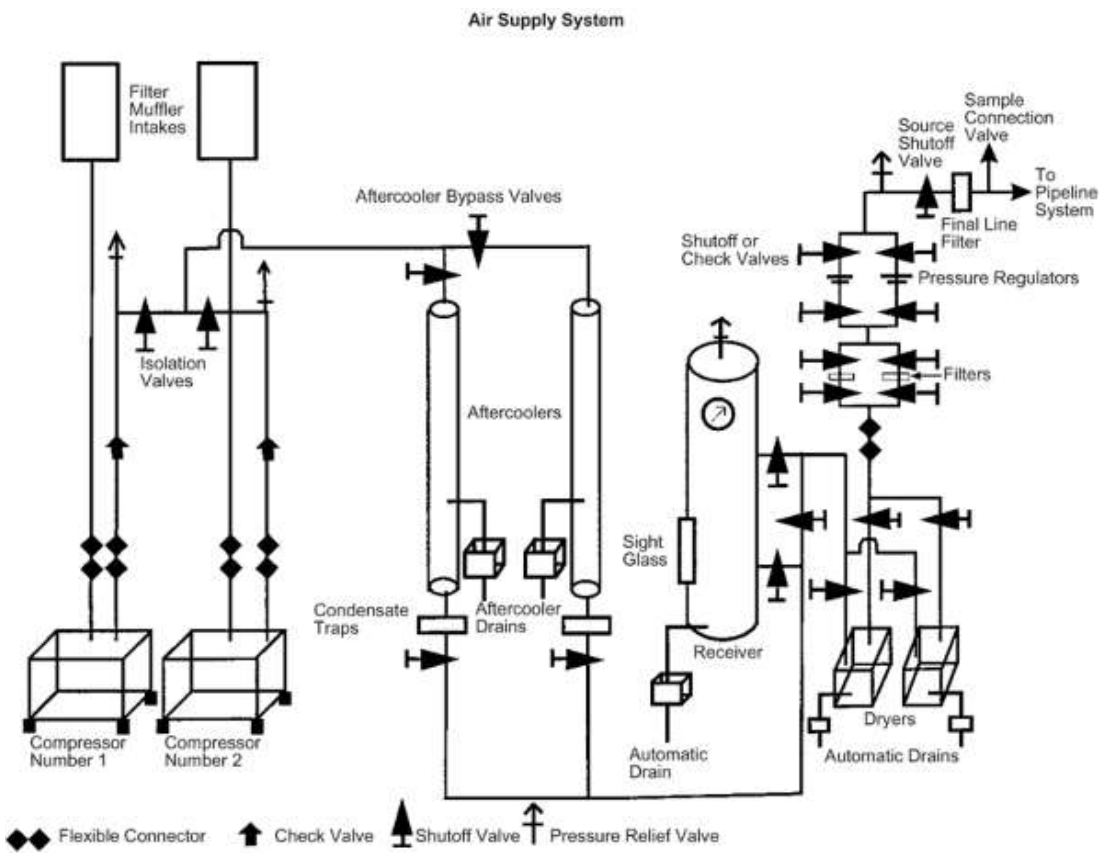

Figure 2.5 Central supply for medical air. The filter/muffler on the inlet side of each compressor removes large particles from aspirated air. Each compressor is provided with an isolation (shutoff) valve and has a pressure relief valve and a check (one-way) valve in its outlet line. Receivers are sized according to the capacity of the compressors. Final line filters trap particulate, oil, and odors introduced by the system. In environments with high concentrations of carbon monoxide, special scrubbers may be used to remove this or other pollutants. Dryers may be of desiccant or refrigerant type. (Redrawn from a figure in National Fire Protection Association. Standard for health care facilities [NFPA 99]. Quincy, MA: Author, 2005.)

Manual shutoff valves are installed in boxes with frangible or removable windows (Fig. 2.7A). A quarter-turn valve with an indicating handle has become standard (Fig. 2.7B). Each valve

should be marked to indicate its function, gas, and area controlled as well as a caution that it should be closed only in an emergency.

A shutoff valve is required at the outlet from the supply source. This allows the entire supply source to be isolated.

The main supply line must be equipped with a manual shutoff valve near the entry into the building unless the source shutoff valve is accessible from within the building. It should be at a location well known and readily accessible to those responsible for maintaining the system but where any attempt to tamper with it would be noticed.

Each riser must be equipped with a manual shutoff valve adjacent to the connection to the main supply line. Each branch (lateral) line except those lines supplying

anesthetizing locations and other vital life support and critical areas (such as postanesthesia care, intensive care, and coronary care units) must have a service shutoff valve where the lateral branches off the riser. A manual shutoff valve is required immediately outside each vital life support or critical care area and must be readily accessible in an emergency.

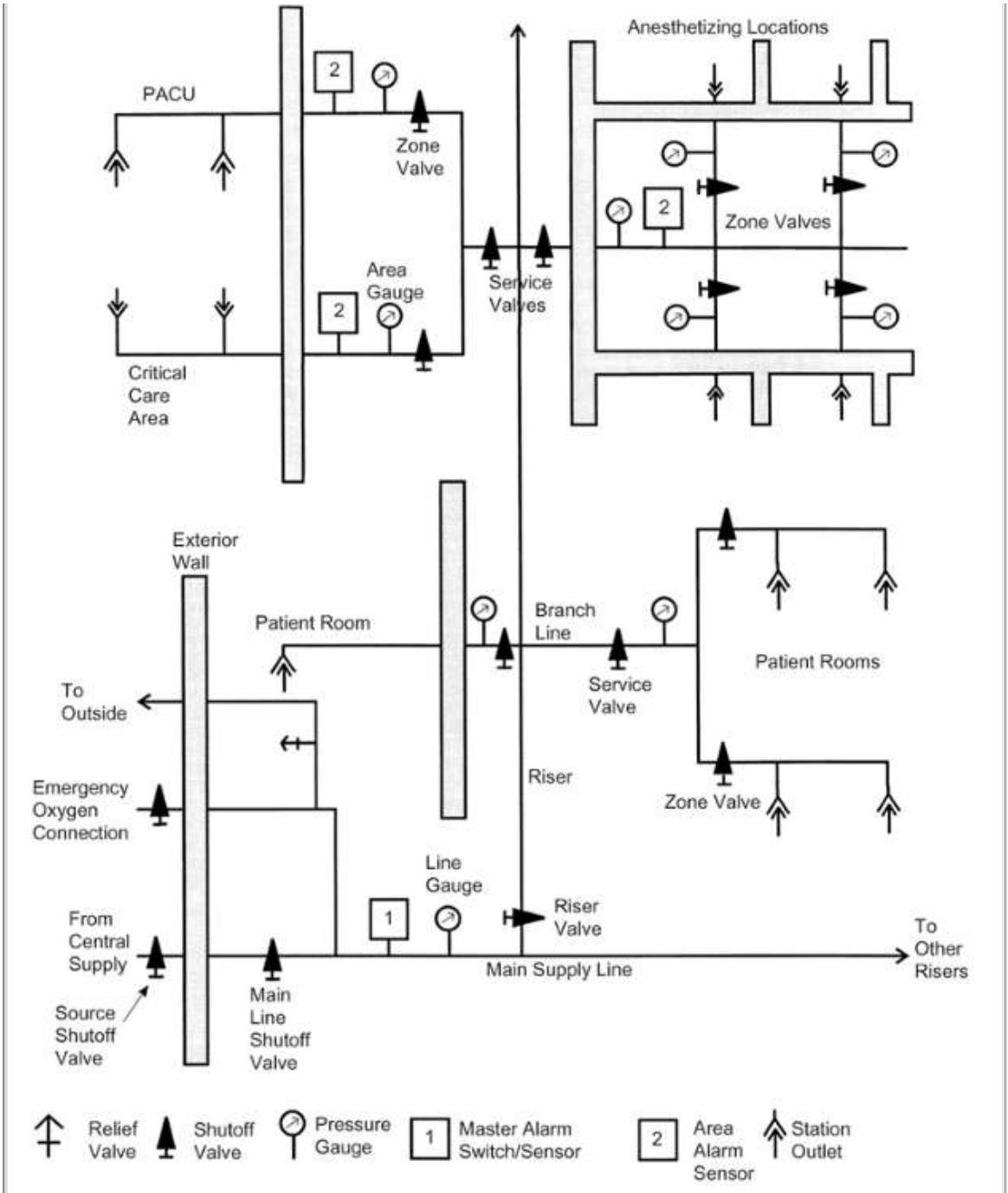

Figure 2.6 Typical medical gas piped distribution system. The main line runs on the same level as the central supply and connects it to risers or branch lines or both. In anesthetizing locations, individual room shutoff valves are located downstream of the area alarm. Other locations have a single shutoff valve for the entire area with the area alarm actuator downstream from the shutoff valve. The master alarm is activated by a

20% increase or decrease in the main line pressure. Area alarms must be installed in branch lines leading to intensive care units, postanesthesia care units, and anesthetizing locations to signal if the pressure increases or decreases 20% from normal operating pressure. (Redrawn from a figure in National Fire Protection Association. Standard for health care facilities [NFPA 99]. Quincy, MA: Author, 2005.)

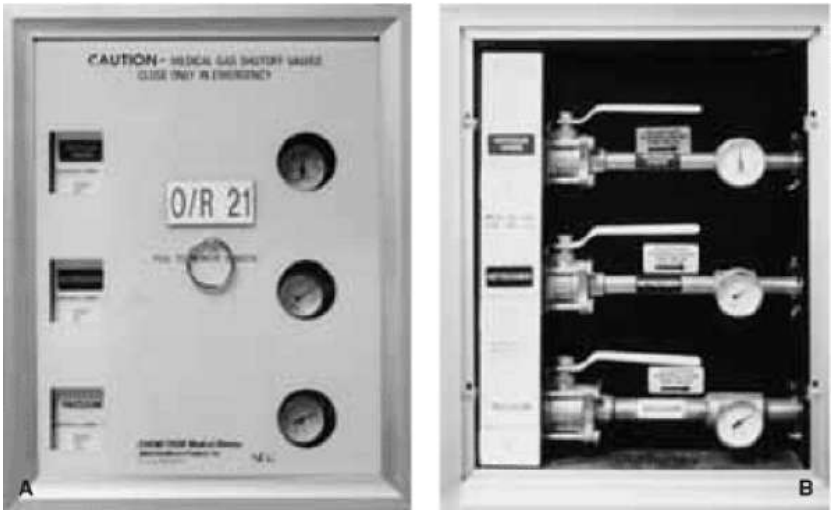

Figure 2.7 A: Box with shutoff valves. The window can be easily removed by pulling the ring in the center. Note that the operating room controlled by the shutoff valves is identified. **B:** Box with cover removed. To close a valve, the handle is pulled a quarter turn. Note that the pipe is labeled to show the gases contained. The front cover cannot be installed if a valve is closed.

A separate manual shutoff valve is required for each anesthetizing location so that shutting off the gas supply to one location will not affect other locations. Shutoff valves should be located where they will be readily accessible to those who need to use them in an emergency and where access is unlikely to be obstructed. The most common location is outside the anesthetizing location so that in an emergency, people inside the room can exit and then shut off gas supplies to the room. A facility is not precluded from installing a shutoff valve inside an anesthetizing location, although additional alarms would be

required. Any person using piped gases should know not only where shutoff valves are located but exactly what they control. The JCAHO has emphasized that shutoff valves are to be properly labeled and that personnel must know their locations.

Emergency Oxygen Supply Connector

When the central oxygen supply is located outside the building it serves and there is not a connected oxygen reserve sufficient for an average day's supply inside the building, a fitting for connecting a temporary auxiliary supply source for emergency or maintenance situations is required (2). The inlet must be located on the building's exterior and be protected from tampering and unauthorized access. The pipe from this fitting attaches to the main supply line immediately downstream of the main line shutoff valve (Fig. 2.6). The inlet should be located where a supply vehicle will have year-round access. In-building emergency reserves may be used in place of the emergency oxygen supply connector.

Alarms

Alarm Types

Master Alarm System

A master alarm system monitors the central supply and the distribution system for all medical gas systems. To ensure continuous responsible observation, master signal panels must be located in two separate locations, wired in parallel to a single sensor for each condition. One panel should be in the principal working area of the department responsible for maintaining the system and one or more panels located to assure continuous surveillance during all working hours (e.g., telephone switchboard, security office, or other continuously staffed location) (2). A centralized computer system may be substituted for one of the master alarms.

Area Alarm Systems

Critical life support areas such as operating room suites, postanesthesia care units, intensive care units, coronary care units, and the like must have an area (local) alarm system to indicate if the pressure increases or decreases 20% from normal

line pressure. In anesthetizing locations, the alarm will be upstream of the shutoff valves to the individual rooms. In other areas, it will be placed downstream of the shutoff valve for the area. Area alarms are sometimes placed in each anesthetizing location.

An appropriately labeled warning signal panel for area alarms must be installed at the nurses' station or other suitable location that will provide responsible surveillance (Fig. 2.8). Many area alarms also sound at the master alarm panel. The alarm components should be monitored daily and the test button exercised monthly (16).

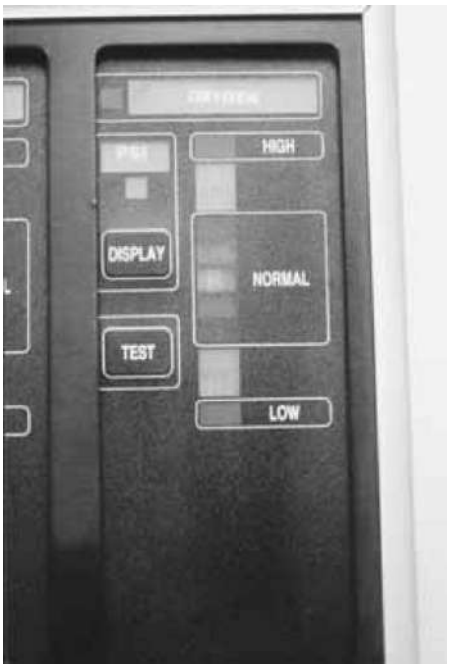

Figure 2.8 Part of area (local) alarm panel. The gas pressure is monitored and a warning provided if the pressure increases or decreases from the normal operating pressure. A button for testing the alarm is provided. Area alarm systems are provided for anesthetizing locations and other vital life support areas such as the postanesthesia care, intensive care, and coronary care units.

Local Alarms

Local alarms are installed to monitor the function of the central medical and instrument air systems as well as the vacuum and anesthetic gas scavenging systems. The signals may be located on or in the control panel of the machinery being monitored, within a monitoring device, or on a separate alarm panel. The master alarm system must include at least one signal from each source equipment location to indicate a problem.

Alarm Conditions and Responses

General Requirements

Each alarm must be labeled for the gas and area monitored. Signals should be both audible and visual. Some systems allow the audible signal to be audio paused (temporarily silenced). The visual signal should continue until the problem is corrected. Each panel should contain a mechanism to test the alarms. Alarms should be designed to function during electrical power failure.

Clear, concise instructions should be given to the persons monitoring the alarms to ensure that signals are reported promptly to the proper parties. Cases have been reported in which an employee did not know what to do when an alarm sounded (7). An activated signal should be reported immediately to the department responsible for operating and maintaining the piping system. The action to be taken will depend on the individual arrangements for each facility. These should be recorded in a procedure manual, that is reviewed periodically, and new employees should be given clear instructions regarding necessary actions.

It is important to update alarms when source equipment is updated or replaced (17).

Alarm Conditions

An alarm should signal (a) when the main supply reaches an average day's supply, (b) when the reserve supply or in-building emergency reserve begins to supply the system, (c) when the reserve supply is reduced to one average day's supply, (d) when the pressure in the reserve supply is below that required to function properly, (e) when the secondary supply becomes the

primary supply, (f) when the pressure in the main line increases or decreases from normal operating pressure, or (g) when the dew point has been exceeded in the medical air or instrument central supply system. In the central medical air supply system, there must be local alarms that indicate compressor malfunction and when the carbon monoxide level exceeds 10 ppm.

Pressure Gauges

A pressure gauge must be installed downstream of each pressure regulator. It is important that the gauge be on the downstream side of a zone valve so that when the valve is closed, this will be indicated by the pressure gauge (17). Pipeline pressure gauges are present on all anesthesia machines. This allows the anesthesia provider to keep a continual check on pipeline pressure in that location. If a significant decrease or increase in pressure occurs, the anesthesia provider should notify the proper personnel and consider using gas from the cylinders on the machine.

Terminal Units

The terminal unit (station outlet, junctional point, interface, pipeline outlet, end use terminal, service outlet, terminal outlet, outlet point, outlet station, outlet assembly, wall outlet) is the point in a piped gas distribution system at which the user normally makes connections and disconnections. Equipment may be connected to a terminal unit either directly or by a flexible hose.

Components

Base Block

The base block is the part of a terminal unit that is attached to the pipeline distribution system.

Primary Valve

The primary valve (automatic shutoff valve; terminal unit valve or check valve; terminal valve; self-sealing valve, device, or unit; primary check valve) opens and allows the gas to flow when the male probe is inserted and closes automatically when the

connection is broken. This serves to prevent gas loss when the removable component is disconnected. Although often called a *check valve*, it is not a unidirectional valve and when open will permit flow in either direction. In some terminal units, the face plate and primary valve are an integral unit.

Secondary Valve

The secondary valve (shutoff valve, terminal stop valve, maintenance valve, automatic service valve, isolating valve, secondary valve, secondary shutoff valve, secondary check valve) is designed so that when the primary valve is removed (e.g., for cleaning or servicing), the gas flow is shut off. When the primary valve is in place, the secondary valve stays open. With hose booms and pendants incorporating hoses, the secondary valve is fitted at or near the end of the permanent pipework.

Gas-specific Connection Point (Socket Assembly)

The receptor for a noninterchangeable gas-specific connector that is either part of or attached to the base block is incorporated into each terminal unit. The connector may be a threaded Diameter Index Safety System (DISS) or a proprietary (manufacturer-specific) quick connector. The corresponding male component of the noninterchangeable connection is attached to the equipment to be used or to a flexible hose leading to the equipment. The female component is called an *outlet connector* or *socket*. The male member is called an *inlet connector*, *probe*, *plug*, *striker*, or *jack*.

Each DISS or quick connector must be equipped with a backflow check valve to prevent gas flow from the anesthesia apparatus or other dispensing apparatus into the piping system.

The Diameter Index Safety System

The DISS was developed to provide noninterchangeable connections for medical gas lines at pressures of 1380 kPa (200 psi) or less (18). As shown in Figure 2.9, each DISS connector consists of a body, nipple, and nut combination. There are two concentric and specific bores in the body and two concentric and specific shoulders on the nipple (Fig. 2.10). The small bore (BB)

mates with the small shoulder (MM), and the large bore (CC) mates with the large shoulder (NN) (Fig. 2.9). To achieve noninterchangeability between different connectors, the two diameters on each part vary in opposite directions so that as one diameter increases, the other decreases. Only properly mated parts will fit together and allow the threads to engage. The American Society for Testing and Materials (ASTM) anesthesia workstation requires that every anesthesia machine have a DISS fitting for each pipeline inlet (Fig. 2.11) (19).

Quick Connectors

Quick connectors (automatic quick couplers valves, quick connects, quick-connect fittings, quick couplers) allow apparatus (hoses, flowmeters, etc.) to be connected or disconnected by a single action by using one or both hands without the use of tools or undue force. Quick connectors are more convenient than DISS fittings but tend to leak more.

Each quick connector consists of a pair of gas-specific male and female components (Fig. 2.12). A releasable spring mechanism locks the components together. Hoses and other equipment are prevented from being inserted into an incorrect outlet by using different shapes and/or different spacing of mating portions.

Face Plate

The face plate should be permanently marked with the name and/or symbol of the gas that it conveys. The identifying color may also be present.

Types

Wall Outlets

Wall outlets (Fig. 2.13) are mechanically simple and well suited to small rooms where the equipment to be connected will be near the wall. In larger rooms, the hoses to the equipment frequently must be long and are often draped across the floor. This leads to personnel tripping over the hoses, difficulty in moving equipment, wear and tear on the hoses, and debris accumulation. For large rooms, more than one set of wall outlets may be advisable.

Ceiling-mounted Hoses

Ceiling-mounted hoses with the terminal unit at the end of the hose (Fig. 2.14) may be used.

Ceiling-mounted Pendants

A ceiling-mounted pendant with one or more articulated arms (Fig. 2.15) keeps wires and hoses from cluttering the floor and can easily be moved to various positions. In addition to terminal units, the pendant may have electrical and data management outlets, space for monitors, telephones, intravenous solution mounts, and suction bottles and regulators.

Ceiling Column

Ceiling-mounted columns (Fig. 2.16) can provide the same services as a pendant but are less versatile with respect to positioning (20). They can be made movable by mounting them on tracks. They can be retractable so that the column can be lowered to attach or detach hoses and then raised to avoid obstruction. Disadvantages include the possibility that people will hit their heads on the column and difficulty gaining access to hoses inside the column. Short personnel may have difficulty attaching hoses to them.

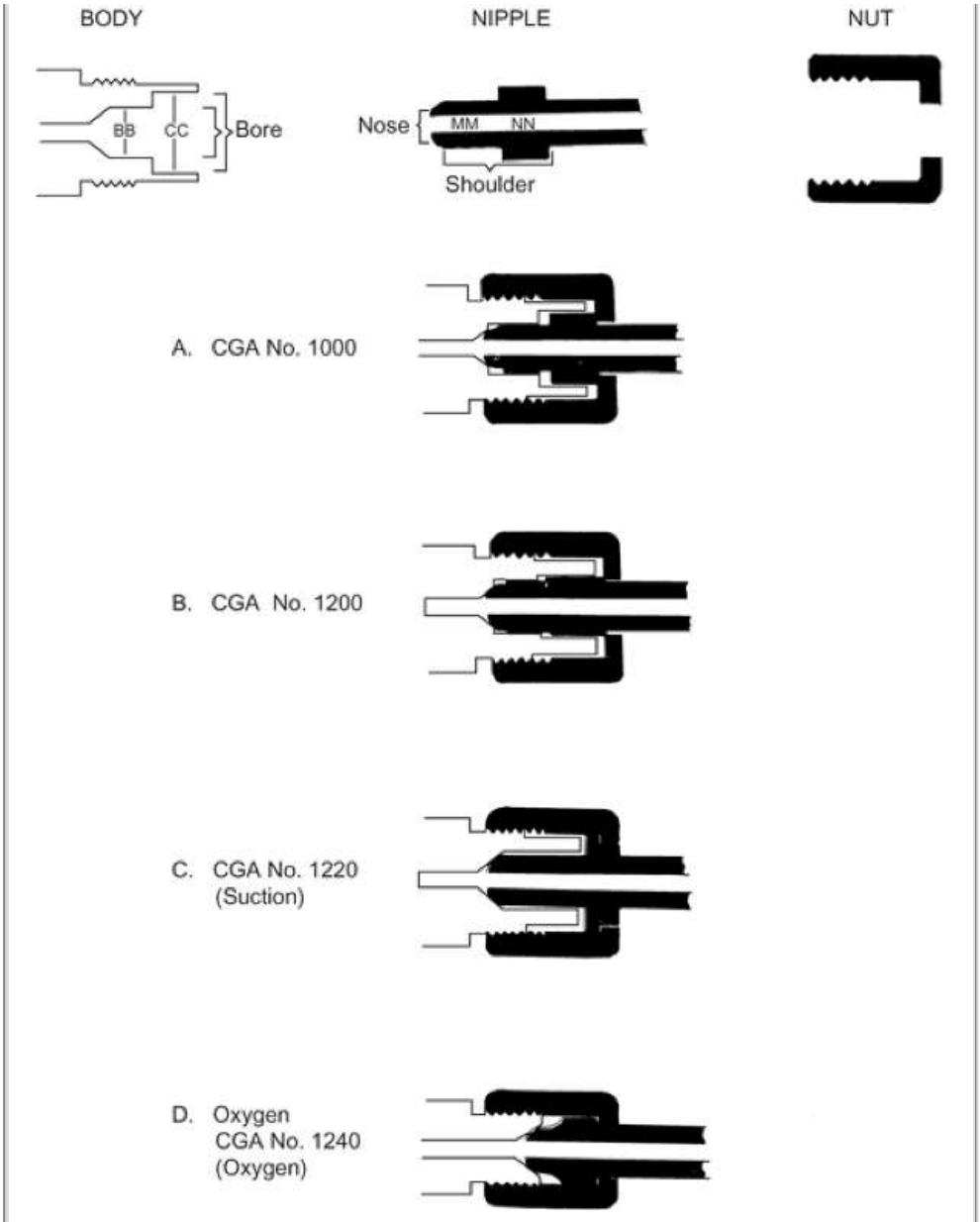

Figure 2.9 Diameter Index Safety System. With increasing Compressed Gas Association (CGA) number, the small shoulder (MM) of the nipple becomes larger, and the large diameter becomes smaller. If assembly of a nonmating body and nipple is attempted, either MM will be too large for small bore (BB) or large shoulder (NN) will be too large for large bore (CC). (Redrawn courtesy of the Compressed Gas Association.)

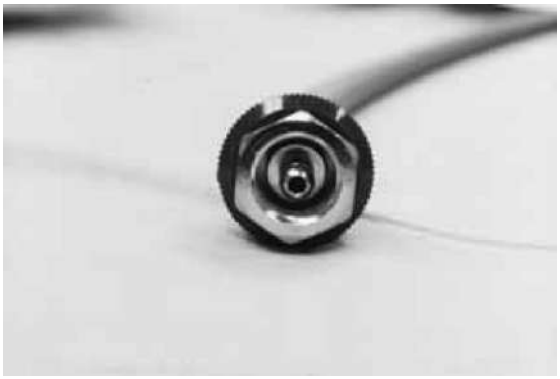

Figure 2.10 End of Diameter Index Safety System connection. Note the two concentric shoulders on the nipple.

Figure 2.11 Pipeline inlets to the anesthesia machine have DISS connectors.

The Nitrogen Piping Terminal Unit

Because the pressure required for nitrogen-driven tools varies, a means of adjusting the pressure at the station outlet is needed. An adjustable regulator similar to those described in Chapter 5 is

used. Figure 2.17 shows a nitrogen terminal unit built into the wall. Two gauges are present, one indicating the distribution pressure and the other the reduced pressure.

Figure 2.12 Quick connector. The two prominences on the hose connector mate with the two slots on the wall outlet to ensure noninterchangeability.

Hoses

Hoses (droplines, hose assemblies, low-pressure hose assemblies, low-pressure flexible connecting assemblies, flexible hose assemblies, pipeline pressure supply hoses, hose pipes) are used to connect anesthesia machines and other apparatus to terminal units (5). Each end must have a permanently attached, noninterchangeable connector. The connector that attaches to a

terminal unit is called the *inlet (supply) connector*. The connector that attaches to equipment such as an anesthesia machine is the *outlet (equipment) connector*.

Figure 2.13 Wall outlets with quick-connector fittings.

A color-coded hose and the name and/or chemical symbol of the contained gas on each connector are desirable. Most hoses have an imbedded braid in the wall for added strength. Hoses should be kept away from any heat source, especially operating room lights, because contact may cause the hose to rupture (21,22). Whenever possible, hoses should be kept off the floor.

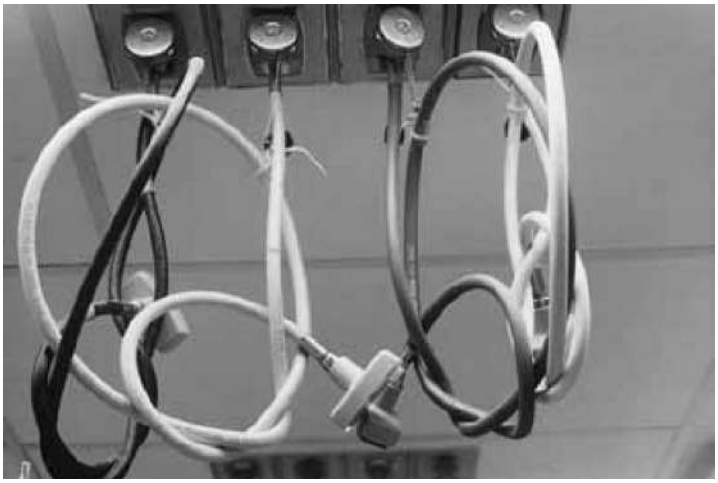

Figure 2.14 Ceiling-mounted hoses. A spring-actuated chain keeps the hose close to the ceiling.

Figure 2.15 Pendant with double-articulated arm. On one side **(A)** is a shelf for equipment and electrical and data management system outlets. On the other side **(B)** are terminal units for the piped gases and additional electrical outlets. The pendant can be raised or lowered or moved from side to side.

It sometimes is necessary to disconnect the pipeline hoses to move the anesthesia machine. This should be performed quickly and preferably without opening the cylinder valve on the anesthesia machine because the cylinder may become depleted if the valve is not closed after the hose is reconnected. If the hose must be disconnected for more than a few seconds, a cylinder should be opened and then closed as soon as the hose is reconnected.

Using several extension hoses is undesirable. It is better to use one long hose, as resistance caused by multiple connections may interfere with gas flow. One long hose is less likely to leak, because most leaks occur in the connectors or where the connector fits into the hose.

Hoses should be kept in good repair and approach the anesthesia machine with a gentle curve, avoiding acute angulations or stretching. After years of use, hoses can weaken, swell, or crack (23,24). Personnel should periodically check for these problems and have the hoses repaired or replaced, if necessary.

Testing Medical Gas Distribution Systems

Because problems with medical gas systems are most likely to occur with a new system or one that has been modified or repaired, it is essential that such a system be thoroughly tested before being used (2,4). If a system is brand new, the entire system must be tested. For a new or modified portion of an existing system, the extent to which it is tested will depend on how much of the existing system can be isolated and not affected by the work.

There has been controversy over who should carry out the final (commissioning) tests to make certain that the piping system complies with regulations. Commercial services that inspect medical gas pipelines and offer certification are available. Test procedures and results should be made part of the facilities permanent records. The American Society of Sanitary Engineering (ASSE) has published a standard on professional qualifications for inspectors and verifiers for medical gas systems (25).

Anesthesia personnel have an obligation to ensure that the system is properly designed and is functioning correctly, so a member of the department should witness the tests performed, especially those for cross connections. A personal independent check using an oxygen analyzer or other gas monitor is an excellent idea.

Installer-performed Tests

Initial Blow Down

After the pipelines have been installed but before the installation of terminal units and other system components (e.g., source equipment, sensors for alarms, pressure gauges, or pressure relief valves), the line must be blown clear of foreign material by using oil-free dry nitrogen.

Figure 2.16 Retractable rigid column. Pipeline outlets are on the bottom. Electrical outlets and hook mounts for intravenous solutions are on the sides.

Initial Pressure Test

Before system components are attached but after the terminal units are installed and before closing of the walls, each section of the piping system must be subjected to a test pressure of 1.5 times the system working pressure, but not less than 1035 kPa (150 psi), by using oil-free nitrogen with the source valve closed. This pressure is maintained until each joint has been examined for leakage. If any leaks are found, they must be corrected.

Test for Cross Connections

Testing for cross connections (anticonfusion or continuity test) is done to ensure that the gas delivered at each terminal unit is that shown on the outlet label and that the proper connectors are present at station outlets.

One gas system is tested at a time. Each gas is turned off at the source valve and the pressures reduced to atmospheric. The pipeline being tested is then filled with oil-free nitrogen at its working pressure. With appropriate adapters matching outlet labels, each station outlet is checked to ensure that test gas emerges only from the outlets of the medical gas system being tested. The cross-connection test is then repeated for each gas system in turn.

Pipeline Purge Test

To remove particulate matter, a heavy intermittent purging must be performed on each outlet until no discoloration is produced on a white cloth that is held over the outlet. The purging is started at the outlet closest to the zone shutoff valve and is continued to the farthest outlet within the zone.

Standing Pressure Test

After the walls have been closed and after installation of station outlet valve bodies and other distribution system components (e.g., pressure alarm devices, pressure indicators, pressure relief valves, etc.), the entire system is subjected to a 24-hour test with a pressure 20% above the normal operating line pressure with the source valve closed. Leaks must be located and repaired, and the test must be repeated until no leaks are found.

System Verification

System verification tests shall be performed after all the installer-performed tests have been completed. Testing shall be conducted by a party who is technically competent and experienced with pipeline installations and who meets the requirements of ASSE 6000 (25).

Standing Pressure Test

Piping systems shall be subjected to a 10-minute standing pressure test at operating line pressure.

Cross-connection Test

Either of the following tests can be used:

- All medical gas systems are reduced to atmospheric pressure. All sources of test gas from all medical gas systems, with the exception of the one system to be checked, are disconnected. The system is then pressurized to 345 kPa (50 psig). Each terminal unit of every medical gas system is then checked to verify that test gas is being dispensed only from the outlets of the medical gas system being tested. Each medical gas system is checked in this way.
- The pressures of all medical gas system are reduced to atmospheric. The test gas pressure in all the medical gas piping system is increased to values in Table 2.1. Following adjustment of pressures, each station outlet is identified by label, and a gas-specific connector with a test gauge is attached to verify that the pressure indicated is that listed.

Figure 2.17 Termination of nitrogen piping system. Two gauges are present, showing pipeline and outlet (reduced) pressure. The reduced pressure can be altered by using the regulator (pressure adjust). The station outlet is at the right.

Valve Test

Valves must be tested to verify proper operation and rooms or areas that they control.

Alarm Test

All master and area alarm systems must be tested for proper functioning.

Piping Purge Test

To remove particulate matter deposited in the pipeline, a heavy intermittent purging of the pipeline is carried out until the purge produces no discoloration in a white cloth that is held over an adapter during the purge.

TABLE 2.1 Test Gas Pressure

Medical Gas	*Pressure (Gauge)*
Gas mixtures	140 kPa (20 psi)
Nitrogen	210 kPa (30 psi)
Nitrous oxide	275 kPa (40 psi)
Oxygen	345 kPa (50 psi)
Medical air	425 kPa (60 psi)

Piping Particulate Test

A minimum of 1000 L of gas must be filtered through a clean, white 0.45 micron filter at a minimum flow rate of 100 L/minute. The filter shall accrue no more than 1 mg of matter from any outlet tested. Twenty-five percent of the zones must be tested at the outlet most remote from the source.

Piping Purity Test

Each medical air system must be tested for dew point, methane, and halogenated hydrocarbons at the outlet most remote from

the source. Maximum allowable values are given in NFPA 99 (2).

Final Tie-in Test

After connection of any work, extension, or addition to an existing piping system, each joint in the final connection between the addition and the existing system must be leak tested with the gas of system designation at the normal operating pressure.

After the final connection is made and leak tested, the area downstream of the point or area of intrusion must be purged.

Operational Pressure Test

Oxygen, nitrous oxide, and medical air outlets must deliver 100 L/minute with a pressure drop of no more than 35 kPa (5 psi) at a static pressure of 345 to 380 kPa (50 to 55 psi). Nitrogen outlets and instrument air must deliver 140 L/minute with a pressure drop of no more than 35 kPa (5 psi) at a static pressure of 1100 to 1275 kPa (160 to 185 psi) (2).

Gas Concentration Test

After purging each system with the gas for which the system is designed, each system must be analyzed for gas concentration. Allowable concentrations are given in NFPA 99 (2).

Medical Air Purity Test

The medical air source must be analyzed for dew point, carbon monoxide, carbon dioxide, gaseous hydrocarbons, and halogenated hydrocarbons. Maximum allowable values are given in NFPA 99 (2).

Labeling

All components must be checked for correct labeling.

Source Equipment Verification

Source equipment must be tested for proper function. All source apparatus must be checked for proper functioning and labeling, including changeovers, signals, master signal panels, and pressure gauges. The quality of medical air produced must be checked after the machinery has run continuously for a minimum

of 24 hours.

Periodic Testing and Preventive Maintenance

A planned preventive maintenance program can prevent potentially hazardous conditions and unexpected loss of service, reduce the economic burden from leaks, and reduce emergency repairs (2). Maintenance should be performed at least as frequently as recommended by the pipeline manufacturer and more frequently if required by heavy use or local conditions. Before maintenance is undertaken, the system should be examined and the accuracy of existing diagrams verified.

Inspection and testing should be performed on a regular basis and the results recorded in a permanent log. If test buttons are provided at area panels (Fig. 2.8), audible and visual alarm indicators should be tested monthly.

All hoses and station outlets in the anesthetizing locations and postanesthesia care units should be checked at least monthly for wear, damage, and proper function. Terminal units should be checked for easy insertion, locking, unlocking, and connector removal; leakage, wear, and damage; contamination; gas specificity; labeling; flow; and pressure.

Shutoff valves to anesthetizing locations can be checked for tightness and components downstream of the valve for leaks by the following test. An anesthesia machine with a pipeline pressure gauge is connected to the piping system. Cylinder valves on the machines are closed, the zone shutoff valve outside the operating room is closed, and gas is released until each pipeline pressure gauge reads 280 kPa (40 psig). This pressure is then monitored for 4 hours. It should remain at 280 kPa. If the pressure rises, the shutoff valve is not working properly. If the pressure falls, there is a leak in the pipe to the room, the station outlet, or the hose to the anesthesia machine. It is essential that the shutoff valves be reopened after this test has been performed.

It is good practice to check alarms regularly. Gauges in area and master alarm panels should be monitored daily for proper pressure. The test button on alarm panels should be pressed monthly to verify audible and visual signals. Burned out bulbs should be replaced, and the testing should be documented. All

master alarm signals should be tested at least annually to verify proper operation. These signals are required to be wired so that if a wire gets cut, it will alarm. If removing the wire from the sensor does not activate an alarm, it is not properly wired (16).

Planned Shutdowns

An existing pipeline system sometimes must be shut down to extend the system, wash or purge it, perform preventive maintenance, or make replacements (26,27,28).

Partially or completely shutting down a medical gas pipeline system is a complex task that involves many risks. The anesthesia department should be actively involved. Careful planning, good communication, and close cooperation will minimize problems and assure uninterrupted gas service. If the shutdown will affect relatively few patients, the simplest alternative supply is cylinders. An alternative method is to back-feed the isolated sections. Following the shutdown, purity and crossover testing of all outlets involved and immediately adjacent areas should be performed.

Problems

Many problems associated with piping systems are caused by anesthesia providers being unaware that these systems can fail as well as because they are not sufficiently familiar with the system to make emergency adjustments. Lack of communication between clinical and maintenance departments and commercial suppliers may also be a contributing factor. Finally, compliance with existing codes is not universal.

Inadequate Pressure

Inadequate pressure is the most frequently reported malfunction (7). Pressure loss may result in a flow inadequate to power a ventilator but sufficient for other purposes. Anesthesia ventilators require a minimum driving gas pressure to operate properly.

Causes

Causes of inadequate pressure include damage, especially during construction projects unrelated to the piping system (7,9,29,30,31,32); fires (33,34); vehicular accidents; nitrous

oxide tank theft (7); environmental forces (earthquake, excessive cold, tornado, lightning) (9,35,36); depletion of or damage to the central supply (10,37,38,39,40); human error, including a closed shutoff valve (7,28,41,42); inappropriate main line pressure regulator adjustment (43); equipment failures (leaks, closed shutoff valve) (44,45,46); standby supply failure during routine maintenance (47); pressure regulator malfunction (7,48,49); problems with automatic switching gear (48,50); pipeline obstruction (frequently by debris left following installation (7,51); failure of a quick coupler to fit into a station outlet or to allow gas flow (52,53,54,55); fractured quick connector (56); plugged connector (57); kinking, leak, or obstruction of a hose (21,22,29,58,59,60,61,62); and a detached terminal unit (63). Deliberate tampering is a possibility that should not be overlooked.

Disaster Plan

Because the consequences that occur when oxygen or air pipeline pressure is lost can be severe, each facility should have a plan to deal with it (43,58). Because no single plan will fit every facility, this section is intended only to provide guidance in the preparation and implementation of that plan.

A key to effective emergency preparedness planning is flexibility, which is attained by considering all possibilities and developing options for action that are maximally effective under each possibility. It is important that the plan be functional at any time of day or night and on any day of the year. The plan should include strategies for conserving existing supplies and acquiring additional supplies from other facilities or vendors, if necessary. Efforts should be coordinated to determine needs and supplies on hand as well as to determine the duration that the gas will be unavailable with the department responsible for the piping system.

An effective response must include reliable communication pathways and individual responsibilities that take into account practical circumstances. The details should be discussed and rehearsed in a mock disaster drill if an effective response is to be expected during a real emergency. Each individual should be aware of his or her role. Shutoff valve locations should be known by the staff so that if the pressure loss is caused by a leak in one area, the pipeline to that section can be isolated to prevent

further loss.

An individual who discovers a fault in the piped supply should immediately inform the telephone operator who, in turn, should inform the department responsible for maintaining the system, respiratory therapy, surgery, the postanesthesia care unit, obstetrics, the emergency room, special care units such as intensive care and the nursery, the nursing supervisor, and administration. Each department should have carefully established procedures to deal with the emergency. These should be reviewed regularly, revised as necessary, and put in policy and procedure manuals.

Because every anesthesia machine should have at least one oxygen cylinder, there should be no immediate threat to life in the operating rooms, but it would be prudent to use low fresh gas flows and manual ventilation. Gas-powered ventilators should not be used, as they will deplete the cylinder contents quickly (64). Electrically powered piston ventilators can continue to be used. Elective surgery should be postponed until adequate supplies can be guaranteed. Attention should be focused on the postanesthesia care unit (recovery room). It may be advantageous to move anesthesia machines that are not in use into the recovery room to supply oxygen until other sources can be obtained. Alternately, patients can be returned to operating rooms. The heart-lung machine may also need supplemental oxygen (30). Potential emergency oxygen sources other than compressed cylinders include portable liquid oxygen containers and oxygen concentrators (Chapter 1).

Emergency Auxiliary Supply

Because the dangers associated with failure of piped oxygen and air systems, special areas such as intensive care units, recovery rooms, emergency rooms, and the like may add an auxiliary oxygen and/or air supply. When an emergency arises, the shutoff valve to the area is closed and the auxiliary source connected to an outlet not in use within the zone or by means of a specially installed T. Outlets within the area can then operate from the auxiliary source.

Leaks

Leaks in various piping system components are common (7).

They may occur anywhere in the piping system. Leaks in pipeline outlets are especially common. These are usually sealed by O-rings that can fail (65). Leaks are expensive and potentially hazardous if oxidizing gases are allowed to accumulate in closed spaces. Nitrous oxide leaks may pose a health hazard to personnel (Chapter 13).

Excessive Pressure

Excessive pressure can cause damage to equipment and barotrauma to patients (49,66,67). Few anesthesia machines or ventilators have mechanisms to prevent damage from high pressures. Some ventilators will not operate properly if the line pressure is too high. A report has been documented regarding an incorrect output gas concentration from a blender when the pressure in the air pipeline was adjusted upward (68).

As shown in Figure 2.6, a pressure relief valve in the main supply line is required. However, this can be set improperly or malfunction.

The most common cause of high pressure is regulator failure. This problem has been reported in association with a cryogenic oxygen tank (69). In humid atmospheres, ice may form on the vaporizers in a liquid oxygen system. This will hamper heat transfer and may result in liquid oxygen passing into the piping system with resultant damage to the regulator and pressure relief valve. This also has been reported after liquid oxygen was added to the main tank (66). Other causes of high pressure include foreign material combustion in a pipeline (7) and deliberately increasing the pressure setting at the main line regulator in an attempt to compensate for low pressure from the central system (49).

Whenever excessive pipeline pressure occurs, it is best to disconnect apparatus from the pipeline system and use cylinders until the problem is corrected.

Alarm Problems

Failure, absence, or disconnection of an alarm is not uncommon (7,49). The alarm may not be heard or the person who hears it may not know the proper course of action or fail to respond (7,70).

False alarms can also occur. They may result from calibration drift in line pressure sensors (43). Repeated false alarms can cause complacency among personnel, which may have serious consequences if a real emergency occurs.

Cross Connection of Gases

Although an uncommon event, accidental substitution of one gas for another can have devastating consequences (71). The most common cross overs have been between nitrous oxide and oxygen, but various other combinations have been reported. Pipeline alarms indicate only pressure faults and give no signal if an incorrect gas is present. Because the consequences are most severe when the cross over results in hypoxia, it is essential that a reliable oxygen analyzer be included as a component of every breathing system. Oxygen monitors should be used in other areas where oxygen is administrated such as obstetrics, the nursery, and intensive care units (72).

Central Supply

Cases have been reported in which liquid oxygen tanks were filled with nitrogen (73,74,75,76,77) or argon (78). Incorrect tanks have been placed on the central supply manifold (52,79,80,81). All employees who deal with the piping system must be familiar with the standards that have been developed to prevent medical gas mix-ups (82). If an institution uses both medical and industrial gases, they should be stored separately (83).

Distribution System

Crossed pipelines usually occur during system installation, alteration, or repair (84,85,86,87,88,89,90,91,92). In one case, a fistula was created between two pipes during construction (93).

Flooding the oxygen line with nitrogen has occurred when nitrogen was used to test for leaks and the shutoff valve to that area did not prevent backflow (33,94,95,96). NFPA now requires that when new piping is connected to an existing system, the source gas, rather than nitrogen, be used to test for leaks (2).

Terminal Units

There are numerous reports of outlets labeled for one gas that delivered another (97,98). The wrong outlet connector may be installed (52,93,99,100). A terminal unit may accept an incorrect connector (101,102,103,104). An air flowmeter may be fitted with an oxygen outlet but retain the air pipeline connection. In one case, a problem occurred when an oxygen flowmeter was connected to a nitrous oxide outlet because a connector pin was broken on the flowmeter quick connector (106,107,108). In another case, the oxygen fitting base flexed enough to allow it to be fitted to a nitrous oxide terminal unit (109). In order to prevent these errors, the medical devices that connect to terminal units must be regularly inspected and those with worn or damaged connectors repaired.

Hoses

Cases have been reported in which the wrong connector was put on one or more hoses (7,94,110,111,112,113). Most of these have involved repairs or alterations performed by hospital personnel. Blue hoses turning green have been reported (114). This could result in an oxygen-specific fitting being attached to one end of a green (previously blue) hose. Whenever a hose is altered or repaired, it should be checked carefully before it is put into service to make certain that the proper connectors are on each end. With extension hoses, this is easily performed by inserting one end of the hose into the other.

A hose connector can become worn, allowing the hose to be connected to the incorrect wall outlet (104,115).

Hoses that run across the floor can make it difficult to move the anesthesia machine or drug cart. They can impede operating room personnel from moving about without tripping on the hoses (116). Devices are available to prevent equipment from being ensnared by hoses. This is discussed in Chapter 14.

Peripheral Devices

Numerous cases have been reported in which an air/oxygen or an oxygen/nitrous oxide mixer, ventilator, or anesthesia machine using both oxygen and another gas had a defect that allowed the gas supplies to become interconnected, and oxygen flowed into the other pipeline or the other gas into the oxygen piping

(48,117,118,119,120,121,122,123,124,125,126,127,128,129,130). Often, the faulty device was not in use but was connected to the pipeline systems. The contamination level depends on the difference in supply pressure between the two gases. Gas from the pipeline with the higher pressure will contaminate the gas in the pipeline with the lower pressure (131). It is suggested that respiratory equipment be disconnected from the pipeline when not in use (126,131).

Gas Contamination

Various types of contamination can be found in the pipeline system. Currently, no available monitor can detect the entire spectrum of potential contaminants in a pipeline system. If contamination of piped gases is suspected, a switch to cylinder supply should be made and the anesthesia machine disconnected from the pipeline. If the pipeline is not disconnected, the machine may preferentially use gas from the pipeline even though the cylinder is open.

Filters can be used to prevent contaminants such as particles, bacteria, and liquid water from entering the apparatus and harming attached medical devices and patients (132,133) (Fig. 2.18). NFPA standards (2) require that medical compressed air systems have an in-line filtration system of 98% efficiency at โค1 ยต and that filters have a visual indication of filter life. However, filters do not remove water vapor and other gases.

As a last line of defense, many ventilators, anesthesia machines, regulators, and other devices that use medical gases have filters (Fig. 2.18). These filters can serve as an early warning of pipeline contamination (133). However, these filters are typically coarse (e.g., 50 ยต). Filters require routine inspection and preventive maintenance and can be a source of obstruction or leaks (134).

Particulate

Particulate matter can accumulate in the piping system during construction (28,135,136,137). Other common sources of particulate contamination are air compressors, receivers, and dryers (14,138). Particles can damage equipment, especially ventilators, blenders, and line pressure sensors, and can cause a significant reduction in flow (43,137,139). Particulate matter can

be harmful to patients if inhaled.

Figure 2.18 Water trap with drain and filter in the air hose leading to the anesthesia machine.

During installation, every effort should be made to keep pipes, fittings, and valves as clean as possible. The majority of particles can be removed by purging, which may require several days, but may never be complete, especially in tall buildings (94).

Gaseous

Volatile substances can be unpleasant and harmful to patients if inhaled, may damage equipment, or create a fire hazard.

Gaseous contamination may result from materials remaining in the pipes after construction (66,93). The inlet to the air compressors is another source of contamination (66). NFPA regulations require that gaseous hydrocarbons be monitored on a quarterly basis (2).

Nitric oxide can be a contaminant in ambient air. Low levels of nitric oxide found in ambient air may cause improved oxygenation in ventilated patients (140,141,142). The role that unwitting nitric oxide levels play in medical air needs to be evaluated (143).

A number of contamination problems have been reported. In one case, the air intake was located in the facility's heating and air-conditioning system (14). Washing the system's coils with an acidic solution resulted in fumes being drawn into the system. In another case, a filter was soaked in cleaning fluid and replaced without allowing it to dry (144). In yet another case, a cleaning solvent was not purged from the hose that connected the gas delivery truck and the main storage tank (145). A similar incident resulting in several deaths occurred when an oxygen tank that had been cleaned with trichloroethylene was connected to the pipeline system before all the solvent had been removed (146,147). In another case, trichloroethylene used to clean a valve was implicated in a child's death (28). Using trichloroethylene on-site has been banned by the NFPA because controlling and disposing it can be difficult (2). Residual trichloroethylene cannot be easily removed and can present a hazard to patients and personnel.

One important lesson to be learned from these accidents is that pipeline odors should always be taken seriously. All medical gases should be odor-free. Any odor originating from a medical gas system must be traced to its source, and steps must be taken to correct the problem. Whenever a pipeline system is breached for any reason, the gases coming from the system should be tested.

Water

Water that is introduced through malfunctioning air compressor components can damage equipment such as ventilators and gas mixers, facilitate oxidation of copper piping, attack and weaken solder joints, and provide growth media for bacteria (14,28,126,148,149). Water in pipelines that are subjected to low temperatures can freeze and occlude gas flow.

Bacteria

Piped medical gases are not sterile, and bacterial contamination

has been documented (150,151,152,153). Water that accumulates in a pipeline can provide a culture medium. In some cases, contamination may be mixed, as occurred when a bird became caught in an improperly installed air intake (105).

Fires

To avoid fires, equipment used with a pipeline system must be clean and free from oil, grease, and particulate matter. In addition to causing inadequate pressure, a fire may result in hazardous fumes that are inhaled by patients. A hose can rupture and burn if it comes in contact with a light (21,22). A leak in a hose inside a surgical boom can exacerbate a fire (154). Chapter 32 discusses fires in the operating room.

When a room with medical gas outlets is converted to another use and the outlets are not removed and not maintained, the outlets can leak, resulting in a potential fire hazard (155). All medical gas lines to the room should be cut and capped, and a blank cover plate should be put over each terminal unit. If an entire zone is taken out of service, the line should be cut and capped just downstream of the zone valve box.

Depleted Reserve Supply

The reserve supply may become depleted by a connection failure, pressure imbalances, and leaks (43,49).

Theft of Nitrous Oxide Cylinders

Theft of nitrous oxide cylinders from a central supply area for recreational purposes is a recurrent problem.

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Questions

For the following questions, select the correct answer.

1. The normal pipeline pressure for oxygen, nitrous oxide, and air in the United States is

A. 240 to 275 kPa

B. 275 to 345 kPa

C. 345 to 380 kPa

D. 380 to 410 kPa

E. 410 to 440 kPa

View Answer

2. The most frequently reported malfunction in medical gas pipeline systems is

A. Inadequate pressure

B. Cross connection

C. Excessive pressure

D. Alarm dysfunction

E. Contamination of gases

View Answer

3. Compressed air is most often supplied by

A. Proportioning devices

B. Cylinder banks

C. Concentrators

D. Compressors

E. Liquid containers

View Answer

4. The DISS is used for devices at pressures of _____ or less.

A. 345 kPa

B. 690 kPa

C. 1000 kPa

D. 1380 kPa

E. 2000 kPa

View Answer

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. if D is correct

E. if A, B, C, and D are correct.

5. What are the results of increased pressure in the oxygen pipeline system?

A. Airway positive end-expiratory pressure

B. Gas blender malfunction

C. Flowmeter rupture

D. Ventilator malfunction

View Answer

6. The following provide standards for pipeline systems:

A. National Fire Protection Association (NFPA)

B. Underwriters Laboratories (UL)

C. Compressed Gas Association (CGA)

D. Association for the Advancement of Medical Instrumentation (AAMI)

View Answer

7. Functions of the Joint Commission on Accreditation of Healthcare Organizations (JCAHO) in relation to medical gas pipeline systems include

A. Inspecting systems

B. Certifying pipeline installations

C. Certifying procedures relating to pipeline usage

D. Ensuring compliance with the various standards that apply to pipeline systems

View Answer

8. Central gas supplies may be located

A. Inside in a special room used only for this purpose

B. Outdoors

C. In an enclosure

D. In a nonsterile area in the operating room suite

View Answer

9. Oxygen may be supplied to the pipeline system by

A. G and H cylinders

B. Oxygen concentrators

C. Bulk liquid systems

D. C cylinders

View Answer

10. Vaporization of liquid oxygen in a bulk tank will result in

A. Loss of oxygen to the atmosphere

B. Loss of oxygen that may be greater than demand

C. Significant loss of oxygen even though there is no use

D. Less loss if the rate of use is low

View Answer

11. Heat must be supplied to vaporize liquid oxygen because

A. Liquid oxygen will freeze because of the low storage temperature

B. As the temperature falls, the pressure in the tank falls

C. Vaporization causes the pressure to fall

D. The heat of vaporization will cause the temperature to fall

View Answer

12. NFPA regulations require a shutoff valve

A. At every lateral branch, adjacent to the connection to the riser

B. Outside each operating room

C. Inside each critical care area

D. At each riser, adjacent to the connection to the main supply line

View Answer

13. A master alarm system panel should be located

A. In the office of the person responsible for maintenance of the system

B. In the operating room

C. At the switchboard or security office

D. In critical care areas

View Answer

14. The DISS

A. Is used for gases at pressures of 250 psig or less

B. Is used at all wall outlets

C. Achieves noninterchangeability by using different screw threads

D. Is required on all pipeline inlets on anesthesia machines

View Answer

15. Preuse testing of a pipeline system should include

A. Pressure testing

B. Purge testing

C. Testing for cross connections

D. Testing for the purity of the gases

View Answer

16. Quick connectors

A. Provide noninterchangeable connections

B. Allow apparatus to be connected or disconnected by a single action

C. May require the use of one or both hands

D. Do not require the use of tools

View Answer

17. Cross connections of pipelines

A. Most commonly involve oxygen and nitrogen

B. May be caused by devices not in use

C. Can be detected by alarms required by NFPA standards

D. Are most commonly associated with construction, alterations, or repair

View Answer

18. Which components are part of a medical gas distribution system?

A. Terminal units

B. Central supply

C. Pipelines

D. Hoses between the wall outlet and the anesthesia machine

View Answer

19. Location of area alarms include

A. Critical life support areas

B. Upstream of the shutoff valve in anesthetizing locations

C. Each anesthetizing location

D. Downstream of the shutoff valve in the critical life support areas

View Answer

20. Which of the following will activate an alarm?

A. The main supply reaches two days' supply

B. The reserve supply begins to supply the system

C. The reserve supply reaches an average of two days' supply

D. The secondary supply begins to supply the system

View Answer

Chapter 3
Suction Equipment

The purpose of suctioning is to remove and/or collect solids, gases, and liquids from the patient, airway devices, and the patient's environment. Suctioning is an important part of anesthesia practice and an essential procedure for patients requiring prolonged intubation to prevent infections and narrowing of artificial airways. Should vomiting or regurgitation occur, suctioning can be lifesaving.

TABLE 3.1 Pressure Equivalents

Unit	*kPa*	*Inches Hg*	*mm Hg*	*cm H_2O*
1 kPa	1	0.295	7.501	111.5
1 inch Hg	3.386	1	25.4	330
1 mm Hg	0.1333	0.004	1	0.77
1 cm H_2O	1.73	0.052	13	1

General Principles

Negative Pressure

‶Vacuum‶ will be used in this chapter to denote a pressure less than atmospheric (negative pressure). Suction (mechanical aspiration) is the movement of gases, liquids, or solids caused by vacuum.

Vacuum is usually stated in gauge pressure, the difference between the measured pressure and ambient atmospheric pressure (which is zero on the gauge). Pressure is the amount of

force acting on a given area, sometimes to maintain a liquid (mercury or water) at a certain height. Table 3.1 gives some commonly used pressure units.

Flow

A complete suction apparatus is shown in Figure 3.1.

All the suction equipment from the source to the patient connection can be thought of as a tube of varying diameter. When the vacuum source is attached or turned ON, flow through the equipment will occur. The rate of flow will depend on the pressure difference between the ends of the tube and the resistance to flow. To ensure good flow, the maximum vacuum and the shortest possible length of tubing should be used; the internal diameter of tubings, connectors, and the suction catheter should be as large as possible; and the vacuum system should not leak (1). Increasing the number of intakes to the piped vacuum system will result in a decrease in vacuum and flow at each intake.

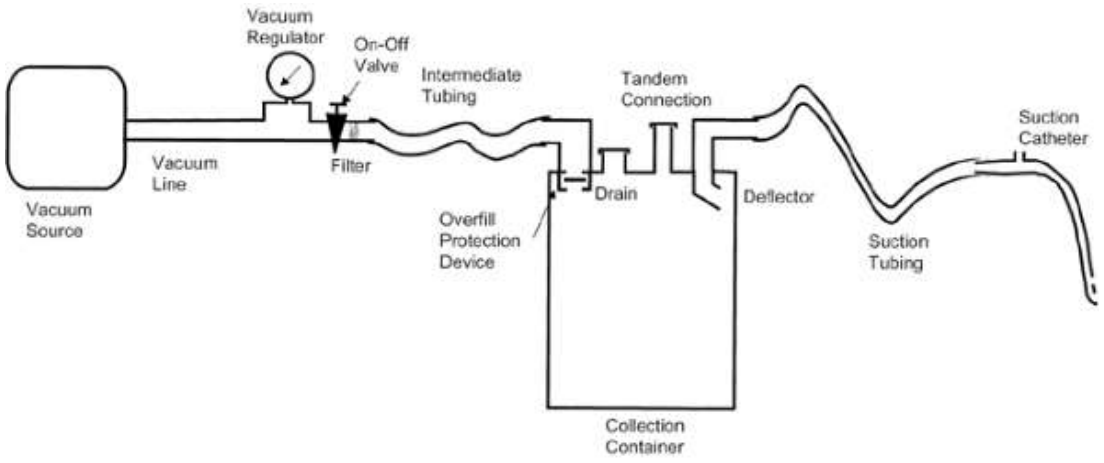

Figure 3.1 Complete suction system. Normally, liquids and solids do not move any farther than the collection container. Note the deflector on the collection container.

Flow through suction apparatus is also affected by the physical characteristics (elasticity, viscosity, adhesion, and cohesion) of the material being suctioned. Water or saline drawn through a

suction catheter before use may act as a lubricant and improve flow. After material enters the collection container, it no longer causes resistance to flow.

Equipment

Vacuum Sources

Suction apparatus requires a source that can generate a subatmospheric pressure. The most common source of vacuum in health care facilities is the pipeline system. In locations where terminal inlets are unavailable, portable devices (see Fig. 3.5) can be used.

Piped Vacuum

In the United States, the National Fire Protection Association (NFPA) produces the standard that applies to piped vacuum systems (2). There is also an International Standard (3).

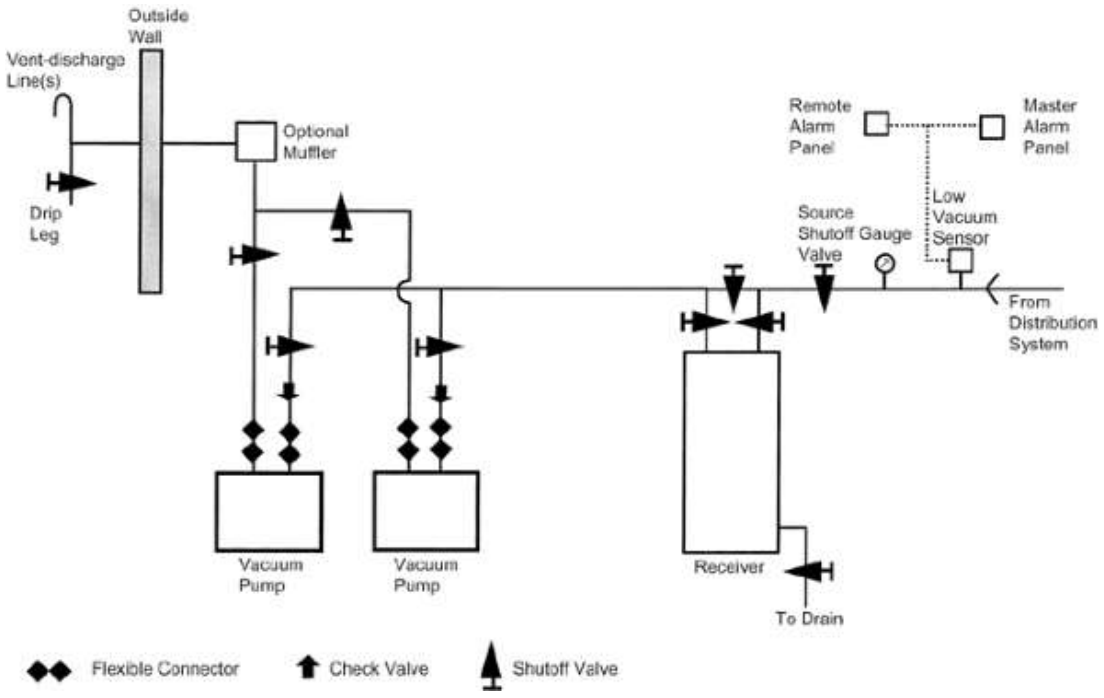

Figure 3.2 Piped vacuum system.

The piped vacuum source includes pump(s) and one or more reservoirs (holding tanks, receivers, receiver tanks) (Fig. 3.2). The system must be capable of maintaining a vacuum of 40.6 kPa (12 inches Hg) at the inlet farthest from the vacuum source when the calculated demand for the facility is drawn into the system (2).

Pumps

The source must have at least two pumps mounted in parallel, each capable of maintaining the minimum vacuum level with the largest pump out of service (2). These serve the system alternately or simultaneously, depending on the demand. Vacuum pumps must be connected to the emergency electrical power supply.

The exhaust from the pumps should be discharged outdoors. The exhaust should not be located near a door, window, air intake, or other opening in the building. Prevailing winds, adjacent buildings, topography, and other factors need to be considered when choosing the exhaust location.

Receiver

The receiver (reservoir) has the same function in a piped vacuum system as in a compressed air system. It helps to even out the vacuum and decreases pump cycling. Fluids or solids may enter the vacuum system and collect in these tanks. There should be a drain mechanism that prevents their buildup yet does not interrupt service from the system.

Piping

The pipeline system (Fig. 3.3) connects the central vacuum source to terminal units (inlets) throughout the facility. Components such as shut-off valves, pressure gauges, alarms, and such are similar to those of medical gas pipelines (2).

The pipes are usually of the same material as used for medical gases but are larger. The internal pipe diameter is the most critical factor in assuring adequate performance in a piped vacuum system. When a pipeline system is designed, pipes are sized according to the expected load. If additional inlets are added to the system, the vacuum available to the existing inlets

is reduced.

Vacuum Inlets

A vacuum inlet (see Fig. 3.8) must be noninterchangeable with those of other services, including those for anesthetic gas-scavenging systems. They should remain closed when there is no component attached. When an area of a health care facility is planned, it is important that an adequate number of vacuum inlets be installed. If this is not done, one or more Y connectors will need to be used (Fig. 3.4). This will decrease the vacuum and airflow.

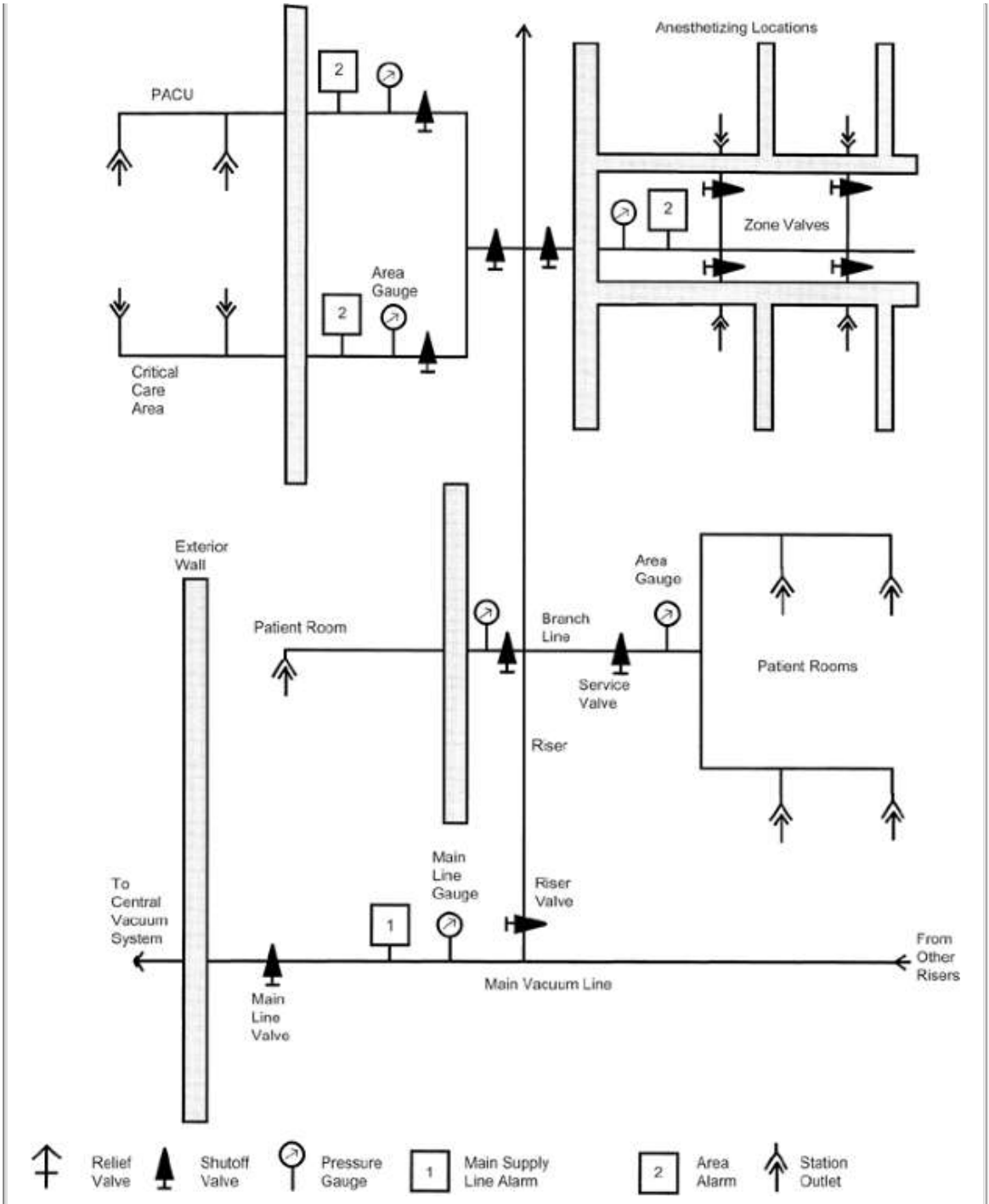

Figure 3.3 Pipeline distribution system for vacuum.

Figure 3.4 Use of multiple Y connectors will result in reduced vacuum and flow.

Portable Suction Units

Portable suction units (Fig. 3.5) are useful in locations where piped vacuum is not available. While these devices may not perform as well as piped vacuum systems, they are usually adequate for clinical purposes (4,5). Most mobile units have the pump, collection container, gauge, and controls on a cart with casters. Some units can be handheld. Health care facilities using mobile units should realize that their maintenance requirements are significant (6). Portable suction equipment may be contaminated more frequently than piped units (7). If a portable suction source is used, the exhaust is evacuated into the room. This could be a source of infection for both the patient and personnel in the room. Most units have a bacterial filter to prevent this, but the filter can become heavily soiled and needs to be changed regularly (8).

Figure 3.5 Portable suction unit.

Electrically Powered

Electricity, either from the main line or battery, powers most portable suction devices. Battery life varies with the individual unit but can be as high as 45 minutes. An international standard covers these devices (9).

Manually Powered

Manually-powered suction devices have a pumping device powered by hand or foot (4,5,10). Usually, this is a spring-loaded bellows arrangement with unidirectional valves (11). Many of these devices do not have pressure regulators or pressure gauges. Handheld units are available. An international standard covers these units (12). For transport, a simple device can be created by attaching a suction catheter to a syringe (13).

Venturi Powered

A Venturi tube (ejector) powered by a compressed gas (usually air) can be used as the source of negative pressure in portable suction apparatus (5,14). This type of device can be noisy and wastes gas.

Vacuum Regulator and Gauge

A vacuum regulator (Fig. 3.6) allows the operator to control the maximum negative pressure at the inlet to the suction apparatus. There usually is a gauge to indicate the pressure on the patient

side of the regulator. The gauge may indicate pressure clockwise or counterclockwise. There may also be a control that allows the

operator to switch between regulated vacuum, full vacuum, and OFF (Fig. 3.6). Magnetic resonance imaging (MRI)-safe and -compatible vacuum regulators are available.

Figure 3.6 Vacuum regulators and guages. Note that the indicator on the gauge may move clockwise **(A)** or counterclockwise **(B)**.

There are two types of controller: conventional high suction and low suction (11). Low suction controllers are deliberately limited to provide safe suction for certain uses such as intrapleural drainage or gastric suctioning.

Trap Bottle

A trap (safety) bottle (overflow safety trap) (Fig. 3.7) situated between the collection container and the vacuum source or regulator will protect against liquids and solids flowing into the vacuum system. Sometimes, overflow devices on the collection container (see page 59 and Fig. 3.11B) do not function correctly. Intermittent suction tubing obstruction can cause frothing and

splashing in the collection container, which could escape into the vacuum system. This makes the use of a trap bottle necessary.

Filters

Filters are used to minimize particles and fluids passing into and contaminating the discharge area and to protect downstream equipment (especially regulators and pumps) (Fig. 3.8). The filter may be part of the collection container.

Using filters in suction systems is controversial (15). If wet or dirty, they can be a source of obstruction. With piped systems, a filter is recommended but not essential because aerosols are directed into the pipeline, presenting no direct contamination risk. With portable suction sources, a filter on the pump discharge is essential to prevent aerosols from contaminating the room air. Filters require routine inspection and frequent replacement.

ON-OFF Valve

To reduce the load on the vacuum system and to ensure good performance when vacuum is needed, suction apparatus should be turned OFF when not in use. The ON-OFF valve may be on the anesthesia machine (Fig. 3.9A) or independent from the machine (Fig. 3.9B). The ON-OFF valve may also be part of a regulator (Fig. 3.6).

Tubing

The intermediate tubing is located between the collection container and the vacuum source (9,16) (Fig. 3.1). The suction (patient, drainage) tubing is between the

collection container and the patient. It is better to have a long length of intermittent tubing than a long length of suction tubing. The wall thickness of both tubings should be adequate to prevent them from collapsing when exposed to high negative pressures.

Figure 3.7 Trap bottle. A trap bottle is needed to prevent liquids and solids that pass through the collection container from entering the vacuum source.

The suction tubing should be transparent so that materials can be seen passing through it. It should be arranged to minimize loops that can accumulate liquid and increase the potential for occlusion. Short, large-bore tubing will reduce resistance, result in a higher flow rate, and is less likely to obstruct (17,18). The suction tubing should be long enough so that it is within easy reach and the catheter can be maneuvered easily once it is attached.

If the suction catheter is not large enough to clear particulate material or the volume of fluid, the suction tubing can be used without a catheter.

Collection Container

The collection (collecting, suction) container (bottle, canister, device, jar, vessel) (Fig. 3.10) is where aspirated materials are collected and measured. At present, most collection containers are made of plastic and are disposable. Reusable plastic containers that can be cleaned and disinfected in automatic machines are available.

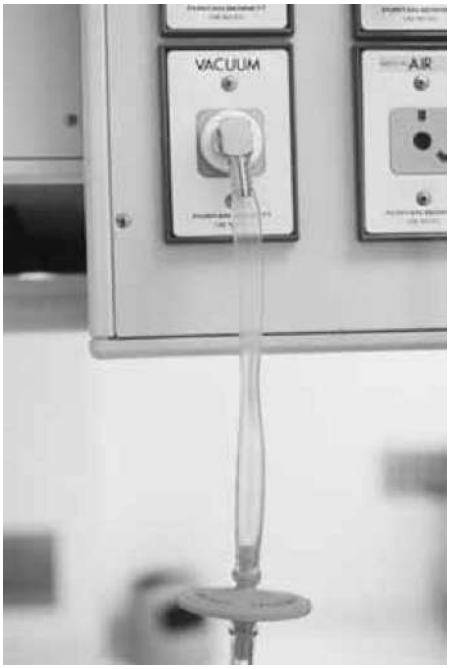

Figure 3.8 A filter will help to protect the vacuum source from liquids or solids.

There is usually a scale on the side of the collection container to allow an estimation of the amount of its contents. A deflector may be present at the base of the inlet port to turn the stream entering the container toward the container wall and prevent incoming liquid from obstructing the exit port (Fig. 3.1). It also decreases fluid agitation, which causes foam and aerosol generation. Some containers have an antifoam substance inside the patient port to reduce frothing (9,19). Foaming is undesirable because it may cause premature closure of the overfill protection device; may pass beyond the collection container and contaminate the filter or pump, causing pump failure; and makes it difficult to estimate the amount of aspirate in the vessel (11). A substance (gelling agent) may be present or added to the collection container to cause the fluid inside the container to solidify.

A typical disposable canister has a removable lid that has a vacuum port with an overfill protection mechanism

and an inlet port (Fig. 3.11). An additional port may be present to allow tandem suctioning (the use of two or more canisters connected in series so that aspirate flows into the second canister when the first fills). A tandem arrangement is used when a large volume of aspirate is anticipated. These ports should be clearly labeled. A pouring port may be present. Each port should have an attached tight-fitting snap-on cover.

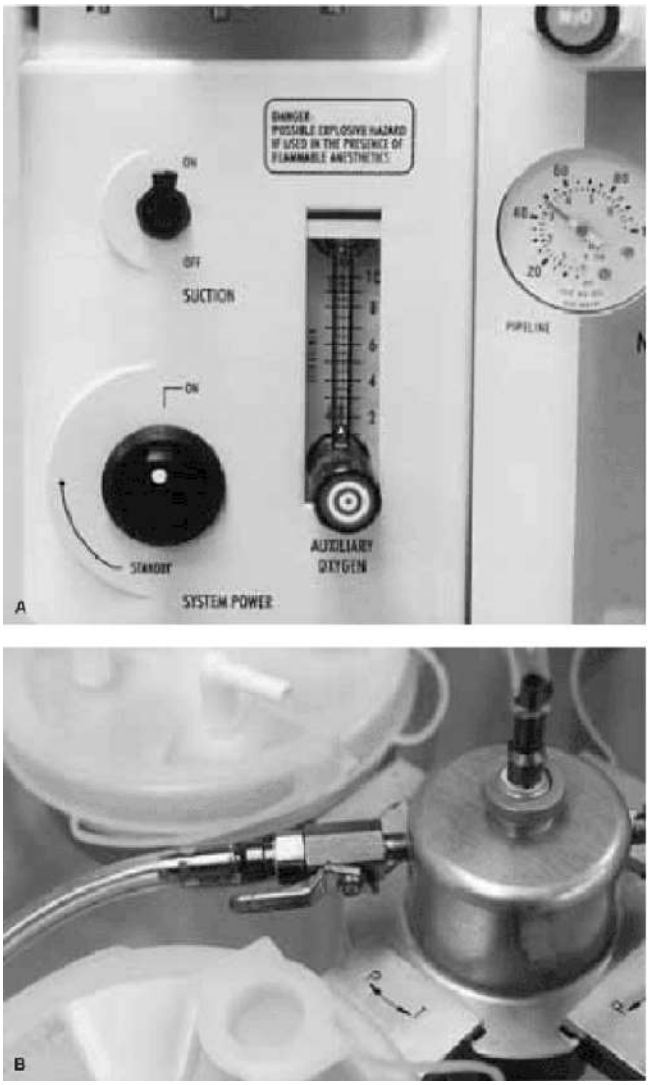

Figure 3.9 A: On-off valve for suction on the anesthesia machine. **B:** On-off valve near the regulator

Semidisposable collection containers are available. In these, a liner is attached to the lid and seats in a reusable housing. The aspirate collects in the liner. The lid and liner are discarded after use.

Figure 3.10 Collection container attached to the side of an anesthesia machine.

The volume of the collection container is important. It needs to be large enough so that it does not need frequent emptying. However, a large container will prolong the time needed to reach maximum vacuum and flow at the patient connection. With the pediatric patient, smaller containers should be used for more accurate measurement.

The location of the collection container is important. It should be close to the point of use and placed where it is unlikely to be tipped or cause tripping. An advantage of having it lower than the patient is that gravity helps to remove liquids and solids. If it

is located higher than the patient, it may be easier to observe, but more negative pressure will be required to lift materials into the container. An additional problem with a higher location is that if the vacuum is interrupted, fluid in the suction tubing could return to the patient. For intermittent gastrointestinal suction, it is preferable to have the container above the patient (20). For continuous gastrointestinal suction, the container may be placed below the patient.

A new container should be used for each patient. When suction is no longer needed or when the aspirate level approaches the last graduation on the volume scale, the canister should be capped (or the patient and vacuum ports connected with a piece of tubing) and disposed of or cleaned and disinfected.

Overfill Protection Device

If liquid or foam flows downstream of the collection container, the vacuum source and regulator may be damaged (14). To avoid this, an overfill protection device (overfill, cut-off, overflow, anti-overflow or shut-off valve, device, or mechanism) is usually placed in the collection container lid. A typical device consists of a float that is lifted by the fluid as the container fills (Fig. 3.11B). It should not activate until the canister contains at least 90% of its nominal capacity (9).

Problems have been reported with overfill protection devices. Some may be activated if vibrated, jarred, or tilted.

Special Adaptors

A special adaptor with an opening can be used to allow a suction catheter to be introduced into the airway during mechanical ventilation without disconnecting the patient from the ventilator circuit and with minimal or no air leak. These can be used to reduce hypoxemia associated with suctioning (21,22,23,24,25,26,27).

Suction Catheters

Suction catheters (nozzles or hand pieces) are usually made of plastic. Rubber catheters are no longer in general use. There is an international (28) and a U.S. standard (29) on suction catheters.

Shaft

The shaft is the main part of the catheter. A transparent shaft makes it easier to determine if material is being removed (30). The distance from the patient end is marked on some catheters.

Suction catheters are sized by the external diameter and shaft length, both in millimeters. For closed system catheters, the marked length is the length that can be inserted into the patient's airway. The outside diameter may also be expressed in French gauge (Charriere) size, which is three times the external diameter in millimeters. An optional system of color identification at the machine end has been incorporated into the International Standards Organization (ISO) but not the U.S. catheter standard (28,31). Table 3.2 shows the color identification.

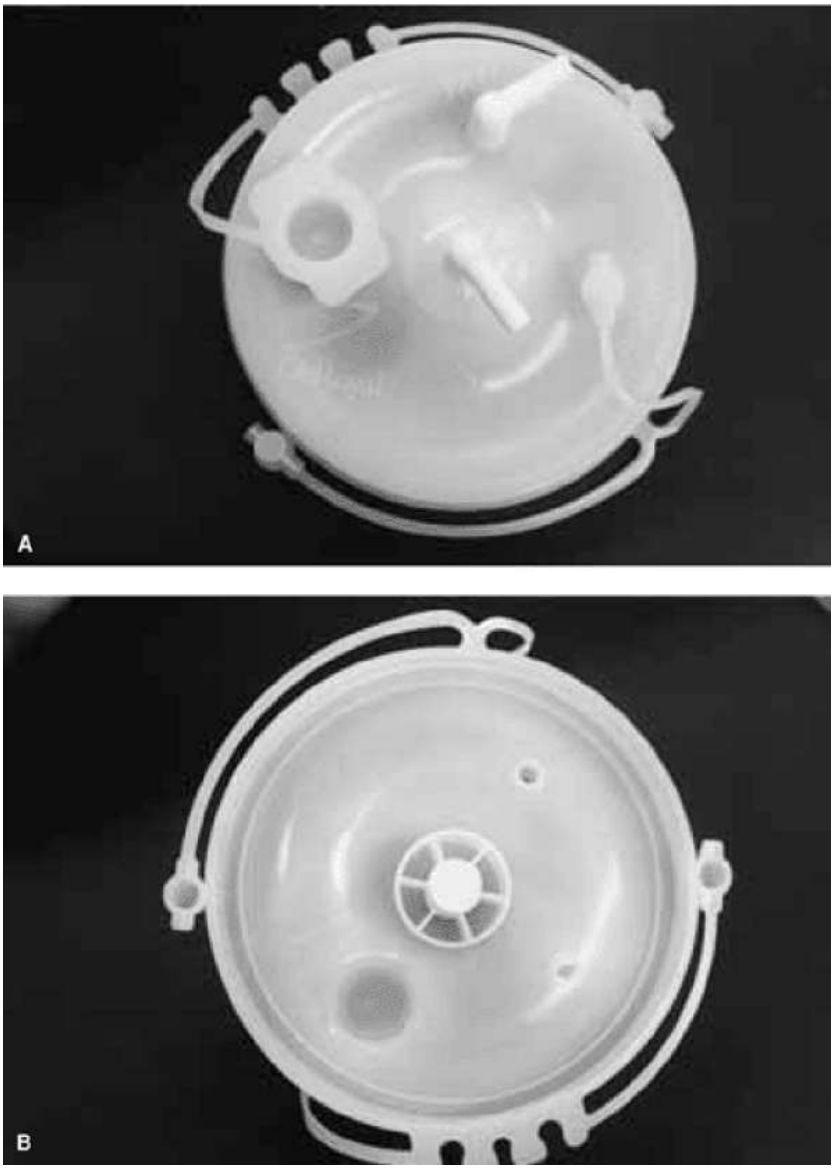

Figure 3.11 Lid for collection container. **A:** The top of the lid has two ports. The center one is the inlet port, and the other (at the 1 o'clock position) is an outlet port. There is an additional port (capped) for use with tandem suctioning. At the left is a drain spout. Note the caps at the perimeter. These should be placed over the ports before transporting a used container. **B:** The underside of the lid. The overfill protection device is in the center.

The catheter should be large enough to remove secretions rapidly but not block the airway. Catheter size is especially important if the catheter is placed inside a tracheal or tracheostomy tube. Smaller catheters allow more air to be entrained around the catheter, limiting the negative pressure that is applied to the lungs. Thin, copious secretions can usually be removed with a relatively small catheter, while thick, tenacious secretions require a larger one.

There are a number of different suction catheters designed for particular uses (Fig. 3.12). The axis at the patient end may be at an angle to the long axis of the shaft (Coudรฉ) (Fig. 3.12D). Curved-tip catheters facilitate insertion into the desired mainstem bronchus (32,33,34,35,36). A guide mark makes it easier to direct the tip (37). J-shaped catheter tips are useful for suctioning the right upper lobe bronchus (38,39,40). Double-lumen catheters with a lumen for oxygen insufflation or for instilling saline are available (41,42,43,44). A single-lumen insufflating suction catheter that allows either insufflation or suction has been described (45). A rigid (Yankauer, tonsil suction) catheter (Fig. 3.13) is useful for suctioning under direct vision, especially in the oral cavity. It can remove large volumes of fluid more rapidly than a flexible catheter but carries the risk of dental damage. Even the Yankauer tip may not be big enough to clear common particulate

material such as vomitus (46). Therefore, large-diameter suction tubing should be available.

TABLE 3.2 Color Identification for Designated Size of Suction Catheter and French Gauge Sizes

Nominal Outside Diameter (millimeters)	*French (Charriere) Size Equivalent*	*Color Identification*
1.67	5	Gray
2.0	6	Light green
2.5	7.5	Pink

2.67	8	Light blue
3.0	9	Turquoise
3.33	10	Black
4.0	12	White
4.67	14	Green
5.0	15	Brown
5.33	16	Orange
6.0	18	Red
6.67	20	Yellow

Patient End

The patient end of the suction catheter should be rounded to prevent mucosal damage. A variety of tips are available (47,48) (Fig. 3.12). The American Society for Testing and Materials (ASTM) catheter standard (31) requires that there be one or more eyes (side holes) near the patient end. The diameter of the terminal orifice (the central opening at the patient end) must be at least 90% of the inside diameter of the catheter (28,31). The tip and side holes (eyes) should be smooth. Tips with side holes grab less mucosa than single-holed catheters (49). However, having more than one hole at the tip will reduce the available vacuum (50).

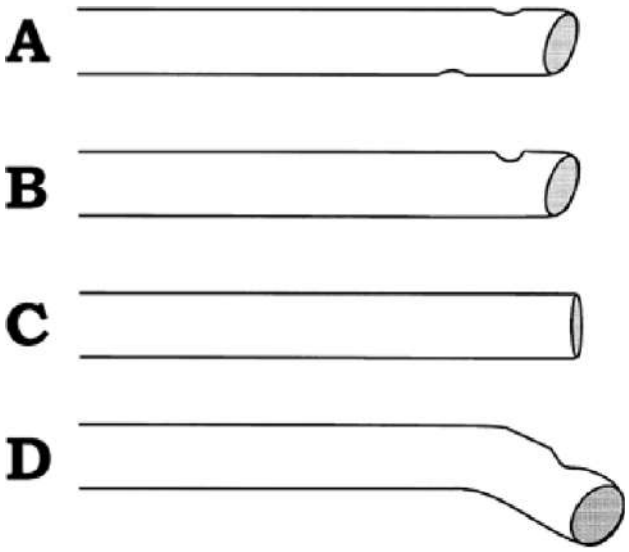

Figure 3.12 Flexible suction catheter tips. **A:** The whistle tip catheter has two side holes, usually perpendicular to each other. **B:** Tip with a single side hole. **C:** Tip with a single end hole and no side holes. **D:** A curved (Coudรฉ) tip is often used for bronchial suctioning.

Figure 3.13 Yankauer suction catheter. Most Yankauer suction catheters have a single hole and several eyes near the tip. Some have finger vents.

Machine End

The machine end is connected to the source of vacuum. It usually has a semirigid or elastomeric male connector but may be female (28,31). If the patient end of the catheter is curved, the machine end should have a means to indicate the direction in which the tip points.

Vacuum Control

Whatever type of catheter is used for tracheal or bronchial suctioning, there must be a method to periodically interrupt the suction without having to switch the whole unit off. This allows the catheter to be introduced without applied suction and permits intermittent suction when withdrawing the catheter (51). If the catheter tip is occluded by tissue, the full vacuum force will be applied, and attempts to pull the catheter away could result in trauma. The vacuum control can be opened to break the seal and allow the tissue to fall away from the catheter.

The vacuum control port (fingerhole, vent, vacuum breaker, side port, leak-in opening) can either be part of the machine end of the catheter (Fig. 3.14) or can be part of a separate connector between the catheter and suction tubing. This allows the operator to switch the flow in the catheter ON and OFF by simply covering or uncovering the vent.

Closed Suction Catheter System

Description

A closed (in-line) suction catheter (Figs. 3.15, 3.16) utilizes an enclosed transparent, flexible plastic sleeve (sheath) that is attached to a specially designed T-piece adaptor, which is left in place adjacent to the tracheal tube. It also can be attached to a T-piece adaptor (52). The adaptor contains a sealing assembly (washer, cleansing collar) to prevent gas leaks around the catheter and to remove secretions from its external surface as it is drawn back into the sheath. At the other end are a manual vacuum control and a connection for the suction tubing. It may be possible to lock the suction control valve in the OFF position. An irrigation (flush, injection) port may be present at either end for tracheal lavage with the catheter inserted or for rinsing the

catheter, cleansing collar, and suction tubing after the catheter is withdrawn from the airway. A physical

partition (rotating piece of plastic, duckbill, or plastic slide) may be present between the suction catheter and the patient (53).

Figure 3.14 Vacuum control on a suction catheter.

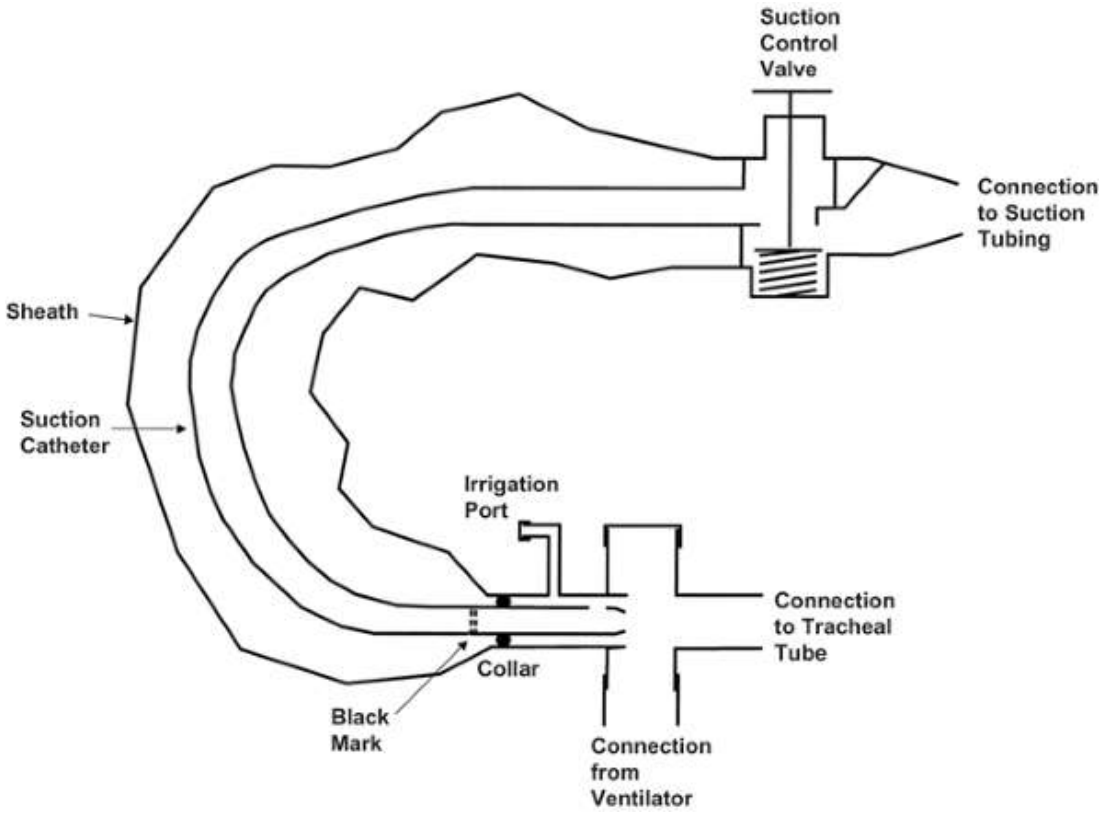

Figure 3.15 Closed suction catheter. Note the mark on the catheter that is visible when the catheter is withdrawn.

Figure 3.16 Closed suction catheter.

When not in use, the catheter rests in the withdrawn position just outside the airway. Most catheters have a marking that is visible when the catheter is properly withdrawn (Fig. 3.15).

Various catheter sizes and lengths as well as a catheter with a directional tip are available. Other features that may be present include an access valve on the adaptor, a means to thread a bronchoscope through the patient connector, a swivel lavage port, color-coded catheters, and the ability to replace the catheter independently of the adaptor (54).

Advantages

A closed suction system offers several advantages over an open system (attaching a catheter to a vacuum source, disconnecting the patient from the ventilator, inserting the catheter through the tracheal tube, suctioning, then reconnecting the patient to the ventilator). There is no need to discontinue ventilation or positive end-expiratory pressure (PEEP) while suctioning, although both the minute volume and end-expiratory pressure will be somewhat lowered (55,56,57,58,59,60,61,62). Oxygenation is usually superior to the open suction technique (56,58,63,64,65,66,67,68). Closed suctioning may make it unnecessary to hyperoxygenate prior to suctioning (69). It is associated with fewer cardiovascular disturbances; decreased coughing, agitation, and strenuous muscle activity; and less patient anxiety (68,70,71).

The closed suction system is convenient. Suctioning can be performed easily and quickly by one caregiver. It allows easy instillation of fluids into the trachea. Equipment setup and cleanup is simple. It is perceived by staff to be easier and less time consuming than open suctioning (72). It does not cause mechanical ventilator malfunction (60).

Because the catheter is enclosed within a sterile closed system, contamination from accidental breaches in sterile technique should not occur. Rates of nosocomial infection have been found to be less than or comparable to rates associated with open suctioning (71,72,73,74,75,76). Autocontamination does not appear to be more of a problem with closed than open suctioning (77).

Closed suction systems limit contamination of the environment

around the patient (78). Health care personnel who use the system do not need to fear that secretions may be splashed back into their faces because exhaled material is propelled into the expiratory limb of the ventilator tubing. However, condensate showering from the irrigation port can be a problem (79,80). For this reason, gloves, a mask, and protective clothing should be worn when performing closed suctioning.

A closed system suction catheter costs approximately 10 times more than a single disposable kit for open system suctioning (65,81,82,83). Whether it is cost effective depends on how often the patient is suctioned and how long it is used. Although most institutions change the catheter every 24 hours, studies indicate that longer use is safe and can further reduce costs (84). Some researchers have suggested that the closed system should stay in place as long as the patient is receiving mechanical ventilation (85). Closed system suctioning can lower costs by reducing personnel time and the spread of infection.

Disadvantages

Some health care providers believe that closed suctioning is not as effective in removing

secretions as open suctioning (52,71,76,79,80,81,86,87). In part, this may be because with the catheter encased in a sheath, the suction or secretions moving through the catheter are more difficult to feel, and the sound is less (53,54). One study found no significant difference between the two techniques in the quantities of secretions removed even though the staff believed that closed suction was less effective (87). Other studies found that open suctioning was superior in removing secretions (67,88). Periodic use of open suction may be useful to increase secretion removal in patients with thick, tenacious secretions. However, this increases costs and may result in loss of sterility associated with the closed system (80).

Another disadvantage of closed suction systems is that the extra weight may pull on the airway, causing trauma or accidental extubation. It is important that the system be supported to prevent these problems. Yet another problem is increased resistance in hygroscopic condenser humidifiers due to saline installations (89). Some health care providers have complained

that the system is more difficult to use, does not provide the same ‘feel’ associated with conventional suctioning, and may cause more trauma (52,80,81,87,90). The vacuum control valve may stick (91).

Continuous Irrigation Suction Catheter

The continuous irrigation suction catheter is a double-lumen catheter that allows simultaneous instillation of fluid and aspiration. Studies show that this is more effective than a conventional suction catheter in clearing secretions (44,92).

Packaging

Flexible catheters may be packaged either coiled or straight. Catheters that are packaged straight are easier to remove from the package, can be introduced into the patient more easily, and are more effective for left bronchial suctioning (93).

Suction Apparatus Efficiency

The efficiency of suction apparatus depends on the subatmospheric pressure generated and the time taken to achieve it, the displacement (the volume of air that the pump is able to move in unit time), the internal resistance of the suction apparatus as a whole, and the viscosity of the matter being aspirated (11).

Suctioning Techniques

The first step in suctioning technique is to set the maximum negative pressure. Before adjusting that pressure, the regulator outlet must be occluded. This can be done either by placing a finger over the collection container intake or by crimping the suction tubing closed (Fig. 3.17). The gauge will then register the maximum vacuum that can be generated at that setting.

Figure 3.17 The negative pressure should be set by occluding the suction tubing and adjusting the regulator while observing the gauge.

When not in use, the vacuum source should be turned OFF or the suction tubing kinked (Fig. 3.18) to reduce the load on the system and improve the pressure and flow available at other inlets. It also prevents dust and debris from being suctioned into the regulator and other equipment. Kinking the suction tubing allows maximum vacuum to be quickly restored.

Devices for holding the suction catheter between uses are available (94). The anesthesia provider can put the suction catheter in the holder arm between uses.

Suctioning under Direct Vision

A rigid catheter with a terminal opening (Yankauer) may be used to quickly remove large mucous plugs, vomitus, blood clots, or large volumes of fluid. It should be used only under direct vision and with a vacuum control device. In a severe emergency, the suction catheter may be

removed and the end of the suction tubing used directly. A flexible suction catheter can also be used for suctioning under

direct vision. It cannot be directed as easily but is less likely to damage the teeth.

Figure 3.18 Keeping the suction tubing kinked when not in use will allow maximum vacuum to be restored quickly. It also reduces the strain on the vacuum system.

An endoscope can be used to direct the catheter to clots or mucous plugs in the lower airway (95,96,97). Large blood clots or mucous plugs in the lower airways may require a tube with a large diameter (such as a tracheal tube) (96).

Mouth and Pharyngeal Suctioning

Suctioning the mouth and pharynx can be performed by using either a rigid or flexible catheter. If the teeth are clenched, it may be possible to insert the catheter laterally behind the last molar or where teeth are missing. Damage to the teeth may occur if a rigid catheter is used. Most fluids found in the mouth and pharynx are not highly viscous and are easily removed. If there is a large amount of blood or vomitus, instilling water into the area being suctioning may aid removal. Usually size 14â€“18

French catheters are used in adults. Many anesthesia providers use unregulated vacuum for oral or pharyngeal suctioning. This may result in mucosal trauma (98,99).

A flexible catheter can be inserted through a nasopharyngeal or oropharyngeal airway. The external surface of the catheter should first be thoroughly lubricated. Suctioning through the nasal cavity without an airway may result in epistaxis.

The vacuum control on the catheter should be open while inserting the catheter. The catheter should be withdrawn slowly with a twisting motion while intermittently occluding the vacuum control.

Suctioning Associated with Extubation

Prior to extubation, secretions in the mouth and pharynx should be removed. This can be accomplished with the same catheter that was used for tracheal tube suctioning.

After oropharyngeal suctioning, the tracheal tube cuff should be deflated and the tube removed while applying continuous positive pressure. An alternative is to have the patient take a deep breath with extubation at the end of inspiration. Secretions around the tube should be expelled as the patient exhales. The oropharynx should then be suctioned to remove expelled secretions.

In the past, some anesthesia providers extubated the patient while suction was applied to the tracheal tube. The rationale behind this maneuver was to remove any secretions that may have passed into the trachea when the cuff was deflated. This is not good practice, because it depletes the lungs of oxygen, removes the path of reoxygenation, and may result in negative pressure pulmonary edema (100,101).

Open Suctioning through a Tracheal or Tracheostomy Tube

Most authorities advocate that tracheal suctioning be performed no more frequently than indicated by the clinical situation (93,102,103,104,105,106,107,108). Indications include audible secretions, a rise in peak inspiratory pressure, or an increase in the peak inspiratory pressure‾€“plateau pressure difference, increased airway resistance, decreased dynamic compliance,

decreased tidal volume delivery during pressure-limited ventilation, decrement in arterial blood-gas values or saturation, increased end-tidal carbon dioxide, altered homodynamic, patient restlessness, unrelieved coughing, and evidence of atelectasis on chest x-ray (109). Routine suctioning may actually stimulate production of airway secretions and can be associated with more adverse effects (110,111).

The catheter should be in the trachea no longer than necessary and never more than 10 to 15 seconds in adults

(48,51,57,104,108,112). Shorter times should be used for pediatric patients (113).

The negative pressure should be set by occluding the suction tubing and adjusting the regulator while observing the gauge (Fig. 3.17). If the pressure is not deliberately set, dangerous pressures may be generated (98). The negative pressure for suctioning the trachea should be no greater than 70 to 150 mm Hg (9.3 to 20 kPa, 50 to 115 cm H_2O) in adults (20,48,57,81,104,108,110,112,114,115). For infants, the negative pressure should be no greater than 60 to 80 mm Hg (8.0 to 10.7 kPa) (116,117). When copious secretions are present, it may be necessary to increase suction pressure to allow more effective removal.

Normal saline, water, or water-soluble jelly may be used to lubricate the outside of the catheter prior to insertion. Drawing water or saline through a catheter before use may improve flow and checks catheter patency.

Hyperoxygenation, hyperventilation, and hyperinflation prior to and following suctioning will help prevent hypoxemia (21,103,114,118,119,120,121,122,123,124,125,126,127,128), as will oxygen insufflation during the procedure (41,42,129,130).

Instilling saline into the tracheal tube before suctioning to dilute secretions or generate a cough is controversial. It should have little effect on clearing secretions, because mucus and water are immiscible (112,131). An exception may be postoperative head and neck surgery patients who often have bloody secretions (132).

There are a number of possible negative consequences to instilling saline into the trachea. It can dislodge bacteria or

secretions from the tracheal tube wall and wash them into the lower airways (133,134). Vials are frequently contaminated during opening (135). Irrigation fluid may pool in the swivel and ventilator connectors, causing saline to mix with bacteria in this area. Subsequent procedures such as turning the patient or lowering the head may cause contaminated fluid to enter the patient's lower airways. Instilling saline may have an adverse effect on patient comfort and cause hypoxemia (136,137,138,139,140,141). Another concern is more environmental contamination due to increased splashing.

The saline used to flush intravenous lines or normal saline intravenous solutions should not be used because of the preservatives that may burn lung tissue (113).

A mask and gown should be worn to protect the health care provider.

Tracheal suctioning requires aseptic technique by using sterile gloves and a disposable sterile catheter. It may be helpful to wrap the sterile catheter around the gloved hand to reduce the risk of contamination. If the suction catheter is disconnected, it should be placed on a sterile drape or glove (104).

A suction catheter used for tracheal suctioning also can be used for oral and pharyngeal suctioning. A catheter that has been used for suctioning in the upper airway should be discarded and a new, sterile catheter touched only with a sterile glove used if further tracheal suctioning is needed.

The smallest catheter necessary to remove the secretions should be used. The external diameter of the catheter should be no more than half the inside diameter of the tracheal tube (17,45,142,143). This may be difficult to achieve in infants (103).

The catheter should be inserted with a smooth, gentle motion, without force and without applying any negative pressure (144). The tracheal tube should be handled carefully to avoid coughing and straining.

If deep tracheal suctioning (entering a mainstem bronchus) is not needed, the catheter should be passed just beyond the end of the tracheal tube (103,113,115,145,146) (Fig. 3-19). If the catheter is inserted too far, mucosal trauma is more likely to occur. If insertion is too shallow, secretions in the tube may not

be cleared (145). The best way to determine how far to insert the catheter is to place an appropriately sized suction catheter into another tracheal tube of the same size. If the length from the patient end is marked on the catheter, this scale can be used to determine the correct depth of insertion. If resistance is met during catheter insertion, the catheter should be withdrawn 0.5 cm before suction is applied to avoid invagination of mucosa into the catheter (145).

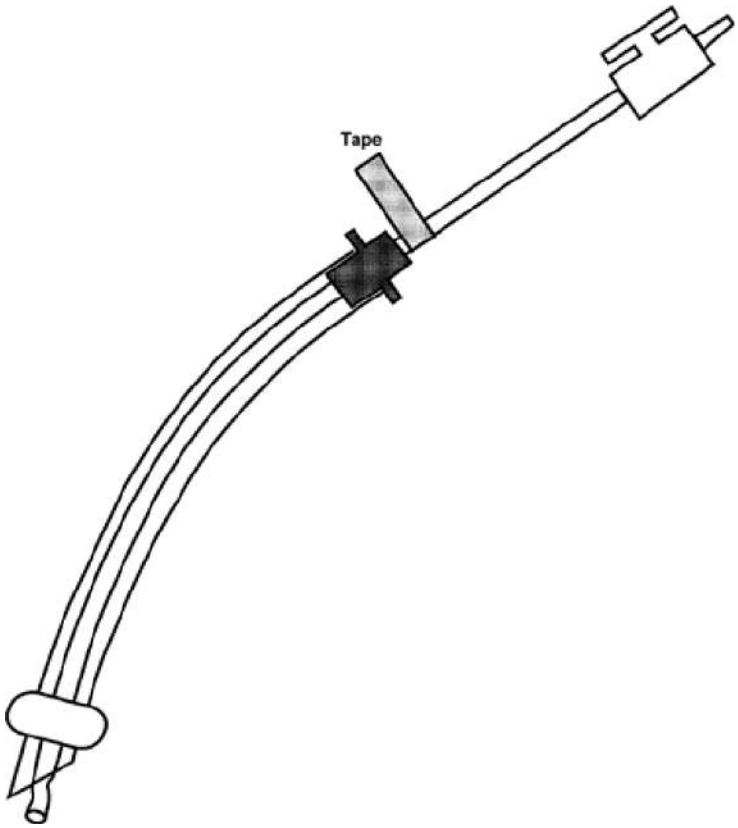

Figure 3.19 Unless deep suctioning is needed, the suction catheter should extend only just beyond the end of the tracheal tube. Placing a piece of tape on the suction catheter will prevent deep insertion.

If deep tracheal suctioning is required, most authors recommend advancing the catheter fully until it reaches the carina, as determined by resistance to insertion or the patient coughing

(112). It should then be withdrawn a few millimeters prior to initiating suctioning (103). In infants, resistance in the tube itself can make detection of resistance at the end of the catheter difficult, so the catheter should be measured and premarked to ensure that it is not inserted more than 1 cm beyond the carina (147).

After the catheter is inserted, suctioning should begin immediately. Most authors recommend that the vacuum control be closed intermittently while the catheter is withdrawn, although some recommend continuous suctioning (112). The catheter may be rotated gently during withdrawal. It should not be jabbed up and down. If the operator feels resistance during withdrawal, the vacuum control should be opened immediately. A convenient way to dispose of the catheter is to coil it, pull off the glove with the catheter inside, and dispose of both as a unit (148,149).

If hyperoxygenation is used, it is important to turn the oxygen down to the previous level at the conclusion of suctioning (150).

Tracheal Suctioning without a Tracheal Tube

If it is necessary to suction the trachea when no tracheal tube is in place, the suction catheter may be directed into the larynx by using a nasopharyngeal airway (Chapter 16). This serves to guide the catheter, minimize the trauma to the nasal mucosa, reduce gag and cough reflexes from the posterior pharyngeal wall, and reduce the introduction of pharyngeal flora into the trachea. This technique is dangerous. If laryngospasm occurs while the catheter is between the vocal cords, hypoxemia can quickly result. If this occurs, the vacuum control should be opened and oxygen insufflated through the catheter.

Closed Suctioning

If possible, closed suctioning should not be used with volume control ventilation because of the risk of high airway pressure during catheter insertion and extreme negative pressure during suctioning (54,57,60,79,151). Pressure control ventilation (Chapter 12) produces less intrinsic PEEP during catheter insertion and less subatmospheric pressure during suctioning. Pressure support ventilation with the trigger level set low is even better in this regard (59,151).

Studies show that with closed suctioning, negative pressures as great as -400 cm H_2O (-300 mm Hg) can be used to remove secretions without impairing gas exchange (88).

The closed system suction catheter is connected to the vacuum source at the distal end, threaded through the plastic sheath, and advanced down the tracheal tube by using the thumb and forefinger of the dominant hand while the nondominant hand stabilizes the adaptor. The suction control valve is depressed and the catheter drawn back into its sheath. If it is not fully withdrawn, the airway may be partially occluded (52,152).

The catheter and collar should be rinsed after each suctioning attempt by flushing saline into the injection port while depressing the suction control valve. If residual secretions are still present, the closed suction system should be replaced.

After use, the catheter should be disconnected from the vacuum source to avoid negative pressure being applied to the breathing system if the vacuum control valve is faulty (153).

Bronchial Suctioning

Selective suctioning of one or both bronchi is sometimes required. The left mainstem bronchus is more difficult to enter than the right in patients over 15 years of age. The success rate may be higher when the patient has a tracheostomy (32,36,154,155,156,157). If the tracheal tube tip is less than 2 cm above the carina, the catheter is less likely to enter the left bronchus than if the tube is positioned more cephalad (36).

A higher rate of success will be achieved with a curved tip catheter directed to the desired side (32,33,34,35,36,93,156,158,159,160). A dual-curvature catheter may also be of benefit (161A). A tip-deflecting wire can be used to manipulate a suction catheter into the desired bronchus (161B). Catheters that are packaged straight rather than coiled are more effective for left bronchial suctioning (93,162). It is important to prevent the catheter from rotating in the tracheal tube and in the trachea. This will be easier if the catheter has a means to determine the direction to which the tip is pointing (35,155).

During bronchial suctioning, it is recommended that the head be turned to the contralateral side or be placed in the midline

(93,155,160,162,163,164). Some studies have shown a slightly higher success rate for left bronchial suctioning if the patient is in the left lateral position (35,165) or if the tracheal tube is in the left or central part of the patient's mouth (157).

Hazards Associated with Suctioning

Hypoxemia

Arterial oxygen saturation decreases during tracheal suctioning and for some time afterward (48,166). Children desaturate more quickly than adults. The

magnitude of the decrease is related to the duration of suctioning as well as whether the ventilation was continued or discontinued during suctioning. The size of the catheter in relation to the size of the tracheal tube is also important. The magnitude of the negative pressure is also a factor. The pattern and amount of negative airway pressure during closed system suction may be influenced by ventilatory mode, settings, and ventilator (61,167).

Another cause of hypoxemia is laryngeal spasm. The vocal cords may close while the suction catheter is in the trachea, which could result in rapid desaturation.

A number of maneuvers have been recommended to prevent hypoxemia associated with suctioning. These may be used separately or in combination.

Maintaining Ventilation

If suctioning is performed by using a method that allows artificial ventilation to continue, the drop in oxygenation is less (64,65,70). This can be done by using special adaptors, closed system suctioning, or high-frequency jet ventilation through a channel in the tracheal tube wall (168).

Hyperoxygenation

Hypoxemia can be avoided or attenuated by administering oxygen at an FiO_2 greater than the patient was receiving or required prior to (preoxygenation), during (insufflation), or after (postoxygenation) suctioning. In adults, this is usually with an

FiO_2 close to 100%, although 20% above maintenance is adequate in most cases (121,169). In newborns, an FiO_2 10% to 20% above baseline is recommended (103,170,171,172). A problem with using 100% oxygen is that the health care provider may fail to return the oxygen concentration to the previous level. Some ventilators have a temporary O_2-enrichment feature that delivers 100% oxygen for a preset period of time (110,173). This avoids the problem of the health care provider failing to return the FiO_2 to the baseline level. Some ventilators are equipped with alarms that are activated if the inspired oxygen level is too high.

Preoxygenation and postoxygenation can be carried out by using a ventilator or a manual resuscitation bag. A ventilator is preferred (174). It is easier to continue PEEP when a ventilator is used. With a ventilator, a period of time (bleed or washout time) is required before the desired concentration of oxygen is delivered. The washout time depends on ventilatory rate, flow, tidal volume, dead space, the initial FiO_2, and the volume of the tubing.

When using a manual resuscitation bag, an elevated oxygen concentration depends on the oxygen flow, size of the reservoir, and minute volume (Chapter 10). Not all manual resuscitation bags can deliver 100% oxygen (175). Using PEEP during manual ventilation may improve postsuctioning PaO_2 slightly (176,177).

Insufflation can be accomplished by using a suction catheter or a tracheal tube with an extra lumen that allows delivery of oxygen (43,178). This can be an effective method of avoiding or minimizing hypoxemia (41,179,180). An oxygen flow of 10 to 15 L/minute should be used (174).

Hyperinflation

Hyperinflation (inflation of the lungs with a volume greater than baseline tidal volume) before or after suctioning when used in conjunction with hyperoxygenation may be effective in maintaining PaO_2 (121,150,166,181,182,183,184). Hyperinflation without hyperoxygenation does not consistently prevent hypoxemia (121,150,182). There is a progressive improvement in oxygenation with increasing volume (125). Up to 1.5 times the baseline tidal volume has been recommended

(114,122,128,183,185). Another recommendation is a peak pressure that is 10% to 20% above baseline (103). Three hyperinflations are more effective than one (128). The use of an inspiratory hold is not more effective (186).

Hyperinflation may be accomplished by increasing the ventilator-set tidal volume, manually triggering preset sighs on a ventilator equipped with this feature, or manually with a resuscitation bag. Using the ventilator is usually superior to the bag (175,185,187,188,189). It is also more efficient, as it requires only one person and no additional equipment. Most manual resuscitation bags are not attached to a spirometer, so there is no way to accurately measure volumes.

Hyperinflation can result in patient discomfort, cardiovascular disturbances, and barotrauma (112,121,125,126,182,190). It could propel secretions farther into the airway. For these reasons, each patient should be assessed individually to determine the need for hyperinflation and the appropriate volume (150). If saturation drops despite hyperoxygenation, hyperinflation should be added and the changes in SpO_2 and other parameters assessed (110). Hyperinflation should be avoided in severely head-injured patients where intracranial pressure is a concern and used with caution in unstable cardiac patients (174).

Hyperventilation

Hyperventilation, an increase in ventilation above baseline, is often performed before or after suctioning. Because of inconsistencies in delivery with a manual resuscitation bag, it is recommended that a ventilator be used (191,192). Hyperventilation is often used in conjunction with hyperoxygenation. It should be used with caution in head-injured patients (115).

Limiting the Duration of Suctioning

The longer suction is applied to the tracheobronchial tree, the greater the magnitude of the hypoxemia.

Suctioning should be limited to less than 10 to 15 seconds in adults (48,51,81,104,108,112). However, since most of the fall occurs within the first 5 seconds, this is of limited value (193).

Adequate rest periods should be taken between suctioning procedures to allow correction of hypoxia and hypercarbia.

Avoiding Laryngeal Spasm

Laryngeal spasm may be avoided by inserting the catheter during inspiration and using topical or intravenous lidocaine. If laryngeal spasm occurs, the operator should immediately open the vent to air and insufflate oxygen through the catheter.

Proper Technique

Negative pressure should be applied only while the catheter is being withdrawn. Excessive negative pressure should not be used. Finally, the outside diameter of the catheter should be no greater than one half of the inside diameter of the tracheal or tracheostomy tube.

Adverse Effects on Respiratory Mechanics

Tracheal suctioning increases respiratory resistance (184,194). The effect is transient and not suppressed by β_2-adrenergic receptor blockade. Intrinsic PEEP is decreased with suctioning. A loss of end-expiratory lung volume is commonly seen. A fall in pulmonary compliance may occur. Right upper lobe collapse in children has been associated with deep suctioning (195).

Trauma

Whenever suctioning is performed, there is the possibility that there will be damage to the airway. Reported problems include irritation, edema, inflammation, decreased mucociliary function, ulceration, necrosis, perforation, granulation tissue sufficient to cause bronchial stenosis, and lobar emphysema.

Trauma is related to the frequency of suctioning, the technique used, and the magnitude of the negative pressure (98,196). Deep suctioning is associated with more trauma, especially to the carina, than shallow suctioning (103,117,145). Although the common clinical perception is that intermittent suction is less injurious than continuous suction, both can cause mucosal damage (197). The suction catheter has a minor role in determining the amount of mucosal damage (49,198,199). Smaller tips have been reported to cause increased mucosal damage (99). A faulty suction catheter can cause considerable

damage (200).

To minimize trauma, unnecessary suctioning should be avoided. The catheter should be inserted only slightly more than the length of the tracheal tube unless deep tracheal suctioning is required. Poking or prodding should be avoided. If blood-stained secretions are observed in the absence of obvious reasons (lung contusion, recent tracheostomy), the entire suctioning technique should be examined.

Suctioning via the nasopharynx often causes trauma to the nasal mucosa. If the tip of the catheter is directed gently along an inferior and medial path with rotation, it will tend to follow the floor of the nasal cavity, and trauma to the turbinates will be minimized. Prior insertion of a nasal airway will usually result in less trauma and more consistent positioning of the suction catheter.

Cross Infection

Many aspirated fluids contain high concentrations of microorganisms or blood, so cross contamination between patients or staff is a hazard (8,201,202). Caution should be used in handling all suction equipment.

Cross infection can occur either by direct contact with contaminated equipment or fluid or from aerosols. Microorganisms are aerosolized into the collection container during suctioning and remain in the space above the liquid. When the container is opened, the microorganisms may be released into the environment. During open suctioning, the spray of condensate and tracheal secretions expelled during exhalation or coughing may contaminate the operator and atmosphere.

Some health care facilities have adopted the risky practice of emptying and reusing disposable suction canisters (203,204). Emptying the canister exposes personnel to microorganisms in the aspirate and risks contaminating the outside of the canister.

Cross contamination can be prevented by using filters, anti-overflow devices and collection containers that can be sealed prior to movement, closed suction systems, and not overfilling the collection container. Materials that cause the fluid inside a canister to solidify are available. This minimizes aerosolization and splashing of the collected fluids. Disinfectant solutions

placed in collection containers often increase frothing. Filters should be examined and changed frequently. Personnel should be encouraged to regard all suction waste as potentially infectious and to handle and dispose of it properly. Hands should be washed after touching suction equipment, even if gloves were worn.

Special disposal systems for waste fluid are available (204,205,206). These dispose of liquid waste into the sewer with no pouring required. Although their initial cost is somewhat high, they may be cost effective if large volumes of fluid are generated by surgical procedures.

Bacteremia

Transient bacteremia can occur during suctioning through a tracheal tube (207) or nasotracheal suctioning (208). Minimizing trauma and using aseptic technique can reduce this risk.

Cardiovascular Disturbances

Cardiac dysrhythmias, tachycardia, bradycardia, hypotension, hypertension, or even cardiac arrest can occur during suctioning (64,68,71,125,126,170,190,191,209,210,211,212,213,214,215,216,217,218). These problems are often related to hypoxemia. Another possible cause is coughing. In the unintubated patient, vocal cord stimulation may cause cardiac dysrhythmias (102). Cardiovascular disturbances are less with closed suctioning (65,68,70,217,219) using a ventilator rather than a manual resuscitation bag for hyperinflation/hyperoxygenation (185,187) and using insufflation rather than preoxygenation (43). Limiting the depth that the catheter is inserted should reduce the risk of vagal stimulation (220).

Increased Intracranial Pressure

Intracranial pressure may increase during suctioning (209,214,215,221,222,223,224,225,226,227,228,229). Measures to limit the increase include preoxygenation; hyperventilation prior to and following suctioning; limiting the duration of suctioning; not rotating the head; limiting the depth of catheter insertion; allowing adequate recovery time following suctioning; and administering drugs such as intratracheal lidocaine,

sedatives, or paralyzing agents (115,117,174,221,224,225,229,230,231). For severely head-injured patients where intracranial pressure is a concern, hyperinflation during and/or after suctioning should not be added to hyperoxygenation (174).

Negative Pressure Pulmonary Edema

Pulmonary edema can occur if negative pressure is applied to a catheter that is inserted through the cords closed from laryngeal spasm. If this happens, suction should be discontinued and oxygen insufflated through the suction catheter. Application of suction to the tracheal tube connector can result in pulmonary edema (100).

Inadequately Removed Material

Consequences of inadequate removal of material such as secretions or vomitus include hypoxia, atelectasis, infection, increased airway pressures (with increased risk of barotrauma, hypoxia, patient discomfort, and anxiety), and excessive coughing (232). Tracheal tube narrowing from the buildup of secretions may occur, especially with prolonged intubation (83).

Inadequate Suction

Misassembly of a suction system so that no collection jar is incorporated in the system can result in loss of suction (233). The system will appear to function during testing, but once fluid reaches the suction controller, the filter will occlude and suction will be lost.

Obstruction of the suction tubing by viscous or particulate vomitus while suctioning a patient's oropharynx is a common problem (18).

It is possible for the overfill protection mechanism to interrupt the flow if it is bumped or jarred. Restoration of suction requires disconnection of the vacuum source and reopening of this valve. This problem can be avoided by mounting the container securely and not allowing the container to become too full.

If the filter becomes wet or clogged, the flow will be interrupted. This can be caused by liquid, foam, or aerosol products from lasers or electrosurgery.

The vacuum control on a suction catheter may be a source of obstruction if the glove on the finger occluding it is sucked into the catheter (234).

Impacted Suction Catheter

A suction catheter can become impacted in a tracheal tube (235,236,237,238). This can occur if the suction catheter exits through the Murphy eye. The patient may need to be reintubated. An alternative is to cut the machine end of the tracheal tube and try to remove the catheter from the shortened tube (236).

Inability to Pass Suction Catheter through a Tracheal Tube

There are a number of reasons why a suction catheter may not pass through a tracheal tube. The catheter may be too large. The tracheal tube may have a special configuration that makes passage difficult. The inner surface of the tracheal tube may be sticky, causing the catheter to hang up as it is inserted (239). There may be an obstruction or narrowing within the tracheal tube lumen.

Other

In one instance, a partially reusable collection container suffered an implosion that resulted in a shower of plastic shards and canister contents (240). A suction catheter may break, and the tip may fall off (241). Part of the suction catheter packaging may stick to the catheter and be deposited in the airway (242).

Using saline instillation in association with closed system suctioning may result in greatly increased resistance in a heat and moisture exchanger (243).

A case has been reported where a high negative pressure caused by suctioning resulted in the lock up of a ventilator (244,245).

A transient high airway pressure may occur during insertion of a suction catheter through a tracheal or

tracheostomy tube (before suctioning has begun) if the ventilator is in volume control mode (60).

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Questions

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

1. The intermediate tubing in the suction system

A. Is located between the wall inlet and the collection bottle

B. Can carry liquids and solids

C. Should be short to reduce resistance

D. Should be as thin as possible

View Answer

2. Situations where large collection containers should be used include the following:

A. Pediatric surgery

B. When maximum vacuum is needed quickly

C. Open suctioning

D. When large volumes of aspirate are expected

View Answer

3. The best location(s) of the suction collection container include

A. On the wall close to the pipeline inlet

B. Below the patient

C. Beside the vaporizers on the anesthesia machine

D. Where it will not be tipped

View Answer

4. Which statement(s) about suction catheter tips are correct?

A. The diameter of the terminal orifice of the catheter must be at least 95% of the inside diameter of the catheter

B. The holes should be smooth

C. Tips with a single hole grab the mucosa less than if there are multiple holes

D. Multiple side holes will reduce the available vacuum

View Answer

5. Function(s) of the vacuum control on the suction catheter include

A. Interrupting suction without switching off the vacuum

B. Facilitating insertion of the catheter

C. Breaking the seal if the catheter tip becomes occluded

D. Reducing tissue trauma

View Answer

6. Advantages of closed suction include

A. Better oxygenation while suctioning

B. Decreased coughing and agitation

C. Reduction of nosocomial infection

D. Facilitating hyperventilation during suctioning

View Answer

7. Proper techniques for clearing secretions during extubation include

A. Extubation during applied positive pressure

B. Suctioning the pharynx after extubation

C. Extubating after the patient takes a deep breath

D. Suctioning through the tracheal tube as it is removed

View Answer

8. Which is not an indication for tracheal suctioning?

A. A rise in peak pressure

B. Increased airway resistance

C. Decreased tidal volume during pressure-limited ventilation

D. Decreased end-tidal carbon dioxide

View Answer

9. Important factors related to proper suctioning techniques include

A. Limiting the negative pressure to 70 to 150 mm Hg in adults

B. Limiting the negative pressure to 60 to 80 cm H_2O in

infants

C. Hyperoxygenation prior to suctioning will help prevent hypoxemia

D. Drawing water through the catheter may reduce suction flow

View Answer

10. Problems associated with instilling saline prior to suctioning include

A. Bacteria may be washed into the lower airways

B. Saline instillation may promote hypoxemia

C. Saline vials may be contaminated during opening

D. Bloody secretions are more difficult to remove

View Answer

11. Proper technique with a suction catheter includes

A. Choosing the largest catheter that will fit through the tracheal tube

B. Using a smooth, gentle motion during insertion

C. Negative pressure applied as the catheter is inserted into the tracheal tube

D. The catheter should be passed just beyond the tip of the tracheal tube

View Answer

12. Correct techniques after the suction catheter has been inserted into the tracheal tube include

A. Dirty catheters coiled and folded inside of the operator's glove

B. Gentle rotation as the catheter is withdrawn

C. If resistance is felt, the vacuum control should be opened at once

D. Continuous suction as the catheter is removed

View Answer

13. Which factors promote a higher rate of success during bronchial suctioning?

A. A tip-deflecting wire

B. Catheters that are delivered coiled

C. Turning the head to the contralateral side

D. Using a catheter with a straight tip

View Answer

14. Factors that promote hypoxemia during suctioning include

A. Increased duration of suctioning

B. Increased magnitude of the negative pressure used

C. Diameter of catheter large in relation to the size of the tracheal tube

D. Continuation of ventilation during suctioning

View Answer

15. Techniques that will minimize the chances of hypoxemia associated with suctioning include

A. Using PEEP during manual ventilation

B. Continuing artificial ventilation

C. Insufflation with oxygen during suctioning

D. Hyperoxygenation before suctioning

View Answer

16. Which statements about hyperinflation to prevent hypoxemia are correct?

A. Only one hyperinflation is necessary

B. The peak pressure should be 10% to 20% above usual

C. Hyperoxygenation is not necessary when performing hyperinflation

D. Up to 1.5 times the tidal volume has been recommended

View Answer

17. Hazards associated with hyperinflation include

A. Patient discomfort

B. Barotrauma

C. Cardiovascular disturbances

D. Secretions may be pushed downward into the airway

View Answer

18. Which factors are frequently related to airway trauma?

A. Magnitude of the negative pressure

B. Depth of suctioning

C. Frequency of suctioning

D. Large-tip suction catheters

View Answer

19. Mechanism(s) responsible for spreading microorganisms between patients include

A. Condensate from the trachea during open suctioning

B. Direct contact with contaminated fluid or equipment

C. Emptying the collection bottle

D. Aerosolization from the collection container

View Answer

20. Practices that prevent cross contamination include

A. Using filters

B. Antioverflow devices

C. Closed suction systems

D. Adding disinfectant solution to the collection container

View Answer

21. Cardiac disturbances are most often associated with which situations?

A. Coughing in the unintubated patient

B. Artificial ventilation

C. Vocal cord stimulation

D. Closed suctioning

View Answer

22. Measures that limit the increase in intracranial pressure during suctioning include

A. Rotating the head to the side

B. Hyperventilation

C. Minimizing the time between suctioning

D. Limited the depth of catheter insertion

View Answer

23. Causes of negative pressure pulmonary edema include

A. Light anesthesia

B. Catheter inserted through the vocal cords, stimulating laryngospasm

C. Discontinuation of oxygen flow

D. Application of suction to the tracheal tube

View Answer

24. Possible causes for interruption of suction include

A. Clogged filter

B. Overfilled collection bottle

C. Obstruction by particulate material

D. Tracheal tube narrowing

View Answer

Chapter 4
Oxygen Concentrators

Introduction

There are circumstances where obtaining oxygen from cylinders or a liquid storage tank is inconvenient, impossible, or prohibitively expensive. This has resulted in increased interest in alternative sources of supply, especially oxygen concentrators. There are now well over 500,000 of these units in use worldwide.

Technology

Most oxygen concentrators use pressure swing adsorber (PSA) technology, which increases the oxygen concentration by adsorbing nitrogen onto a molecular sieve and allows oxygen and trace gases, especially argon, to pass through. The result is a gas with an oxygen concentration between 90% and 96% (1,2,3,4,5,6,7). The product gas from the concentrator is referred to as Oxygen 93% USP (U.S. Pharmacopoeia), Oxygen 90+, or oxygen-enriched air (3,4,8).

Two international and one U.S. standard for medical oxygen concentrators have been published (8,9,10).

Most concentrators use an inorganic silicate belonging to a class of crystalline compounds known as zeolites for the molecular sieve. Within each zeolite granule is a system of precisely arrayed cavities and pores that are uniform in size so that molecules are either readily adsorbed or completely excluded. The molecular size and polarity of a gas determine whether it is retained by the sieve material.

Pressurized air is passed through a sieve bed. Oxygen (along with argon) passes through freely, while nitrogen, carbon dioxide, carbon monoxide, water vapor, and hydrocarbons are trapped. These are then desorbed (released) by venting the sieve bed to atmosphere, thereby reducing the adsorptive force. Regeneration of the sieve bed is then completed by purging with some product gas.

A continuous output of oxygen-enriched gas is achieved by using two sieve beds in a sequential adsorption-desorption process known as pressure swing adsorption. As one sieve adsorbs nitrogen under pressure, the other sieve is desorbed and purged. The output depends on the size of the installation.

The molecular sieve has a strong affinity for water. Water in the sieve will displace other molecules, reducing the capacity to adsorb nitrogen. During normal operation, room humidity does not affect the sieve's adsorbent ability. A sieve at the entrance to the bed or column acts to adsorb moisture. This is returned to the atmosphere during the purge (exhaust) phase. Oxygen

concentrators can be used under humid conditions if the concentrator has been designed with adequate purges, low dead space, and enough heat to assist desorption of the water (11). The beds must be kept sealed from the atmosphere to prevent moisture from migrating into them.

Concentrator Design

A schematic design for a typical oxygen concentrator is shown in Figure 4.1. Designs vary among manufacturers, and all the components that are shown may not be present in every concentrator.

Filters at the inlet remove particles and bacteria. A muffler reduces the sound level. The compressor receives the filtered air and compresses it to a higher pressure. A heat exchanger in the form of a coiled tubing may be used downstream of the compressor to cool the gas. In some concentrators, the compressed gas enters a reservoir (surge tank), which acts to dampen pulsations generated by the compressor.

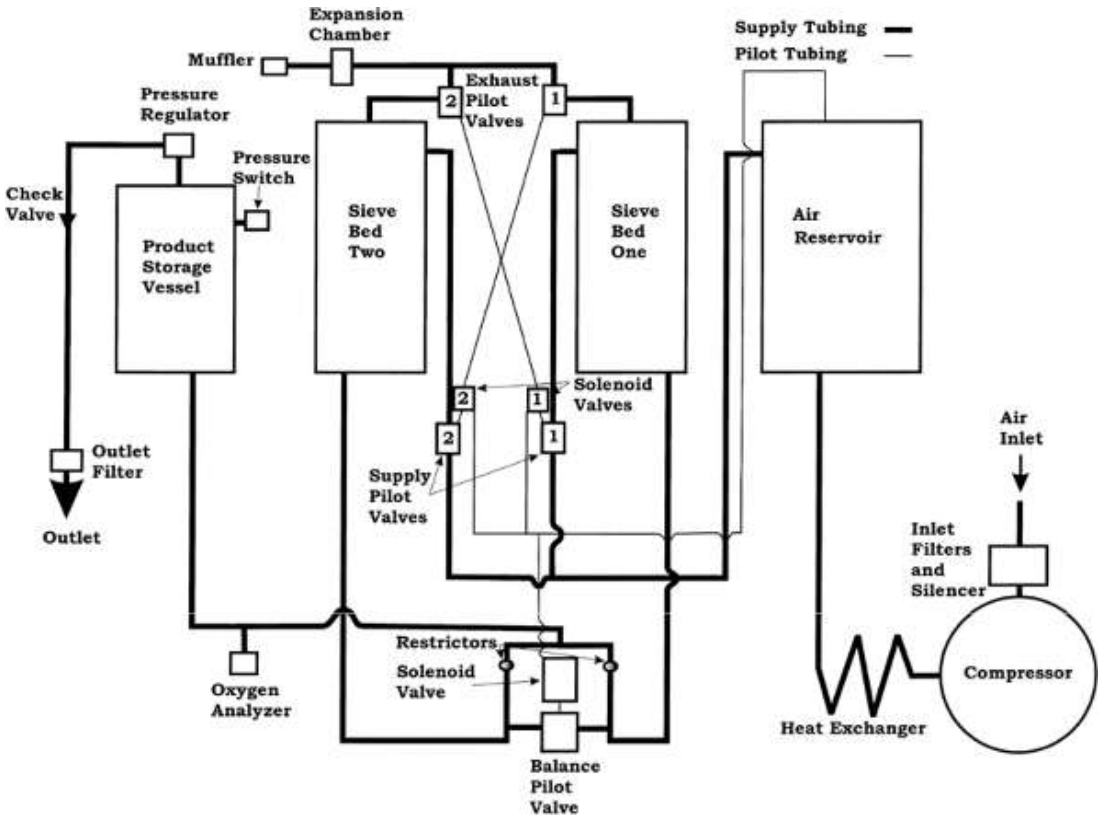

Figure 4.1 Typical oxygen concentrator.

Electrically or pneumatically controlled valves direct the gas flow though the concentrator. The two beds filled with zeolite allow continuous oxygen production and sieve regeneration.

The product (accumulator) tank functions as a reservoir of product gas. It may also serve as a source of purge gas. A pressure regulator is used to reduce the pressure of the gas flowing to the outlet to a lower, more constant level. A check valve between the pressure regulator and the outlet prevents room air from being sucked into the sieve beds when the concentrator is turned OFF. A filter is located near the outlet to prevent sieve material, bacteria, and other matter from contaminating the outflow.

Concentrators for domiciliary use a flowmetering device to control the flow of product gas (Fig. 4.2). It must be accurate to ยฑ10% of indicated flow or ยฑ0.5 L/minute, whichever is greater

(9,10). An oxygen concentration status indicator (OCSI) is required by the international and

U.S. standards to warn of low oxygen concentration in the product gas (8,9,10).

Figure 4.2 Oxygen concentrators for domiciliary use. Note flowmeter and oxygen concentration status indicator on each. (Pictures courtesy of Puritan Bennett, Inc., and AirSep Corporation.)

Operation

After being turned on, the apparatus will require two and a half to 19 minutes to achieve maximum concentration (1,6,12,13). The concentration process becomes less efficient if the flow rate is increased above the optimum level (1,4,6,12,13,14,15).

Applications

Domiciliary Use

Oxygen concentrators are widely used to provide oxygen-enriched gas for domestic use (1,14,16,17). These units are compact, lightweight devices with wheels and a handle for easy delivery and transport.

Remote Locations

In locations where the oxygen supply from pressurized oxygen cylinders and liquid oxygen are unavailable, unreliable or prohibitively expensive oxygen concentrators can provide a reliable source of oxygen (2,11,18,19,20,21). They may also be useful in field hospitals, disaster situations, ambulances, aircraft, and ships at sea.

An oxygen concentrator can be combined with an air compressor, breathing system, draw-over vaporizer, and ventilator to form an anesthesia delivery system similar to those found in more developed areas (5,18,22,23,24).

Source of Supply for Oxygen Pipeline Systems

Large-scale oxygen concentrators have been used to provide oxygen for pipeline systems and to supply a pipeline system during deliberate or accidental shutdown (2,3,4,25,26,27) (Fig. 4.3).

The pipeline system is supplied from a pressurized reservoir of oxygen 90+ that is large enough to cope with the peak flows. This provides protection against temporary electricity failure. The reservoir is usually supplied by a number of oxygen concentrators connected in parallel. A fall in pressure in the reservoir causes one or more concentrators to be brought into use until the pressure is restored.

Figure 4.3 Oxygen concentrator supply system for a piped gas system. (Picture courtesy of AirSep Corporation.)

There needs to be a reserve supply that automatically supplies the system if there is a concentrator malfunction or if the oxygen concentration falls below a preset minimum. The system may be set up so that the cylinders are filled with gas from the oxygen con-centrator.

Modern anesthesia machines are not adversely affected by oxygen-enriched gas from oxygen concentrators (3). Argon does not alter oxygen flow character-istics (3).

Advantages

Cost Savings

The product gas of an oxygen concentrator can be less expensive than liquid or cylinder oxygen (4,17,18,21,25,28,29). This depends on the cost of the concentrator, oxygen supplied by other means, electricity, and maintenance.

Contaminant Filtration

Most airborne contaminants, including exhaust hydrocarbons, ethylene oxide, sulfur dioxide, and chemical warfare gases, are filtered by the molecular sieve and released back into the atmosphere (3).

Compatibility with Most Gas Monitors

Infrared, galvanic, and paramagnetic gas analyzers (Chapter 22) are not adversely affected by the presence of argon.

Reliability

Most concentrators perform well for long periods of time (18,28). They are not affected significantly by altitude changes.

Simplicity

Oxygen concentrators provide an increased oxygen concentration without depending on compressed or liquefied gas and their associated delivery problems.

Disadvantages

Maintenance

Regular servicing is required, particularly for the compressor. It is important that the air intake filters be cleaned or replaced at the intervals recommended by the manufacturer.

Less Than 100% Oxygen Produced

The maximum attainable oxygen yield for a molecular sieve concentration is about 96%. However, in medicine, it is rarely essential to use 100% oxygen (30).

Hazards

Fires

The concentrator should be kept away from sources of heat, open flames, or electrical equipment that may spark or become heated during operation (16). A tube could rub against another part, rupture, release oxygen, and ignite live conductors in the concentrator (31,32). Overheated electrical components and loose connections can also cause a fire (33,34). Oil and grease should not be allowed to contact the concentrator. Warnings such as ĺ€NO SMOKING OR NAKED FLAMESĺ€ should be posted in the area where the oxygen concentrator is in use.

Water Contamination

Under normal circumstances, humidity is not a problem. However, very high humidity can cause the oxygen concentration in the product gas to be lowered (16,35).

Contaminated Intake Air

The air intake should be located where it is not likely to be contaminated by fumes, water, or other atmospheric pollutants (1). These contaminants could damage the

sieve medium and lead to premature sieve exhaustion (28).

Device Malfunction

Electrical or mechanical malfunction may occur and interrupt the flow of oxygen (1). It may be possible for the concentrator to be running but not concentrating oxygen. In one case, this was reported after a liquid caused an intake filter to become nonfunctional (35). Compressor faults can cause malfunction. Malfunction caused by failure of the valve linking the two sieve beds has been reported (16,30). If the sieve bed valve becomes stuck in one position, the output gas will become the same as room air (16). Circuit board failures have been reported (36).

If the air flow to the concentrator is restricted, the device can overheat, decrease performance, emanate an odor, cause excessive noise, and possibly shut down (37). One common cause is the intake filter becoming clogged (16). Cases have been reported where kinked transfer hoses in the units affected the output (38,39).

Argon Accumulation

Argon is not trapped by the molecular sieve and is concentrated much the same as oxygen. It can reach concentrations above 5%. If Oxygen 93 is added to a circle system used with low fresh gas flows, the argon may accumulate. This has not been found to be a problem if the fresh gas flow is above 0.5 L/minute (11). There are no known patient effects from long- or short-term exposure to low concentrations of argon (3).

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Questions

For the following questions, select the correct answer.

1. In an oxygen concentrator, which of the following is most likely to cause deterioration of the adsorbent medium?

A. Carbon dioxide

B. Nitrogen

C. Hydrocarbons

D. Water vapor

E. Carbon monoxide

View Answer

For the following questions, answer

if A, B, and C are correct

if A and C are correct

if B and D are correct

is D is correct

if A, B, C, and D are correct.

2. Which gases can pass through an oxygen concentrator?

A. Carbon dioxide.

B. Argon

C. Helium

D. Oxygen

View Answer

3. The product gas from a concentrator is referred to as

A. USP 96%

B. Oxygen 90+

C. Oxygen 96

D. Oxygen USP 93%

View Answer

4. In an oxygen concentrator,

A. The product gas is used to purge the retained gases from the sieve bed

B. Aluminum silicates are used to trap specific molecules

C. Polarity and size determine which molecules are retained by the concentrator medium

D. Adsorption efficiency is greatly enhanced by the use of subatmospheric pressure

View Answer

5. Present-day applications of oxygen concentrators include

A. Domiciliary use

B. Supplying ambulances

C. Supplying medical gas pipeline systems

D. Supplying anesthesia machines

View Answer

6. Advantages of the oxygen concentrator include

A. Savings associated with the purchase, handling, and delivery of gas cylinders.

B. Infrequent maintenance

C. Contaminants in the air are filtered out of the product gas

D. Constant oxygen output

View Answer

7. Hazards associated with using oxygen concentrators include

A. Argon accumulation

B. Fires

C. Unrecognized failure to concentrate

D. Contamination of the sieve medium

View Answer

Chapter 5
The Anesthesia Machine

The Anesthesia Workstation

The traditional pneumatic anesthesia machine has evolved into a complex electrical, mechanical, and pneumatic multicomponent workstation. An anesthesia workstation integrates most of the components necessary for administration of anesthesia into one unit. It consists of the anesthesia machine, vaporizers, ventilator, breathing system, scavenging system, and monitors. Added to this may be drug delivery systems, suction equipment, and a data management system. This chapter is limited to the anesthesia machine portion of the workstation. Most of the other components are covered in other chapters.

The anesthesia workstation offers many benefits. Monitoring and control functions as well as alarms can be integrated and data displayed on a single or multiple screens. Reduced external connections should reduce the likelihood of misconnections, disconnections, or kinked connections (1). A certain amount of the preuse checking procedure (Chapter 33) can be performed automatically. These workstations have built-in safeguards in case of machine failure (2,3).

Disadvantages of workstations include potential disruption of mechanical ventilation and gas delivery, display failure, electrical failure, fires, and liquid spills (2,4,5,6). They may malfunction or act in a way that the anesthesia provider does not recognize. The anesthesia provider must take the time to understand how these workstations function and what needs to be done in case of failure. It is not possible in a text such as this to provide enough information that a user can be qualified to use any particular workstation. It is essential that the user manual be studied prior to using these devices. The ability to use one make or model does not automatically qualify the clinician to use other makes or models.

Standards

Anesthesia workstations and their components are covered by American Society for Testing and Materials (ASTM) standard (7). All manufacturers selling anesthesia machines in the United States have agreed that machines sold after the year 2000 will comply with that standard. Previous standards were published by American National Standards Institute (ANSI) (8) and ASTM (9).

System Components

Electrical Components

Many components of modern anesthesia machines are powered by electricity. Turning the machine ON enables these devices. This overcomes the problem of the operator forgetting to turn ON individual devices.

Master Switch

On most anesthesia machines, a master (main power) switch activates both the pneumatic and electrical functions (Figs. 5.1, 5.2). On most machines, when the master switch is in the OFF position, the only electrical components that are active are the battery charger and the electrical outlets. On some machines, electrical components can be activated without pneumatic power. The

standby position is frequently used on computer-controlled machines to allow the system to be powered up quickly.

Figure 5.1 Master switch. Turning the master switch to the ON position activates both pneumatic and electrical functions of the machine as well as certain alarms and safety features.

Figure 5.2 Master switch. Turning the master switch to the ON position activates both pneumatic and electrical functions of the machine as well as certain alarms and safety features.

Electronic machines utilize a complicated power-up procedure that includes a system checkout when the machine is turned ON. In addition to an electronic checkout, the computer gathers data that is necessary for proper function. Computer-driven machines should be turned OFF and restarted with a full checkout at least every 24 hours. If the STANDBY mode is used for an extended period, computer information may become corrupted, some components may not function properly or the entire machine may cease to function.

Most electronic machines have a means to bypass the checkout in an emergency. Some machines limit the number of consecutive times this bypass can be used. A machine may keep a record of when and how often the bypass is used, and this information may be discoverable in legal proceedings.

One of the characteristics of modern machines is the coordination of all the functions under a central control. On most machines, the ON-OFF switch activates both the electronic and mechanical components of the machine. Cases have been reported where the master switch has been accidentally turned OFF (10,11,12,13,14). Cases have been reported where the master switch was in an intermediate position between OFF or STANDBY and ON, and this resulted in no gas other than oxygen from the oxygen flush being delivered to the common gas outlet (15,16).

Power Failure Indicator

Most machines are equipped with a visual and/or audible indicator to alert the anesthesia provider to the loss of mains power (Fig. 5.3).

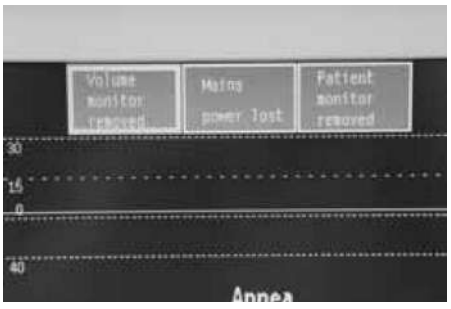


Figure 5.3 The machine will usually give an indication when mains power is lost.

Reserve Power

Since electricity is crucial for many machine functions, a backup source of power for the occasional outage is necessary. The anesthesia provider should check the battery status during the preuse checkout procedure.

On older machines, many individual monitors had their own backup power. These backup systems may need to be turned ON individually or may be activated automatically when the machine is powered up. A disadvantage of this arrangement is that it is necessary to check the battery status of each monitor. The duration of the backup will vary.

On new anesthesia workstations, components may be backed up with a single power source. An advantage of this system is that only one backup source needs to be checked. The duration will depend on the number of instruments being supported. Manual or spontaneous ventilation may extend battery life, as ventilator control is electronic in most of the new workstations.

While some older anesthesia machines used replaceable batteries, most new machines use rechargeable batteries. Battery recharge times vary. If the machine is continually connected to mains electrical power, backup power should be at its highest possible level. If a machine is unplugged for an extended period, the charge may be incomplete. It usually takes a number of hours to fully recharge a battery after it has completely discharged. The duration of battery backup will depend on the power usage. A noninterruptible power source may be added to the anesthesia machine for a longer backup (Fig. 5.4).

Most electronic anesthesia machines have a way for the user to determine the charge on the battery and if the battery is in use (Fig. 5.5, also see Fig. 5.43).

Electrical Outlets

Most modern anesthesia machines have electrical outlets (Fig. 5.6). These are intended to power monitors and

other devices. They usually cannot supply electricity in the case of a power failure.

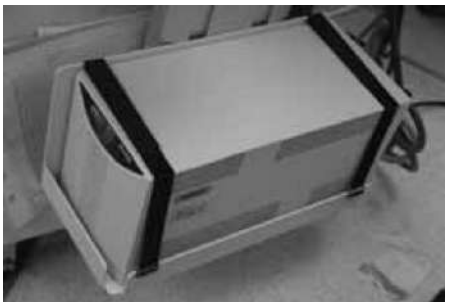


Figure 5.4 An extra source of power may be attached to the anesthesia machine to extend the life of the electrical power in the machine.

As a general rule, these outlets should only be used for anesthesia monitors. Other appliances should be connected directly to mains power.

If the power requirements exceed that for which the outlet was designed, a circuit breaker will be activated. High-frequency surgical devices or operating room beds should not be connected to these outlets, because this may cause the leakage current to rise above the permitted value or the rated power to be exceeded.

Circuit Breakers

There are circuit breakers for both the anesthesia machine and the outlets (Fig. 5.6). Anesthesia providers should consult the instruction manual to become familiar with their locations. When a circuit breaker is activated, the electrical load should be reduced and the circuit breaker reset.

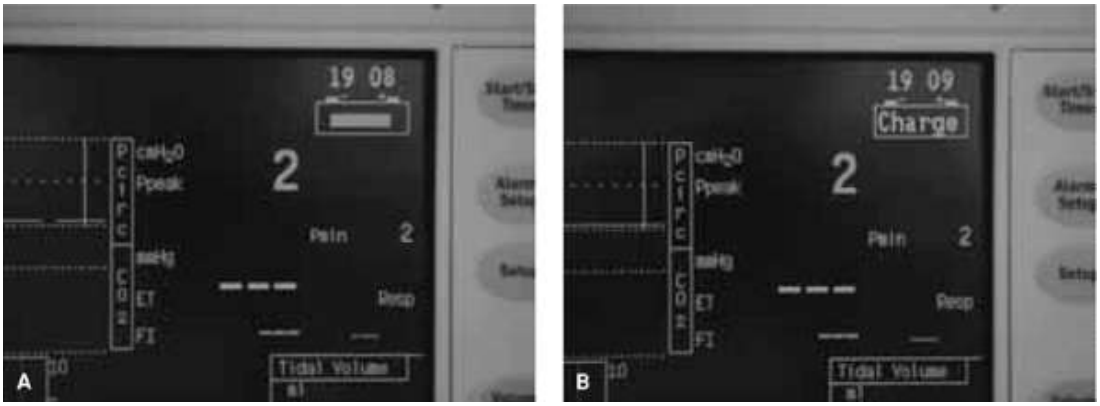


Figure 5.5 A: In the right upper corner of the screen, the amount of energy in the battery is displayed. **B:** If the battery does not carry a full charge, it can be charged by using mains power.

Data Communication Ports

Most modern anesthesia machines have data communications ports (Fig. 5.7). These are used to communicate between the anesthesia machine, monitors, and the data management system.

Pneumatic System

As shown in Figure 5.8, the pneumatic part of the machine can be conveniently divided into three parts: High-, intermediate-, and low-pressure systems.

The High-pressure System

The high-pressure system receives gases from cylinders at high, variable pressures and reduces those pressures to lower, more constant pressure suitable for use in the machine.

Hanger Yoke

The hanger yoke orients and supports the cylinder, provides a gas-tight seal, and ensures a unidirectional gas flow. The workstation standard requires that there be at least one yoke for oxygen and nitrous oxide. If the machine is likely to be used in locations that do not have piped gases, it is advisable to have a double yoke, especially for oxygen.

The hanger yoke is composed of several parts: The body, which is the principal framework and supporting structure; the retaining screw, which tightens the cylinder in the yoke; the nipple, through which gas enters the machine; the index pins, which prevent attaching an incorrect cylinder; the washer, which helps to form a seal

between the cylinder and the yoke; a filter to remove particulate matter; and the check valve assembly, which ensures a unidirectional flow of gas through the yoke.

Figure 5.6 Convenience electrical outlets on the back of the anesthesia machine. These should be used only for anesthesia monitors and not for general operating room use. Note the cautions regarding the total electrical load. Next to each outlet is a circuit breaker.

Body

The body of the yoke is threaded into the frame of the machine. It provides support for the cylinder(s). On the swinging gate (toggle handle, swivel gate)‐“type yoke (Fig. 5.9), the distal part is hinged. When a cylinder is being mounted onto or removed from a yoke, the hinged part can be swung to the side.

Retaining Screw

The retaining screw (clamping device, retaining bar) is threaded

into the distal end of the yoke (Fig. 5.9). Tightening the screw presses the cylinder valve outlet against the washer and nipple so that a gas-tight seal is achieved. The conical point of the retaining screw is shaped to fit the conical depression on the cylinder valve (Chapter 1).

Nipple

The nipple is the part of the yoke through which the gas enters the machine. It projects from the yoke and fits into the port on the cylinder valve. If the nipple is damaged, it may be impossible to obtain a tight seal with the cylinder valve.

Index Pins

The Pin Index Safety System (Chapter 1) pins are below the nipple (Fig. 5.9). The holes into which the pins are fitted must be of a specific depth. If they extend too far into the body of the yoke, it may be possible to insert an incorrect cylinder into the yoke (17).

Washer

A washer (gasket) is placed around the nipple (Fig. 5.9) to produce a seal between the cylinder valve and the yoke. A washer is usually supplied with each full cylinder.

When a cylinder is fitted to a yoke, care should be taken to ensure that the washer is present and in good condition. A broken or curled washer should not be used.

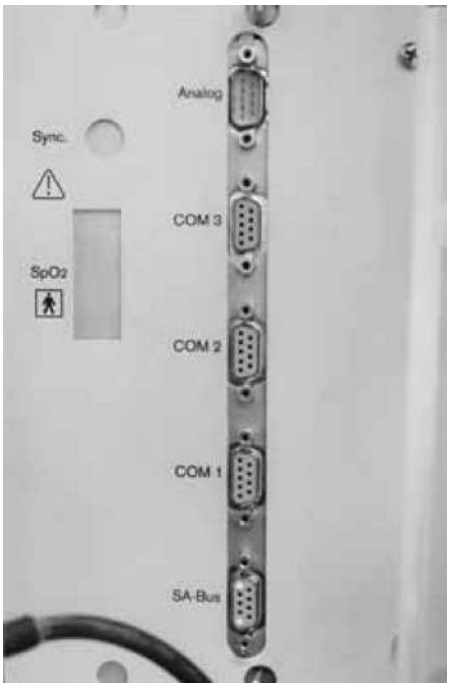


Figure 5.7 Data communication ports.

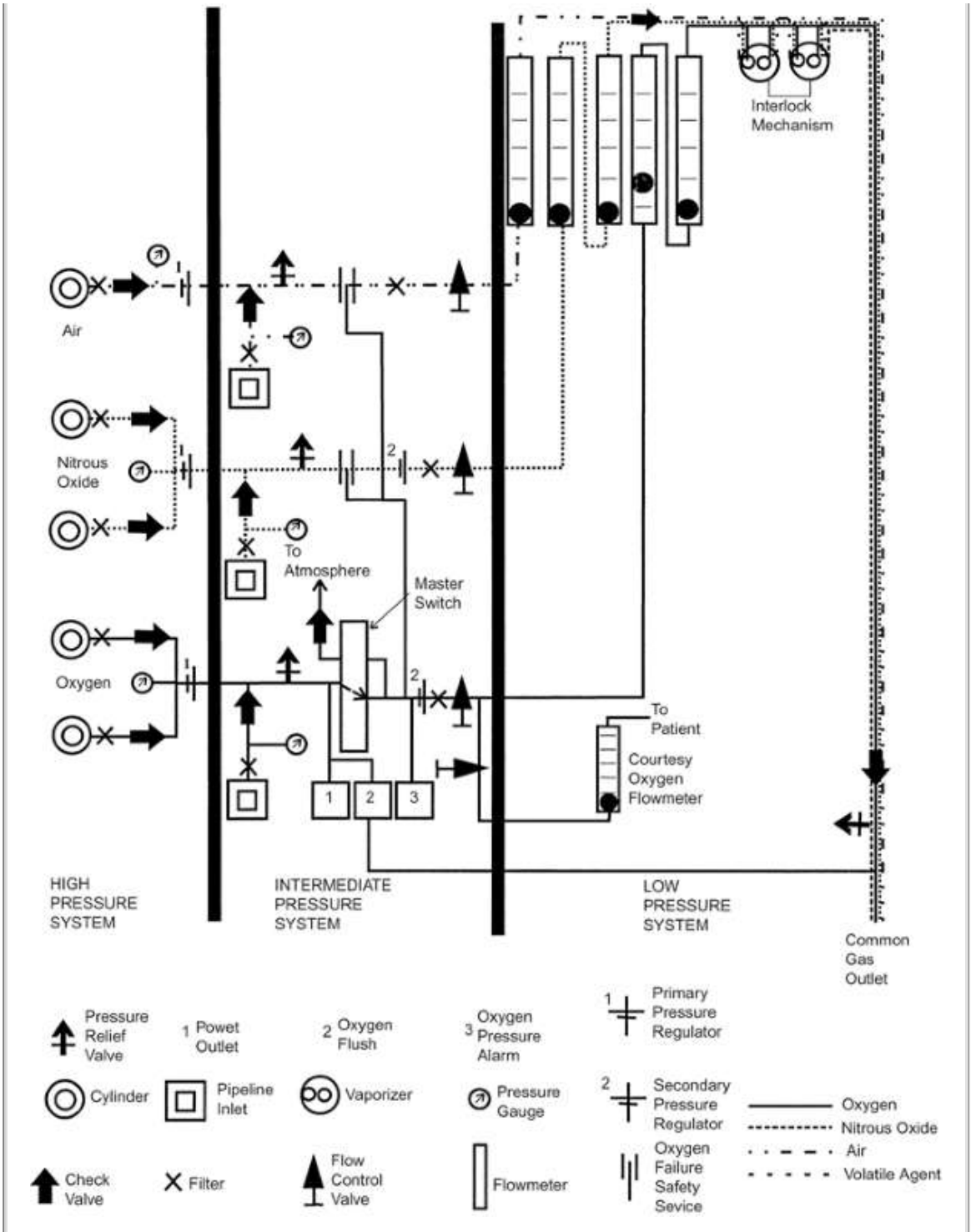


Figure 5.8 Diagram of a generic three-gas anesthesia machine. The components and their arrangement may differ somewhat with machines from different manufacturers.

An extra washer should be kept in case one becomes damaged. No more than one washer should be used, because multiple washers may prevent a tight seal from being established or may override the Pin Index Safety System (17).

Filter

The anesthesia workstation standard requires that a filter be installed between the cylinder and pressure regulator or flow control valve to prevent particulate matter from entering the machine (7).

Check Valve Assembly

The check valve assembly allows gas from a cylinder to enter the machine but prevents gas from exiting the machine when there is no cylinder in the yoke. This allows an empty cylinder to be replaced with a full one without losing gas. It also

prevents gas from being transferred from a cylinder with a higher pressure to another one with lower pressure when both are connected to a double yoke and turned ON at the same time.

Figure 5.9 Swinging gateโ€“type yoke. Note the washer around the nipple and the index pins below.

A typical check valve assembly is shown in Figure 5.10. It

consists of a plunger that slides away from the side where the pressure is greater. When cylinder pressure exceeds the pressure on the machine side, the plunger is pushed to the right, and gas passes around it and into the machine. When machine pressure exceeds cylinder pressure, the plunger moves to the left, blocking the gas flow.

These check valves are not designed to act as permanent seals for empty yokes and may allow a small amount of gas to escape. To minimize such losses, a yoke should not be left vacant. As soon as a cylinder is exhausted, it should be replaced by a full one. If a full cylinder is not available, a yoke plug (dummy cylinder block or plug, blanking cap or plug) (Fig. 5.11) should be placed in the empty yoke. A yoke plug is a solid piece of metal or other material that has a conical depression on one side to fit the tip of the retaining screw and a hollowed area on the other side to fit over the nipple. When in place, the plug forms a seal to prevent the gas from escaping from the machine. In the absence of a yoke plug, gas can flow retrograde through an open flow control valve and out through the yoke (18). Manufacturers often chain yoke plugs to the machine.

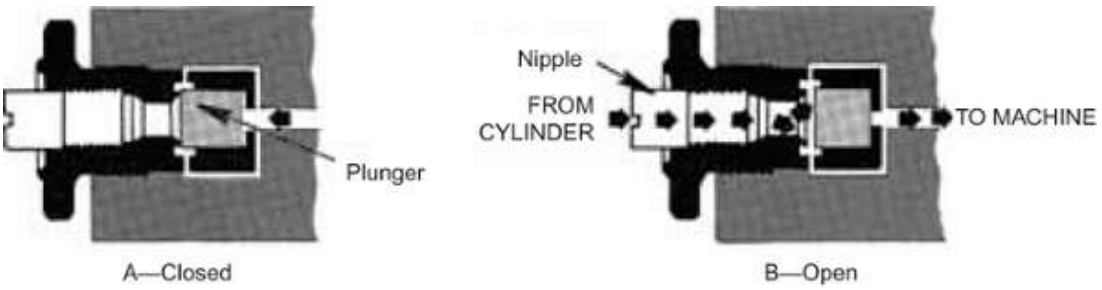


Figure 5.10 Yoke check valve assembly. This assembly allows gas to enter the machine but does not allow gas to exit the yoke. When the pressure in the machine exceeds that in the cylinder, the plunger moves to the left, preventing escape of gas from the machine. When cylinder pressure exceeds machine pressure, the plunger moves to the right, and gas flows into the machine. (From a drawing furnished by Ohmeda, a division of BOC, Inc.)

To prevent transfilling between paired cylinders as a result of a defective check valve, only one cylinder of a gas should be open at a time.

Placing a Cylinder in a Yoke

It is important that cylinder valves and yokes not be contaminated with oil or grease, because this could present a fire hazard (Chapter 32). Persons placing a cylinder in a yoke should always wash their hands first.

Before a cylinder is mounted in place, the yoke should be checked to make certain that the two Pin Index Safety System pins are present. A missing pin could allow the safety system to be bypassed (19).

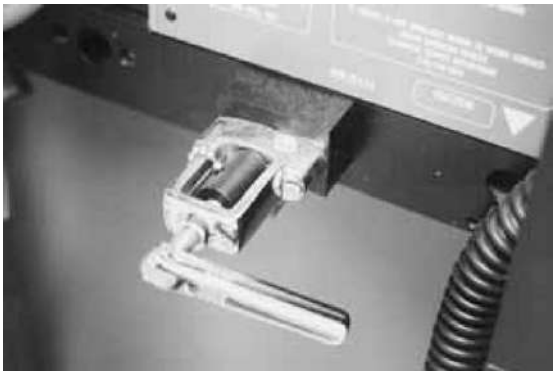


Figure 5.11 Yoke plug in place. Note the chain to the machine.

The first step in placing a cylinder in a yoke is to retract the retaining screw. With the gate-type yoke, the gate is swung open. The washer is placed over the nipple. The cylinder is then supported with the foot and raised into the yoke (Fig. 5.12). The port on the cylinder valve is guided over the nipple and the index pins engaged in the appropriate holes. The gate is then closed. The retaining screw is tightened so that it contacts the conical depression on the cylinder valve and pushes the valve over the nipple and index pins. It is important to ensure that the

cylinder is correctly placed before tightening the retaining screw. Otherwise, the retaining screw may be inserted into the safety relief device on the cylinder. After the cylinder has been tightened onto the yoke, it should be opened to make certain that the cylinder is full and that there is no leak (as evidenced by a hissing sound). The most common cause of a leak is a defective or missing washer. If the cylinder valve leaks or is difficult to operate, the cylinder should be returned to the supplier.

Figure 5.12 Placing cylinder in yoke. The cylinder is supported by the foot and guided into place manually.

After the cylinder has been attached to the yoke, **the valve should be closed** unless it is to be the primary gas supply for the machine. If it remains open, fluctuations in the gas pressure in the machine could allow some or all of the gas to exit the cylinder. In the event that pipeline pressure is lost, gas could be used from the cylinder without the user being aware of the change. The first time that the user might be aware of the lost pipeline pressure could be when the cylinder becomes empty. If only one gas cylinder is present, there would be no gas available.

Cylinder Pressure Indicator (Gauge)

The anesthesia workstation standard requires that there be a pressure indicator that displays the cylinder pressure for each gas supplied by cylinders (7). The indicator may be located near the cylinders or on a panel on the front of the machine (Figs. 5.13, 5.14). The scale must be at least 33% greater than the maximum filling pressure of the cylinder or the full indication position.

Many indicators are of the Bourdon tube (Bourdon spring, elastic element) type, illustrated in Figure 5.15. A hollow metal tube is bent into a curve, then sealed and linked to a clocklike mechanism. The other end is

connected to the gas source. An increase in gas pressure inside the tube causes it to straighten. As the pressure falls, the tube resumes its curved shape. Because the open end is fixed, the sealed end moves. These motions are transmitted to the indicator, which moves over a calibrated scale. Gauges are required to be calibrated in kilopascals (kPa) but pounds per square inch (psi) may also be used (Fig. 5.13).

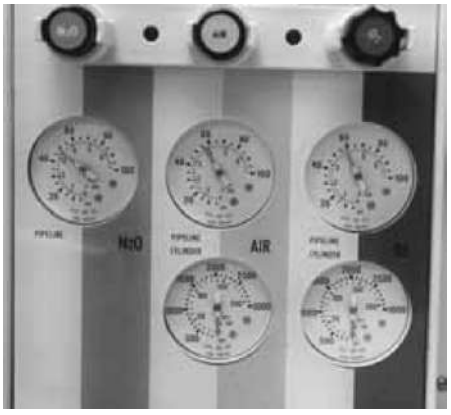


Figure 5.13 Cylinder and pipeline pressure indicators. Kilopascals ร— 100 are indicated in the inside of the dial while pounds per square inch gauge are on the outside.

Figure 5.14 Digital pressure indicators. Pipeline pressures are at the top. Cylinder pressures are below. At left below is the vacuum regulator and gauge and ON-OFF control for suction. To the right of this is the alternative oxygen source, which can be used if there is total loss of electrical power. To the right is the recessed oxygen flush control.

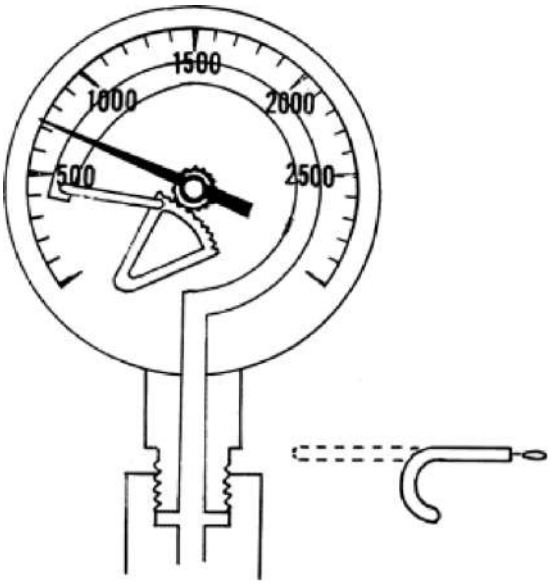


Figure 5.15 Bourdon pressure gauge. As gas pressure within the flexible tube increases, the tube tends to straighten. The motion is translated through the gearing mechanism so that the indicator shows a higher pressure. The tail end of the pointer is shorter

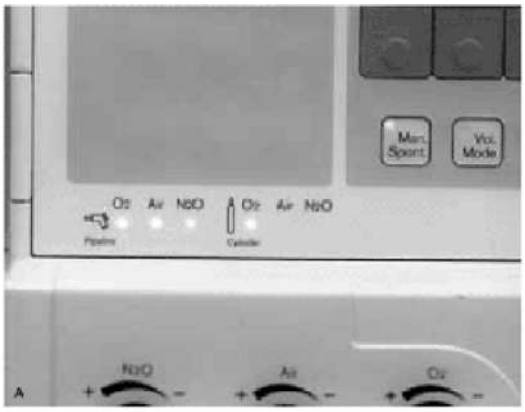
than the indicating end and blends into the background. The lowest pressure indication is between the 6 o'clock and 9 o'clock positions on a clock face.

Digital pressure readouts are used on some modern electronic anesthesia machines (Fig. 5.14).

Some electronic machines have light-emitting diodes (LEDs) to indicate cylinder pressure (Fig. 5.16A). If the cylinder valve is open and the pressure is adequate, the LED is green. If the valve is open but the pressure is inadequate, the LED will flash red. It will be dark if the cylinder valve is not open. These machines may also display the actual pressure for pipelines and cylinders on a screen during the checkout (Fig. 5.16B). It can be available on demand or on a continuous basis (see Fig. 5.43).

Pressure Regulators

The pressure in a cylinder varies. To maintain constant flow with changing supply pressure, the anesthesia machine is fitted with pressure regulators (reducing valves, reducing regulators, reduction valves, regulator valves, gas pressure reducing device/system). A pressure regulator reduces the high and variable pressure found in a cylinder to a lower, more constant pressure suitable for use in an anesthesia machine. Without a regulator, it would be necessary for the anesthesia provider to constantly alter the flow control valve to maintain a constant flow through the flowmeter as the pressure in the cylinder decreased. The anesthesia workstation standard requires a pressure regulator for each gas supplied from cylinders (7).



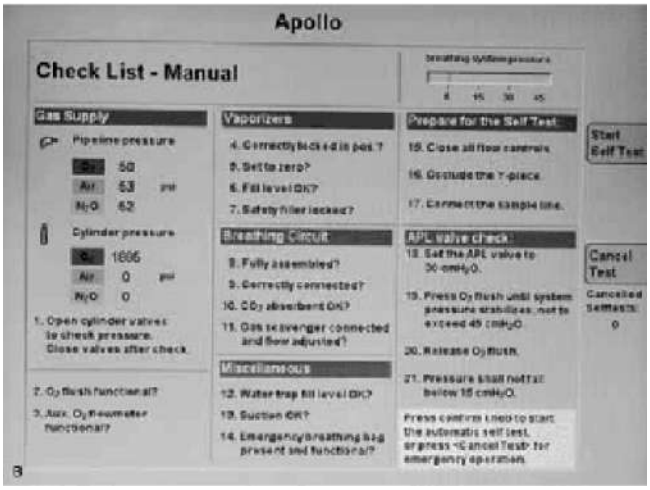


Figure 5.16 A: LEDs indicate cylinder pressure. If the cylinder valve is open and the pressure is adequate, the LED will be green. If the valve is open but the pressure is inadequate, the LED will flash red. It will be dark if the cylinder valve is not open. **B:** Some machines use LEDs to indicate cylinder pressure. These do not give adequate information when it is necessary to know how much gas is in a cylinder. The specific information can be brought up on the screen during the checkout phase.

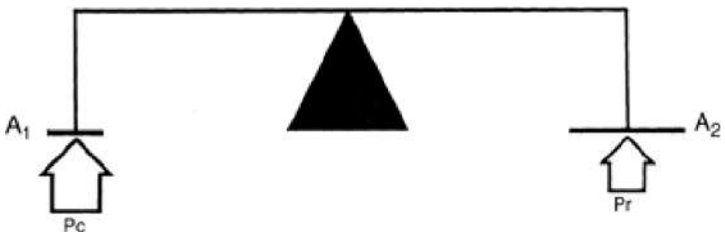


Figure 5.17 A large pressure acting over a small area is balanced by a smaller pressure acting over a large area. The relative sizes of the arrows represent the magnitudes of the pressures.

Physical Principles

Pressure is defined as force acting against an area. Force can be increased either by increasing the pressure or by increasing the area over which the pressure acts. To illustrate this, consider the simple balance shown in Figure 5.17.

A large pressure, Pc, acting on a small area, A_1, is balanced by a smaller pressure, Pr, acting on a large area, A_2. The force exerted by the higher pressure is

Pc ร— A_1

This is balanced by the force on the right:

Pr ร— A_2

Because these forces are equal, it follows that

Pr ร— A_2 = Pc ร— A_1

Solving for Pr,

Pr = A_1/A_2 ร— Pc

These same principles apply in a pressure regulator. Figure 5.18 shows a cylinder of gas under a high pressure, Pc (inlet pressure). R is the inside of a pressure regulator containing gas

at reduced pressure, Pr (outlet pressure). The opening between C and R is occluded by a seat of area A_1. A_2 is the area of a flexible diaphragm on which Pr acts. When the stopcock, S, is closed, the forces are in balance. The seat seals the opening from the cylinder so that no gas flows from C into R.

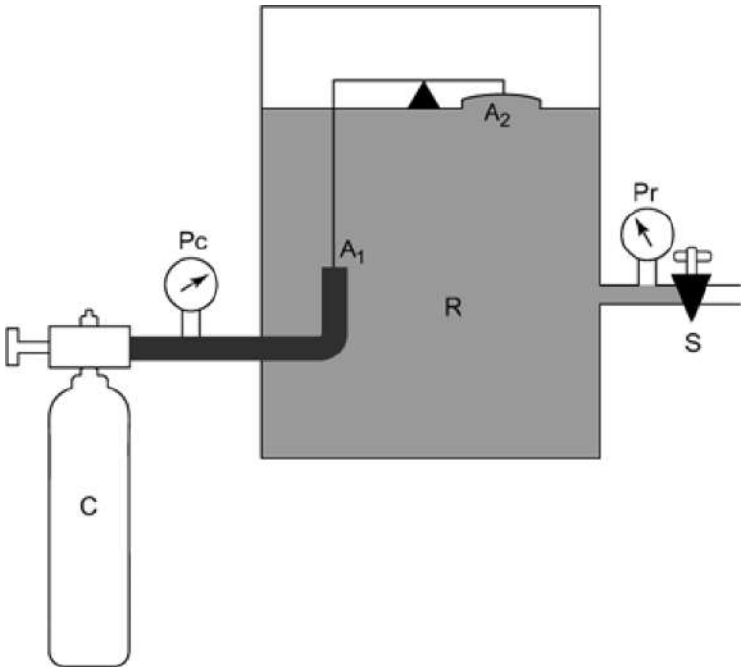


Figure 5.18 The simplified pressure regulator is in the closed state. (See text for details.)

In Figure 5.19, the stopcock is open and gas flows from R, causing the pressure, Pr, to drop. The forces are no longer balanced because Pc × A_1 > Pr × A_2. The flexible diaphragm becomes flatter, the balance tips to the right, and the seat no longer occludes the opening from the cylinder so that gas flows from the cylinder into R. As long as the stopcock is open, the forces will be in balance, and gas will continue to flow from the cylinder. This is analogous to opening the flow control valve on the anesthesia machine. When the stopcock is closed, gas will continue to flow briefly into R, until Pr increases to the point where a balance of forces is restored. The small increase in Pr after the stopcock is closed is called the *static increment*.

The pressure regulator shown in Figures 5.18 and 5.19 will yield a constant reduced pressure only if the supplied pressure, Pc, is constant. If Pc decreases, as when the cylinder pressure falls, Pr must decrease to preserve the balance of forces. With this type of pressure regulator, the flow indicator would constantly need to be adjusted to compensate for the pressure drop.

To remedy this, a main spring, S_1, is added (Fig. 5.20). This spring exerts a downward force on the flexible diaphragm. The magnitude of this force depends on an adjustable screw. Now, the forces acting to push the diaphragm upward remain at

Pr × A_2

Forces acting to push the diaphragm downward are

(Pc × A_1) + Fs_1

where Fs_1 is the force exerted by the spring. If the values for Pc, Pr, A_1, and A_2 remain unchanged, there would be an imbalance of forces, because the force of the main spring would be added to the force of Pc acting on A_1. To compensate for this imbalance, A_1 may be reduced, A_2 may be increased, or both. At equilibrium,

(Pc × A_1) + Fs_1 = Pr × A_2

Solving this equation for Pr,

$$\mathrm{Pr} \times (\mathrm{Fs}_1/\mathrm{A}_2) + \mathrm{Pc}(\mathrm{A}_1/\mathrm{A}_2) \qquad (1)$$

The force exerted by Pr acting on the diaphragm, therefore, is opposed by two forces: A constant force from the spring (Fs_1/A_2) and a variable force from Pc acting on the seat, Pc(A_1/A_2). If the force exerted by the

spring is large in comparison with the force exerted by Pc, large variations in Pc will cause only slight variations in Pr.

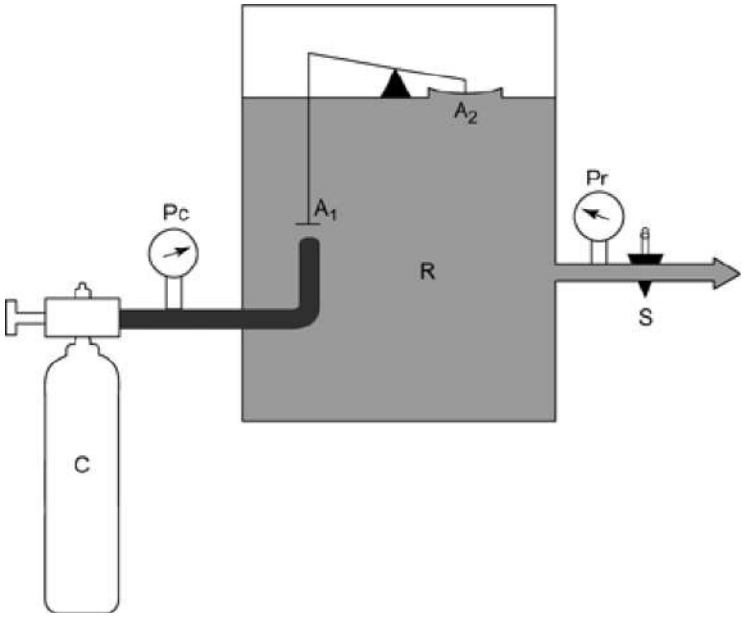


Figure 5.19 The pressure regulator with its stopcock *(S)* open. An imbalance of forces is created, allowing gas to pass from the cylinder into the pressure regulator. (See text for details.)

The value of Pr will depend on Fs_1. The tension in the spring can be varied by means of the adjustable screw, and in this way, Pr can be varied. For this reason, the main spring is sometimes called the *adjusting spring*. One more addition to the regulator is necessary. In Figure 5.21, a sealing (shutoff) spring, S_2, is added. This acts to force the seat against the opening from the cylinder. This prevents gas from flowing from C to R when the adjusting spring is completely relaxed and the stopcock open. Equation 1 then becomes

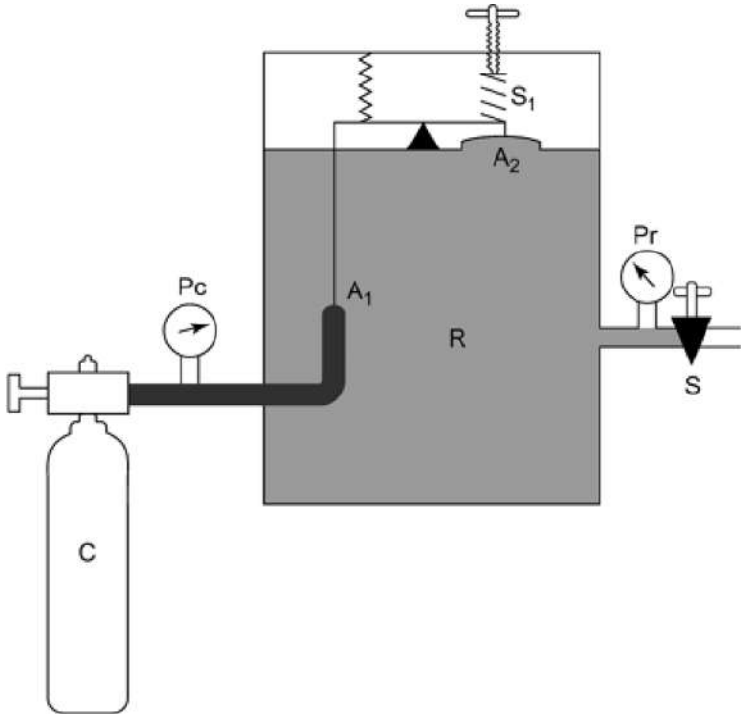


Figure 5.20 A mainspring *(S_1)* and adjusting screw have been added to the pressure regulator. (See text for details.)

$$Pr = (Fs_1 - Fs_2)/A_2 + Pc(A_1/A_2) \qquad (2)$$

The value of Fs_2 is considerably smaller than Fs_1 so that (Fs_1 – Fs_2) is large compared with Pc, and Pr will remain relatively constant despite variations in Pc.

There will, however, be some variations in Pr with variations in Pc. A change, Δ”Pc, in cylinder pressure will

produce a change, Δ”Pr, in the reduced pressure. From Equation 2,

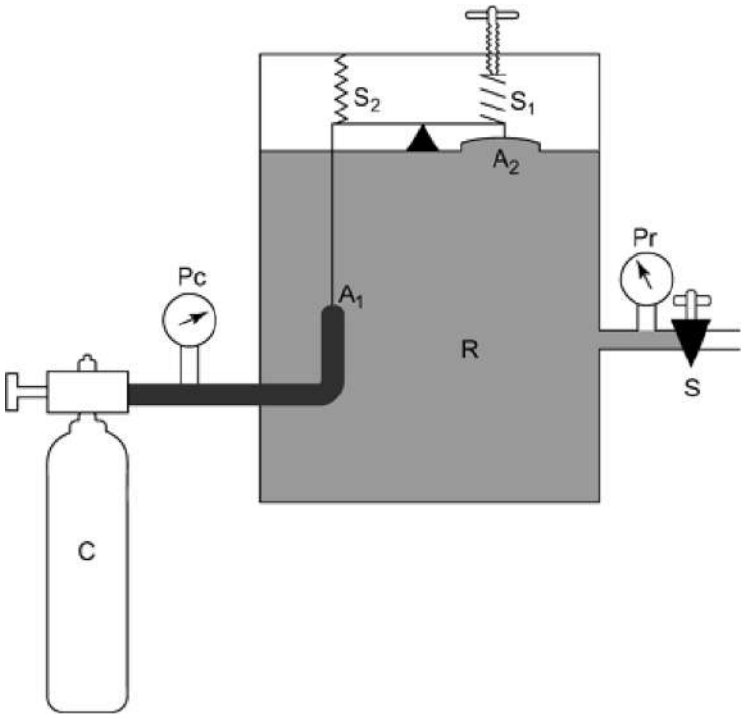


Figure 5.21 A sealing spring has been added to complete the pressure regulator. (See text for details.)

ฮ”Pr = ฮ”Pc (A_1/A_2)

As Pc decreases, Pr also decreases (pressure-proportioned reduction). The magnitude of the change in Pr is governed by the ratio A_1:A_2.

The pressure regulator illustrated in Figures 5.18 to 5.21 is an example of a direct-acting pressure regulator. This is because the components are arranged so that the cylinder pressure tends to open the valve.

An indirect-acting pressure regulator is shown in Figure 5.22. In this case, Pc acts to close the valve. Equation 2 then becomes

$Pr = (Fs_1-Fs_2)/A_2 - Pc(A_1/A_2)$

The variation in Pr with variation in Pc is given by the equation

ฮ”Pr = ฮ”Pc (A_1/A_2).

As Pc decreases, Pr increases (pressure inversion).

The Modern Pressure Regulator

Modern pressure regulators are depicted in Figures 5.23 and 5.24. A direct-acting pressure regulator is shown in Figure 5.23. Its function is determined by a balance of forces acting to position the seat, A_2. With the valve closed, the force of the sealing spring, S_2, pushing the seat up against the nozzle, is greater than the downward force exerted by the main spring, S_1, and the inlet pressure, Pc, against the seat. No gas flows from the inlet into the pressure regulator. Pr is 0.

When the valve is opened by tightening the adjusting screw, the downward force of the main spring, S_1, is increased. This force is transmitted along the valve thrust pin to the seat and, in combination with the inlet pressure, overcomes the force of the sealing spring. Gas at reduced pressure flows into the space under the diaphragm and exerts an upward force on the diaphragm. Gas then flows to the outlet. The forces are not in balance, but Pr will remain constant because a steady state is soon achieved. Gas will continue to flow until either the cylinder is empty or the gas flow is turned OFF at a point downstream of the pressure regulator. If it is turned OFF, gas will continue briefly to flow into the space under the diaphragm. Here, its pressure will increase (static increment) until the force of the reduced gas on the diaphragm (Pr ร— A_2) plus the force of the sealing spring, S_2, balance the force of the cylinder pressure and the main spring (Pc ร— A_2 + F_2), as in Equation 2.

Figure 5.24 illustrates an indirect-acting pressure regulator. With the valve closed, gas enters the space surrounding the sealing spring, S_2, and the valve seat, A_1. Its own pressure, Pc, tends to hold the valve seat against the nozzle. When the adjusting screw is turned so that the main spring exerts a downward force on the diaphragm, Fs_1, the valve thrust pin moves downward, opening the seat, so that gas at reduced pressure, Pr, expands through the holes for the thrust pin and into the cavity under the diaphragm. When the gas flow is turned OFF distal to the pressure regulator, gas continues to flow briefly into the space under the diaphragm. Here, its pressure increases (static increment), pushing

the diaphragm upward until the seat closes against the nozzle, stopping further flow.

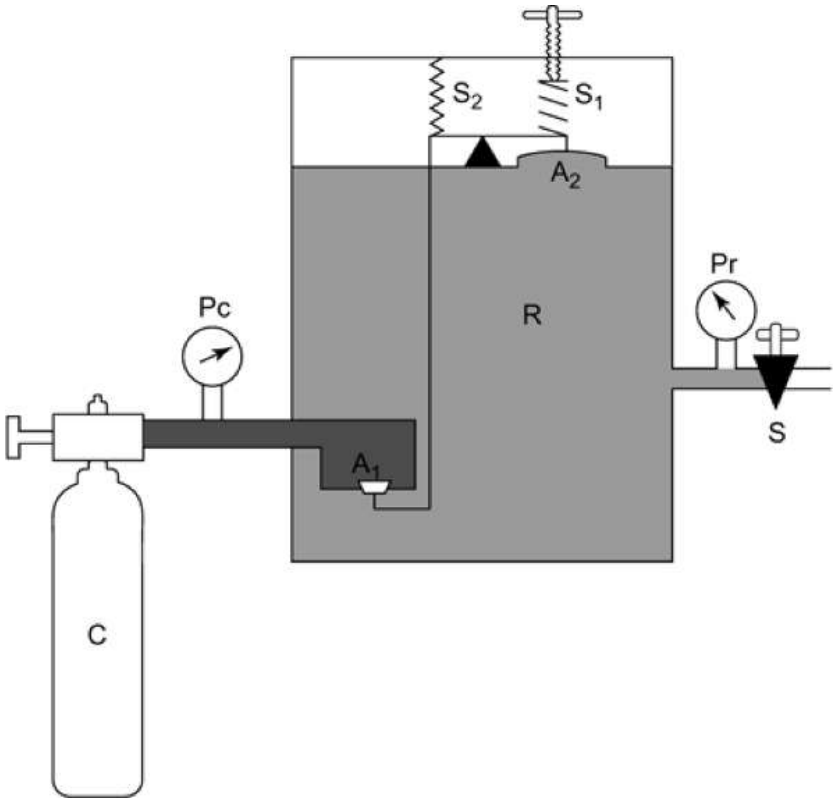


Figure 5.22 Indirect-acting pressure regulator. The components are arranged so that cylinder pressure tends to close the valve. (See text for details.)

A pressure regulator may be adjustable or preset. An adjustable pressure regulator has a means for the user to adjust the delivery pressure. This type of valve is usually found on transport gas cylinders. A preset pressure regulator requires a tool to adjust the delivery pressure.

Pressure regulators used in anesthesia machines are preset at the factory. One regulator may serve a single- or a dual-hanger yoke. The anesthesia workstation standard requires that the flow from the cylinder not exceed 10 mL/minute when pressure in the gas pipeline system is 345 kPa (50 psig) (7). This can be

accomplished by keeping the pressure delivered by the regulator at a lower level than pipeline pressure.

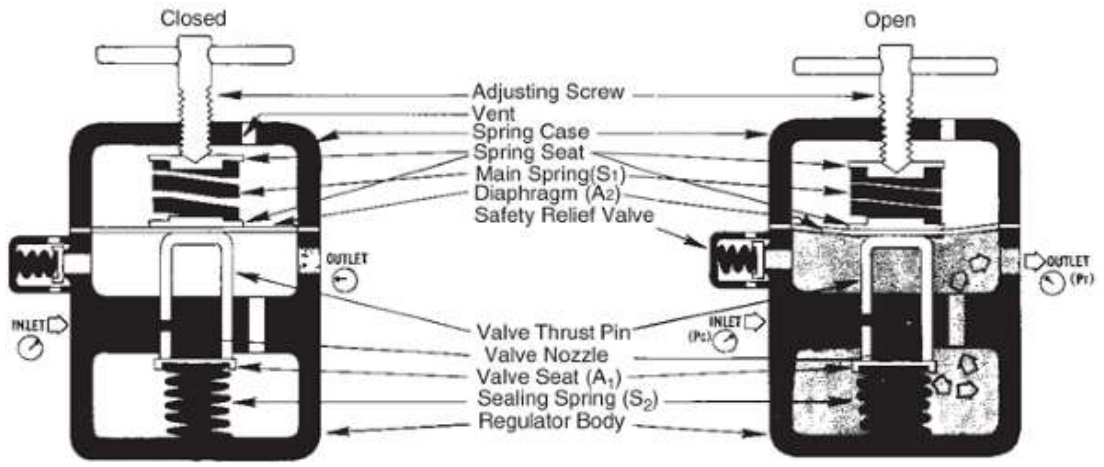


Figure 5.23 Direct-acting pressure regulator. The *darker shades* are used for gas under high pressure, whereas the *lighter shades* represent gas under reduced pressure. The *arrows* indicate the path of gas flow. The valve is opened by turning the adjusting screw. (See text for details.) (Redrawn from a drawing furnished by Ohmeda, a division of BOC, Inc.)

A defective pressure regulator may block the gas flow from a cylinder or cause widely fluctuating flows (20,21).

Intermediate Pressure System

The intermediate pressure system (Fig. 5.8) receives gases from the pressure regulator or the pipeline

inlet to the anesthesia machine. Oxygen may enter the pneumatic components by way of the master switch. When the master switch is turned OFF, the pressure in the intermediate pressure system will drop to zero. The intermediate pressure system pneumatic components include the pneumatic part of the master switch, pipeline inlet connections, pipeline pressure indicators, piping, the gas power outlet, oxygen pressure failure devices, the oxygen flush, additional pressure regulators (if so equipped), and the flow control valves.

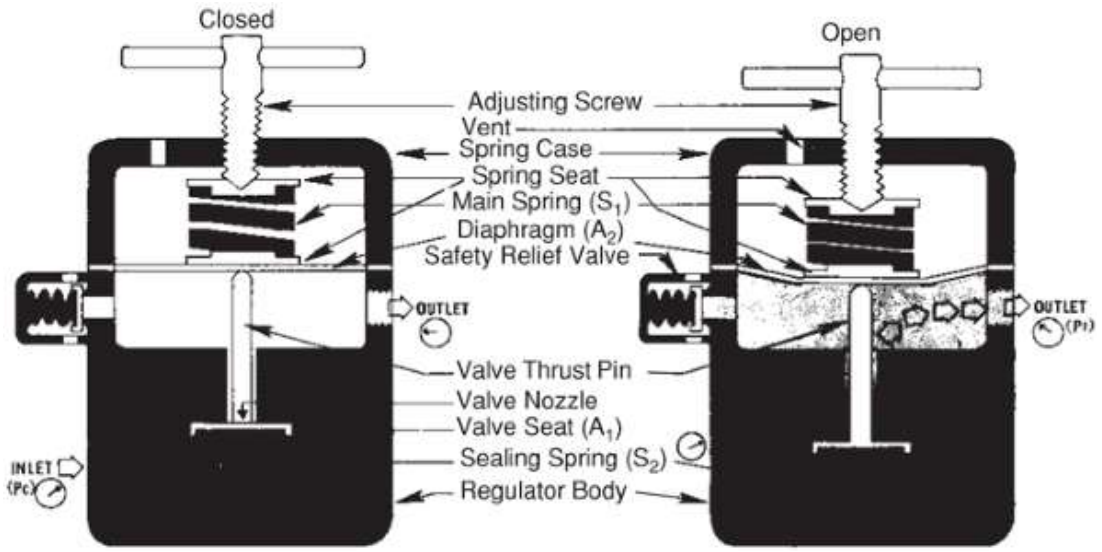


Figure 5.24 Indirect-acting pressure regulator. The cylinder pressure opposes the opening of the valve. When the adjusting screw is opened, gas flows from the lower to the upper chamber along the valve thrust pin. (Redrawn from a drawing furnished by Ohmeda, a division of BOC, Inc.)

Master Switch (Pneumatic Component)

The pneumatic portion of the master switch is located in the intermediate pressure system downstream of the inlets for the cylinder and pipeline supplies. The oxygen flush is usually independent of this switch. The master switch may be a totally electronic switch that when activated controls the various pneumatic components in the anesthesia machine.

Figure 5.25 Pipeline inlets. Note the DISS connections.

Pipeline Inlet Connections

The pipeline inlet connection is the entry point for gases from the pipelines. The anesthesia workstation standard requires pipeline inlet connections for oxygen and nitrous oxide (7). Most machines also have an inlet connector for air. These inlets are fitted with threaded noninterchangeable Diameter Index Safety System (DISS) fittings (Chapter 2) (Fig. 5.25).

Each inlet must contain a unidirectional (check) valve to prevent reversed gas flow from the machine into the piping system (or to atmosphere if no hose is connected). Problems have been reported with this check valve. In one case, the check valve stuck in the closed position, obstructing oxygen flow (22). There are case

reports where the valve failed to prevent reverse flow (23,24).

Each pipeline inlet is required to have a filter with a pore size of 100 ยตm or less. The filter may become clogged, resulting in a reduction in gas flow (25).

Pipeline Pressure Indicators

Indicators to monitor the pipeline pressure of each gas (Figs. 5.13, 5.14) are required by the anesthesia workstation standard (7). They are usually found on a panel on the front of the machine and may be color coded for the gases that they monitor. On some machines, the correct range of pressures is indicated by a colored zone.

Some machines have digital pressure indicators (Fig. 5.14). The pipeline pressure is displayed either continuously or on demand.

On some newer electronic machines, LEDs indicate pipeline pressure (Fig. 5.16A). A green LED indicates that the pipeline is connected and the pressure is adequate. If the LED is OFF, the pressure is inadequate or the pipeline is not connected. If the transducer is inoperable, the LED is dark. A digital pressure can

be displayed on the screen to augment the information from the LEDs (see Fig. 5.43).

The workstation standard requires that the indicator be on the pipeline side of the check valve in the pipeline inlet (Fig. 5.8). If the indicator is on the pipeline side of the check valve, it will monitor pipeline pressure only. If the hose is disconnected or improperly connected, it will read ĺ€0ĺ€ even if a cylinder valve is open (26,27). If the indicator were on the machine (downstream) side of the check valve, it would not give a true indication of the pipeline supply pressure unless the cylinder valves were closed. If a cylinder valve is open and the pipeline supply fails, there will be no change in the pressure on the indicator until the cylinder is nearly empty (28).

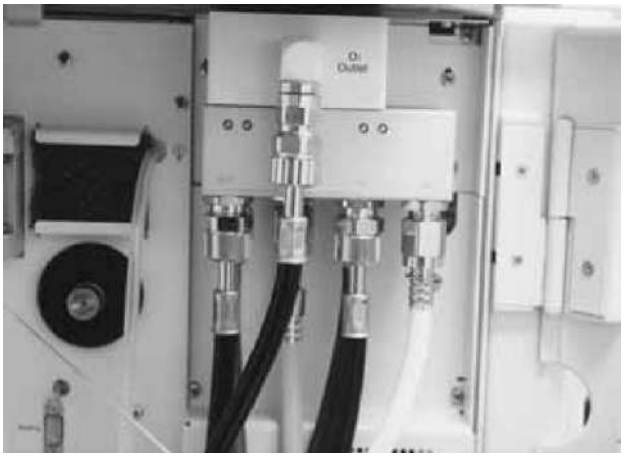


Figure 5.26 Gas power (auxiliary gas) outlet on an anesthesia machine.

The indication of an adequate pressure on the pipeline indicator does not guarantee that gas is not being drawn from a cylinder. If for any reason the gas pressure coming from a cylinder via a pressure regulator exceeds the pipeline pressure and a cylinder valve is open, gas will be drawn from the cylinder. Therefore, cylinder valves should always remain closed when the pipeline supply is in use.

Pipeline pressure indicators should always be checked before the machine is used. The pressure should be between 50 and 55

psig (345 and 380 kPa). The indicators should be scanned repeatedly during use.

Piping

Piping is used to connect components inside the machine. It must be able to withstand four times the intended service pressure without rupturing (7).

The anesthesia workstation standard specifies that leaks between the pipeline inlet or cylinder pressure reducing system and the flow control valve not exceed 25 mL/minute (7). If the yoke and pressure reducing system are included, the leakage may not exceed 150 mL/minute.

Piping cross connections inside the machine have been reported (29). Disconnections in the piping may occur but are rare (30).

Gas Power Outlet

One or more gas power (auxiliary gas) outlets may be present on an anesthesia machine (Fig. 5.26). It may serve as the source of driving gas for the

anesthesia ventilator or to supply gas for a jet ventilator. Either oxygen or air may be used, and if there is a choice, there should be a gas power outlet for each gas.

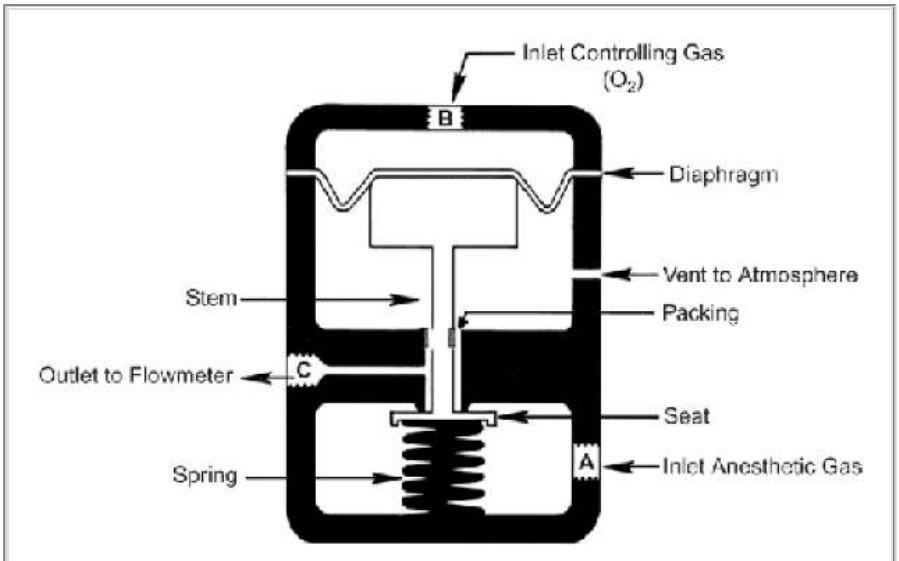


Figure 5.27 Oxygen failure safety valve. When oxygen

pressure in the machine is normal, it will push the diaphragm and stem downward, opening the valve. The anesthetic gas then flows in at *A*, around the stem, and out at *C*. When the oxygen pressure falls, the stem moves upward, closing the valve. The middle chamber is vented to atmosphere to prevent mixing of anesthetic gas and oxygen in the event that the diaphragm ruptures or the packing leaks. (Redrawn from a drawing furnished by Ohmeda, a division of BOC, Inc.)

In the past, the power outlet was usually present when the ventilator was an add-on part of the anesthesia machine, and one of several different ventilators could be used. However, with modern anesthesia machines, the ventilator is an integral part of the machine and breathing system and is connected to the ventilator with internal piping. Therefore, the power outlet is not found on many anesthesia machines today.

Oxygen Pressure Failure Devices

One of the most serious mishaps that occurred with early machines was depletion of the oxygen supply (usually from a cylinder) without the user's awareness. The result was delivery of 100% anesthetic gas. Numerous inventions have been devised to prevent this problem. Among these are devices that shut off the supply of gases other than oxygen (oxygen failure safety device) or alarm when oxygen pressure has fallen to a dangerous level.

Oxygen Failure Safety Device

The anesthesia workstation standard requires that whenever the oxygen supply pressure is reduced below the manufacturer-specified minimum, the delivered oxygen concentration shall not decrease below 19% at the common gas outlet (7,31).

The oxygen failure safety valve (oxygen failure safety device, low-pressure guardian system, oxygen failure protection device, pressure sensor shutoff system or valve, fail safe, pressure sensor system, nitrous oxide shutoff valve) shuts off or proportionally decreases and ultimately interrupts the supply of nitrous oxide if the oxygen supply pressure decreases. On many modern machines, the air supply is also cut off but may not be (1,32).

When the pneumatic system is activated, oxygen pressure reaches the oxygen failure safety device, allowing other gases to flow. Turning OFF the pneumatic system causes oxygen in the machine to be vented to atmosphere. The resulting decrease in oxygen pressure causes the oxygen failure safety device to interrupt the supply of other gases to their flow control valves.

One such device is shown diagrammatically in Figure 5.27. When oxygen pressure is normal, the plunger and seal assembly are depressed so that anesthetic gas can flow through the valve. When the oxygen pressure decreases, the spring forces the plunger and seal assembly upward, narrowing the valve opening in proportion to oxygen supply pressure loss. If the oxygen supply pressure fails completely, the valve closes. To determine if a machine has a properly functioning oxygen failure safety device, the flows of oxygen and the other gas (usually nitrous oxide) are turned ON. The source of oxygen pressure is then removed. The fall in oxygen pressure is noted on the cylinder or pipeline pressure gauge. If the oxygen failure safety device is functioning properly, the flow indicator for the other gas will fall to the bottom of the tube just before the oxygen indicator falls to the bottom of its tube.

Oxygen Supply Failure Alarm

The anesthesia workstation standard specifies that whenever the oxygen supply pressure falls below a manufacturer-specified threshold (usually 30 psig (205 kPa)), at least a medium priority alarm shall be enunciated within 5 seconds (7,33,34,35). It shall not be possible to disable this alarm.

Because both the oxygen failure safety device and alarm depend on pressure and not flow, they have limitations that are not always fully appreciated by the user. They aid in preventing hypoxia caused by problems occurring upstream in the machine circuitry (disconnected oxygen hose, low oxygen pressure in the pipeline, and depletion of oxygen cylinders). These devices do not offer total protection against a hypoxic mixture being delivered, because they do not prevent anesthetic gas from flowing if there is no flow of oxygen. Equipment problems (such as leaks) or operator errors (such as a closed or partially closed oxygen flow control valve) that occur

downstream are not prevented by these devices. They do not guard against accidents from crossovers in the pipeline system or a cylinder containing the wrong gas.

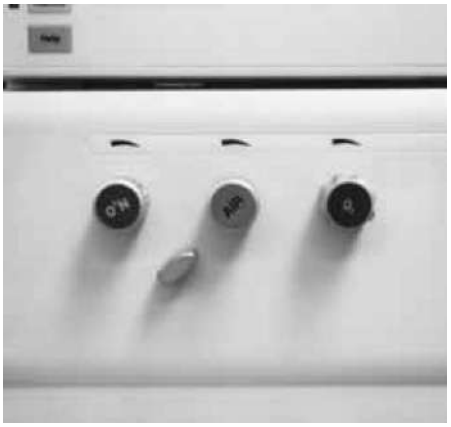


Figure 5.28 Gas selector switch. In the N_2O position, only oxygen and nitrous oxide can be used. In the air position, only oxygen and air can be administered.

Gas Selector Switch

Some machines have a gas selector switch that prevents air and nitrous oxide from being used together. Two types of switches are shown in Figures 5.28 and 5.29.

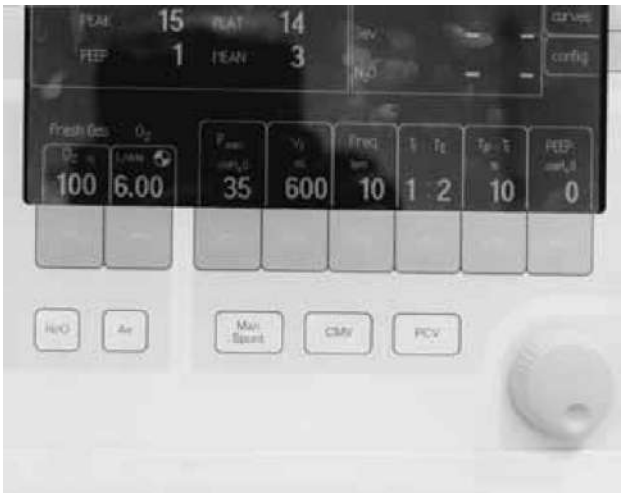


Figure 5.29 Electronic gas selector switch. Either nitrous oxide or air can be selected by pushing the appropriate button **(lower left)**. Total gas flow and oxygen percentage are set by pushing the hard keys and rotating the wheel at the lower right. The balance of the fresh gas flow will be the other gas chosen (nitrous oxide or air).

Second-stage Pressure Regulator

Some machines have pressure regulators in the intermediate pressure system just upstream of the flow indicators. These receive gas from either the pipeline or the pressure regulator and reduce it further to around 26 psi (177 kPa) for nitrous oxide and 14 psi (95 kPa) for oxygen. The purpose of this pressure regulator is to eliminate fluctuations in pressure supplied to the flow indicators caused by fluctuations in pipeline pressure. By reducing the pressures below the normal fluctuation range, the flow will remain more constant. Not all anesthesia machines are equipped with this device.

Oxygen Flush

The oxygen flush (oxygen bypass, emergency oxygen bypass) receives oxygen from the pipeline inlet or cylinder pressure regulator and directs a high unmetered flow directly to the common gas outlet. It is commonly labeled ĺ€O_2+.ĺ€ On most anesthesia machines, the oxygen flush can be activated regardless of whether the master switch is turned ON or OFF.

The anesthesia workstation requires that the oxygen flush be a single-purpose, self-closing device operable with one hand and designed to minimize unintentional activation (7). A flow between 35 and 75 L/minute must be delivered.

An oxygen flush is shown in Figure 5.30. It consists of a button and stem connected to a ball. The ball is in contact with the seat. When the button is depressed, the ball is forced away from the seat, allowing the oxygen to flow to the outlet. A spring opposing the ball will close the valve when the button is not depressed. The button

is commonly recessed or placed in a collar to prevent accidental activation (Figs. 5.14, Fig. 5.31).

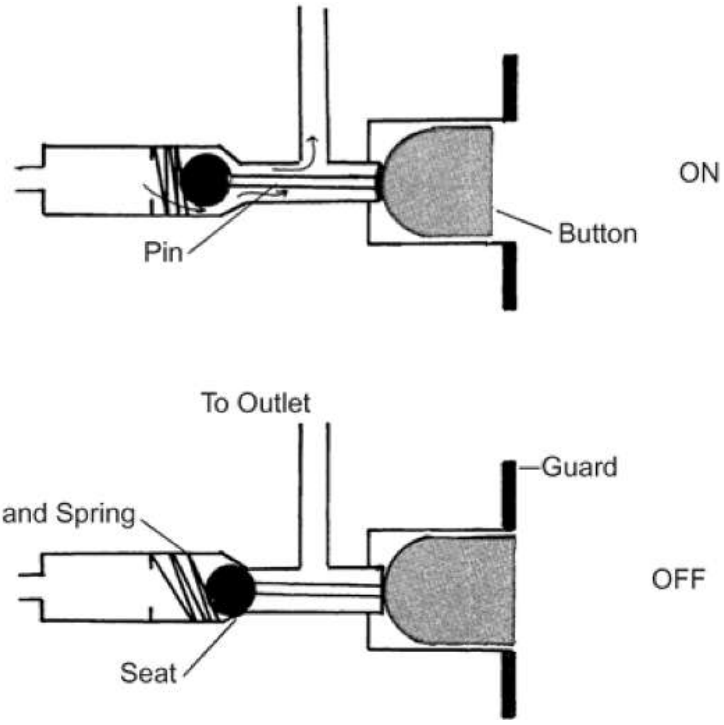


Figure 5.30 Oxygen flush valve. Depressing the button causes the pin to push the ball away from the seat, allowing oxygen to pass directly to the machine outlet. (Redrawn from a diagram furnished by Ohmeda, a division of BOC, Inc.)

Oxygen flush activation may or may not result in other gas flows being shut off and may result in either a positive or negative pressure in the machine circuitry, depending on the design of the inlet and the flush line into the common gas line. This pressure will be transmitted back to other structures in the machine, such as flow indicators and vaporizers, and may change the vaporizer output and the flow indicator readings. The effect caused by oxygen flush activation will depend on the pressure generated, the presence or absence of check valves in the machine, and the relationship of the oxygen flush valve to other components. The anesthesia workstation standard requires that the connection of the flush valve delivery line to the common gas outlet be

designed so that activation does not increase or decrease the pressure at the vaporizer outlet by more than 10 kPa or increase the vapor output by more than 20% (7).

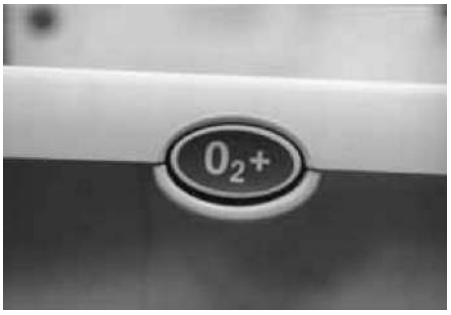


Figure 5.31 Oxygen flush valve. Note the protective ring to prevent accident activation. O_2+ is a symbol for the oxygen flush valve.

Reported hazards associated with the oxygen flush include accidental activation (36,37,38) and internal leakage, which resulted in an oxygen-enriched mixture being delivered (39,40). The flush valve may stick in the ON position (41,42,43). There is a report of a flush valve sticking and obstructing the flow of the gases from the flowmeters (44). Barotrauma and awareness during anesthesia have resulted from its activation (38,45). Oxygen flush activation during inspiration delivered by the anesthesia ventilator will result in delivery of high tidal volumes and possible barotrauma. Ventilators that exclude fresh gas flow from the breathing system during inspiration will not present this problem. These features are discussed in Chapters 9 and 12.

Using the oxygen flush to ventilate through a catheter inserted percutaneously has been investigated (46). Some machines provide sufficient pressure for effective jet ventilation, but others do not. Most anesthesia machine manufacturers do not recommend using the oxygen flush for this purpose.

Flow Adjustment Control

The flow adjustment controls regulate the flow of oxygen, air, and other gases to the flow indicators. There are two types of flow adjustment controls: mechanical and electronic. The anesthesia workstation standard requires that there be only one flow control for each gas (7). It must be adjacent to or identifiable with its associated flowmeter.

Mechanical Flow Control Valve

The mechanical flow control valve (needle valve, pin valve, fine adjustment valve) controls the rate of gas flow through its associated flowmeter (47). Some also have an ON-OFF function. On some machines, the ON-OFF function is controlled by the master switch. Mechanical flow control valves are used with both mechanical and electronic flowmeters.

Components

Body

The flow control valve body screws into the anesthesia machine.

Stem and Seat

The stem and seat are shown in Figure 5.32. The stem and seat have fine threads so that the stem moves only a short distance when a complete turn is made. When the valve is closed, the pin at the end of the stem fits into the seat, occluding the orifice so that no gas can pass through the valve. When the stem is turned outward, an opening between the pin and the

seat is created, allowing gas to flow through the valve. The greater the space between the pin and the seat, the greater the volume of gas that can flow. To eliminate any looseness in the threads, the valve may be spring loaded (48). This also minimizes flow fluctuations from lateral or axial pressure applied to the flow control knob.

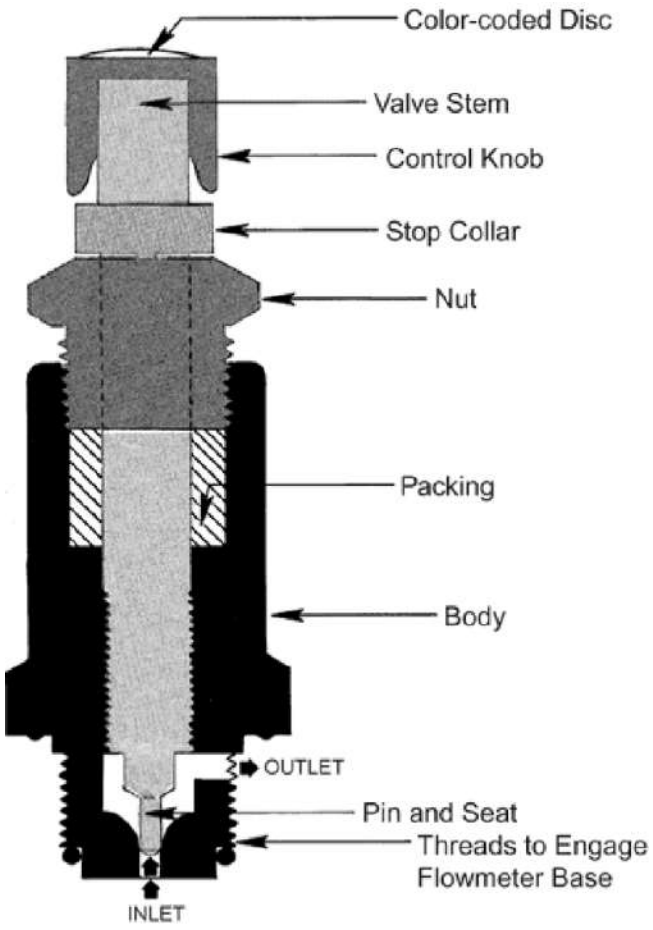


Figure 5.32 Flow adjustment control, shown in the closed position. Turning the stem creates a leak between the pin and seat so that gas flows to the outlet. The stop collar prevents overtightening of the pin in the seat. (Redrawn from a drawing furnished by Foregger Co., a division of Puritan Bennett Co., Inc.)

Figure 5.33 Flow control valves. Note that the oxygen flow control valve is fluted and larger than the other flow control valve. Also note the guard around each flow control valve. To the left of each valve is the flow. At the left is a flowmeter for total flow.

It is advantageous to have stops for the OFF and MAXIMUM flow positions. A stop for the OFF position avoids damage to the valve seat. A stop for the MAXIMUM flow position prevents the stem from becoming disengaged from the body.

Control Knob

The control knob is joined to the stem. If it is a rotary style knob, the oxygen flow control knob must have a fluted profile (Figs 5.13, 5.28, 5.33, 5.34) and be as large as or larger than that for any other gas (7). All other flow control knobs must be round. The knob is turned counterclockwise to increase flow. If other types of flow control valves are present, the oxygen control must look and feel different from the other controls.

Accidental changes in position can also be minimized by a shield, bar, or other protective barrier (Figs. 5.33, 5.34) and by placing them high above the working surface to lessen the likelihood of contact with objects on that surface.

Use

The flow control knob should be turned clockwise only until the gas flow ceases. Further tightening may result in damage to the

pin or seat (49).

When a machine is not being used, the gas source (cylinder or pipeline) should be closed or disconnected. The flow control valves should be opened until the gas pressure is reduced to zero and then closed. If the gas source is not disconnected, the flow control valve should be turned OFF to avoid the fresh gas desiccating the carbon dioxide absorbent (Chapter 9) and to conserve gas.

Before machine use is resumed, the flow control valves should be checked to make certain that they are closed. Sometimes, a flow control valve remains open

after the gas is bled out or opened when the machine is cleaned or moved. If the gas supply to an open flow control valve is restored and the associated flow indicator is not observed, the indicator may rise to the top of the tube where its presence may not be noticed. Even if no harm to the patient results, the sudden indicator rise may damage it and impair the flowmeter accuracy (50).

Figure 5.34 Flow control valves below conventional flowmeters.

Problems with Flow Control Valves

If the flow control valve knob is loose or worn, it may respond to a light touch or even accidental brushing (48).

Flow control valves should be closed when not in use. If there is no yoke plug or cylinder in the yoke or the one-way valve in the pipeline inlet does not work well, gas from an unused gas system could flow retrograde through a flowmeter with an open flow control valve and leak to atmosphere (18,51,52,53,54).

The stem or seat can block the flow (21,55,56,57).

Electronic Flow Control Devices

Electronically activated flow control devices can be used to alter gas flows (Fig. 5.29). In this case, the knob is turned clockwise to increase the flow. The flow adjustment may utilize a solenoid valve (58). There is usually a mixing area that collects the gas mixture. A common configuration is that one control alters the oxygen concentration and another control the total flow. If less than 100% oxygen is desired, the difference is made up from the second gas (air or nitrous oxide) selected. Flow and pressure transducers as well as temperature sensors are used to maintain accuracy.

Low-pressure System

The low-pressure system (Fig. 5.8) is downstream of the flow control devices. Pressure in this section is only slightly above atmospheric and variable, depending on the flow from the flow control valves, the presence of back pressure devices (check valves), and back pressure from the breathing system. Components found in this section include flowmeters, hypoxia prevention safety devices, unidirectional valves, pressure relief devices, and the common gas outlet. Vaporizers and their mounting devices are found in the low-pressure system but will be considered in Chapter 6.

Flowmeters

Flowmeters (flow indicators, flow tubes, rotameters) indicate the rate of flow of a gas passing through them. They may be mechanical or electronic. Electronic flowmeters usually have a

representation of a mechanical flowmeter on a screen or a number representing the flow. Even with electronic flowmeters, there

may be a mechanical flowmeter for total fresh gas flow at the common gas outlet to provide a sense of security for clinicians who do not fully trust electronic flowmeters.

Mechanical Flowmeters

Measuring gas flow in a mechanical flowmeter is based on the principle that flow past a resistance is proportional to pressure. Mechanical flowmeters measure the drop in pressure that occurs when a gas passes through a resistance.

Physical Principles

Traditional mechanical flow indicators used in anesthesia machines have been of the variable orifice (variable area, Thorpe tube) type. A vertical glass tube (Fig. 5.35) is internally tapered with its smallest diameter at the bottom. It contains an indicator that is free to move up and down inside the tube. When there is no gas flow, the indicator rests at the bottom of the tube. As shown in Figure 5.35B, when the flow control valve is opened, gas enters at the bottom and flows up the tube, elevating the indicator. The gas passes through the annular opening between the indicator and the tube and on to the outlet at the top of the tube. The indicator floats freely in the tube at a position where the downward force caused by gravity equals the upward force caused by the gas pressure on the bottom of the indicator. As gas flow increases, the number of gas molecules hitting the indicator bottom increases, and it rises. Because the tube is tapered, the size of the annular opening around the indicator increases with height, and more gas flows. When the flow is decreased, gravity causes the indicator to settle to a lower level. A scale marked on or beside the tube indicates the gas flowrate.

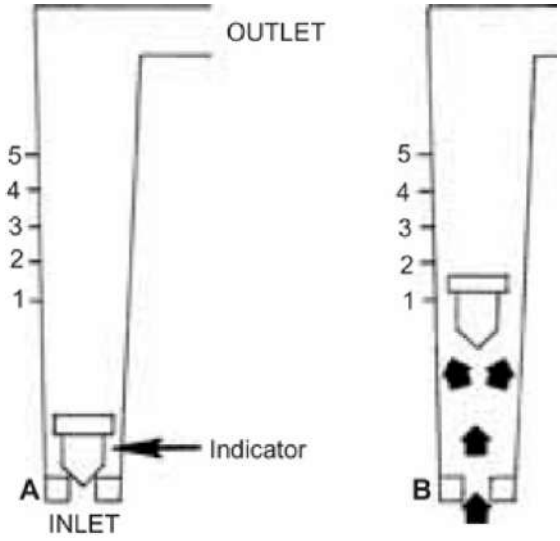


Figure 5.35 Variable orifice flow indicator. **A:** No gas flow. **B:** Gas enters at the base and flows through the tube, causing the indicator to rise. The gas passes through the annular opening around the float. The area of this annular space increases with the height of the indicator. Thus, the height of the indicator is a measure of gas flow.

The rate of flow through the tube will depend on three factors: The pressure drop across the constriction, the size of the annular opening, and the physical properties of the gas.

Pressure Drop across the Constriction

As gas flows around the indicator, it encounters frictional resistance between the indicator and the tube wall. There is a resultant loss of energy reflected in a pressure drop. This pressure drop is constant for all positions in the tube and is equal to the weight of the float divided by its cross-sectional area.

Size of the Annular Opening

In the variable orifice flowmeter, the annular cross-sectional area varies while the pressure drop across the indicator remains constant for all positions in the tube. For this reason, these flowmeters are often called *constant-pressure flowmeters*.

Increasing the flow does not increase the pressure drop but causes the indicator to rise to a higher position in the tube, thereby providing greater flow area for the gas. The elevation of the indicator is a measure of the annular area for flow and, therefore, of the flow itself.

Physical Characteristics of the Gas

When a low gas flow passes through the tube, the annular opening between the float and the wall of the tube will be narrow. As flow increases, the annular opening becomes larger. The physical property that relates gas flow to the pressure difference across the constriction varies with the form of the constriction. With a longer and narrower constriction (low flows), flow is laminar and is a function of the viscosity of the gas (Hagen-Poiseuille equation). When the constriction is shorter and wider (high flows), flow is more turbulent and depends on gas density (Graham's law).

Temperature and Pressure Effects

Flowmeters are calibrated at atmospheric pressure (760 torr) and room temperature (20ยฐC). Temperature and pressure changes will affect both the viscosity and the density of a gas and so influence the accuracy of the indicated flow rate. Variations in temperature as a rule are slight and do not produce significant changes.

In a hyperbaric chamber, a flowmeter will deliver less gas than indicated. With decreased barometric pressure (increased altitude), the actual flow rate will be greater than that indicated. The following equation can be used to derive an approximate correction factor for changes in atmospheric pressure (58A):

$F_1 = F_o$ ร— (d_o/d_1)

where

F_1 is the flow at ambient pressure,

F_o is the flow indicated on the scale calibrated at sea level,

d_o is the density of the gas at sea level, and

d_1 is the density of gas at ambient pressure.

Flowmeter Assembly

The flowmeter assembly consists of the tube through which the gas flows, the indicator, a stop at the top of the tube, and the scale that indicates the flow. Lights are available on most machines to allow the flowmeters to be observed in a dark room. Each assembly must be clearly and permanently marked with the appropriate color and name or chemical symbol of the gas measured.

Flowmeters are usually protected by a plastic shield. The flowmeter assembly empties into a common manifold that delivers the measured amount of gases into the low pressure system.

Tube

Flowmeter tubes (flow tubes) are usually made of glass. Glass tubes intended for a ball indicator have rib guides, which are thickened bars that run the length of the tube (Fig. 5.36). As the tube widens, the space between the indicator and the inside of the tube increases. The rib guides hold the ball indicator in the center of the tube.

The flowmeter tube can have a single or double taper (Fig. 5.37). Single-taper tubes have a gradual increase in diameter from the bottom to the top. They are usually used where there are different tubes for low and high flows. Dual-taper flowmeter tubes have two different tapers on the inside of the same tube€”one corresponding to fine flows and one for coarse flows. These tubes are used when only one tube is used for a gas.

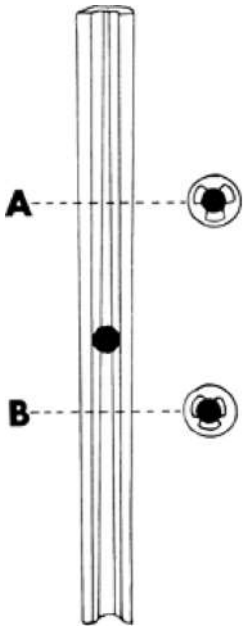


Figure 5.36 Flow indicator tube with rib guides. This is used with ball indicators. The triangular thickening of the inside of the tube keeps the ball centered. The area through which the gas flows increases with increasing height in the tube. (Redrawn courtesy of Fraser Harlake, Inc.)

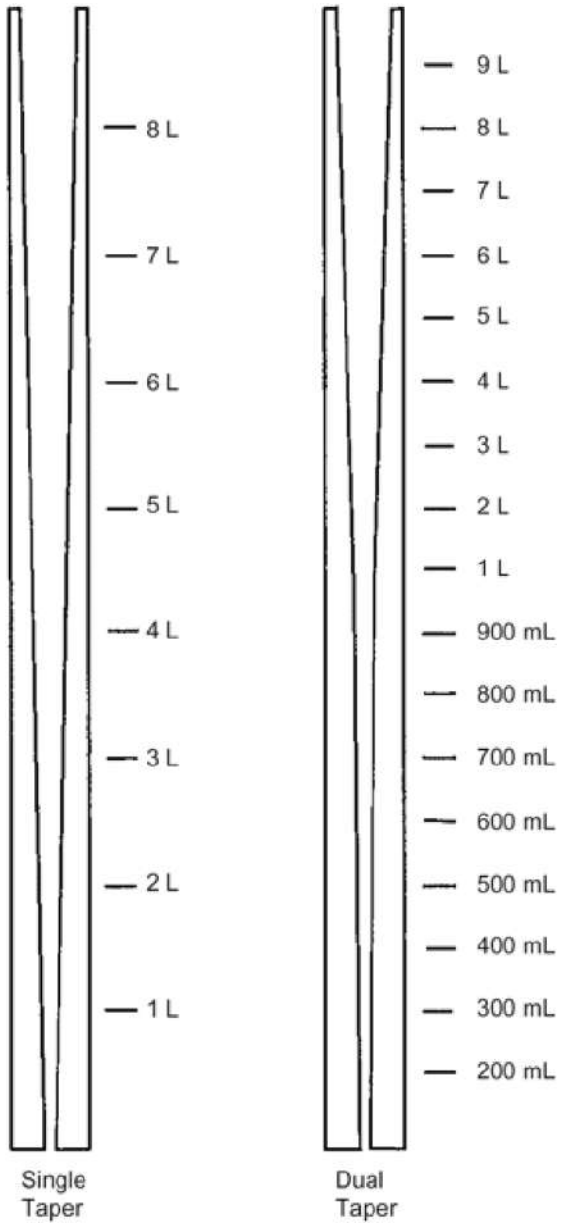


Figure 5.37 Dual- and single-taper flow indicator tubes. With the single-taper tube, the opening gradually increases from the bottom to the top of the tube. With the dual-taper tube, the opening size increases more rapidly above 1 L/minute.

Indicator

The indicator (float or bobbin) is a free-moving device within the tube. It is important to observe the indicator frequently during an anesthetic and especially when the flow is altered. If the indicator moves erratically, the readings may be inaccurate.

The nonrotating floatโ€“type indicator (Fig. 5.38) is designed so that gas flow keeps the float in the center of the tube if the tube is kept vertical. The reading is taken at the upper rim.

Rotating indicators (rotameters) (Figs. 5.38, 5.39) have an upper rim of which the diameter is larger than that of the body. Slanted grooves, or flutes, are cut into the rim. There is often a colored dot on one side of the

indicator that makes it easier to observe that the indicator is rotating. A rotating indicator is evidence that gas is flowing and the indicator is not stuck. When gas passes between the rim and the tube wall, the flutes cause the indicator to rotate. If the tube is vertical, the free spinning maintains the float in the center of the tube. This prevents fluctuations, reduces wear and tear, assists the passage of small particles, and reduces errors caused by friction between the tube and the indicator. Deviations from the vertical position will result in the rotor striking the side of the tube. The reading is taken at the upper rim.

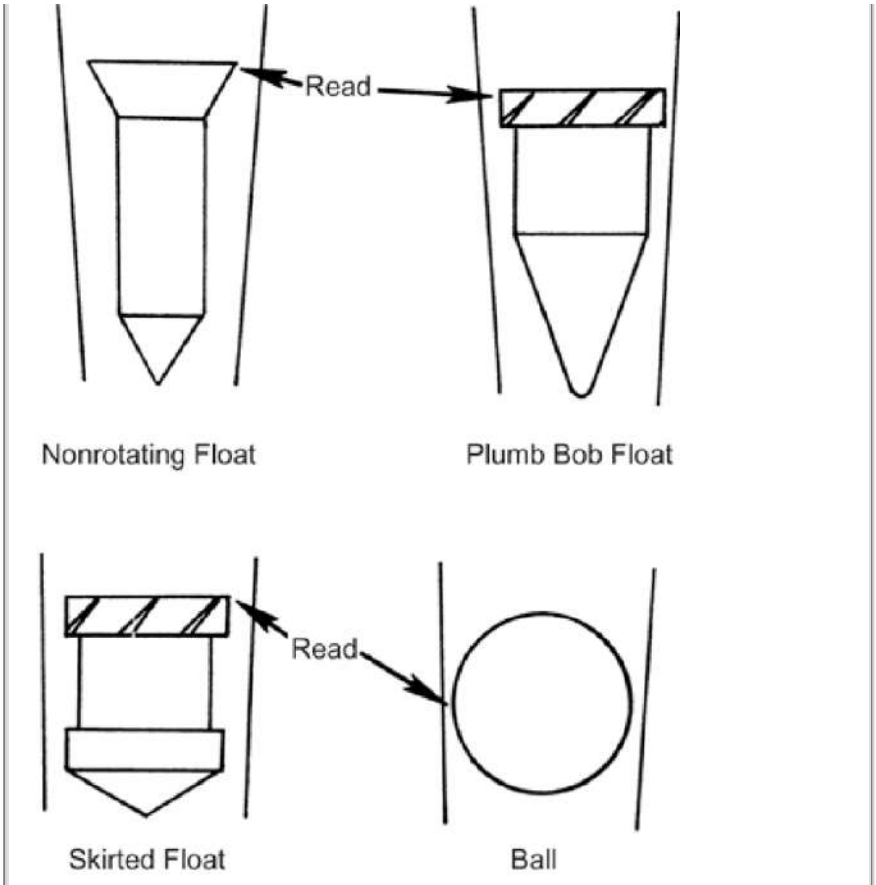


Figure 5.38 Flow indicator indicators. The plumb bob and skirted floats are kept centered in the tube by constant rotation. The reading is taken at the top. The ball indicator is kept centered by rib guides. The reading is taken at the center. The nonrotating float does not rotate and is kept centered by gas flow. (Adapted from Binning R, Hodges EA. Flowmeters. Can they be improved? Anaesthesia 1967;22:643Ì €“646.)

With a ball indicator (Figs. 5.33, 5.34A, 5.38), the reading is taken at the ball's midpoint. The ball is kept in the center of the tube by rib guides. The ball rotates and sometimes has two colors so that the rotation can be easily seen. Rotation is an indication that the ball can move freely in the tube and that the reading is accurate.

Stop

The stop at the top of the flowmeter tube (Fig. 5.39) prevents the indicator from plugging the outlet, which could lead to damage to the tube (47). It also prevents the indicator from ascending to a point in the tube where it cannot be seen. This is important, because a flowmeter with the indicator hidden at the top looks much like one that is turned OFF.

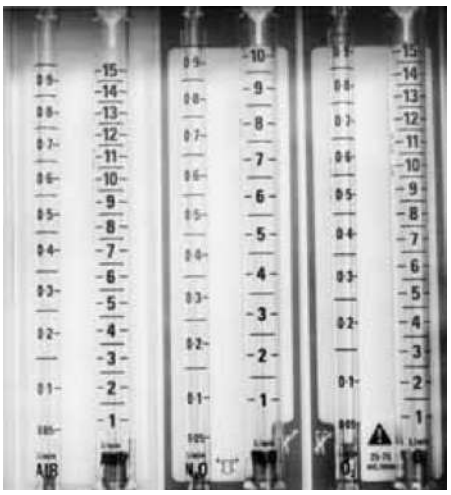


Figure 5.39 Skirted float indicators. Note the stops at the top of the flow indicator tubes. The flow indicator tubes are in series. The total flow is that shown on the higher flow tube, not the sum of the two tubes.

In some instances, a stop has been known to break off and fall down into the tube. If it descends far enough to rest on the indicator, it will cause the indicator to register less flow than is actually occurring.

Scale

The anesthesia workstation standard requires that the flow indicator scale either be marked on (Figs 5.33, 5.34, 5.39) or immediately adjacent to the tube (7). Flowmeters are calibrated in liters per minute. For flows below 1 L/minute, the flow may be expressed either in milliliters or in decimal fractions of a liter per minute with a zero before the decimal point.

Lights

Flow indicator lights are offered as an option on most modern anesthesia machines. These are useful when the machine is used in a darkened room.

Flowmeter Tube Arrangement

Flowmeter tubes for different gases are grouped side by side. The various gas flows meet at the common manifold (mixing chamber) at the top. Sometimes, there are two flowmeters for the same gas: One for low and one for high flows. The tubes are arranged in series (tandem) (Figs. 5.39 and 5.40). There is one flow control valve for the both flowmeter tubes. Gas from the flow control valve first passes through a tube calibrated up to 1 L/minute, then passes to a second tube that is calibrated for higher flows. The

total flow is not the sum of the two tubes but that shown on the higher flow tube. Series flowmeter tubes offer increased accuracy (59).

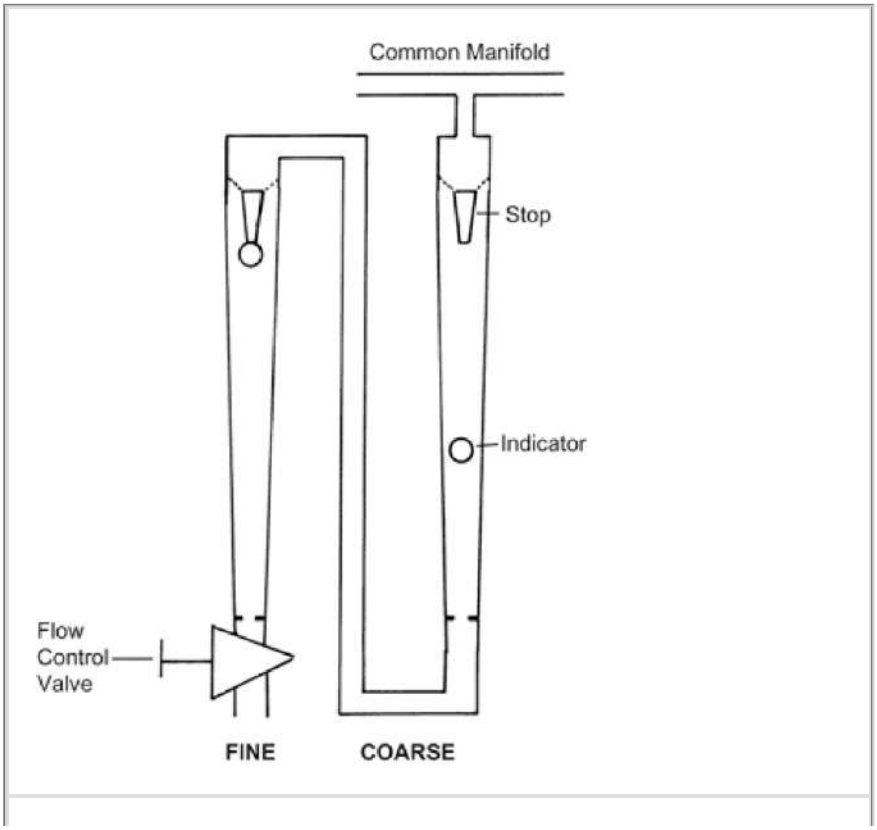


Figure 5.40 Flow indicator tubes in series. The total flow is that shown on the higher flow tube, not the sum of the two tubes.

Flowmeter tube sequence can be a cause of hypoxia (60). Figure 5.41 shows four different arrangements for oxygen, nitrous oxide, and air flowmeters. Normal gas flow is from bottom to top in each tube and then from left to right at the top. In Figure 5.41A/B, a leak is shown in the unused air flowmeter, showing potentially dangerous arrangements because the nitrous oxide flowmeter is located in the downstream position. A substantial portion of oxygen flow passes through the leak while all the nitrous oxide is directed to the common gas outlet. Safer configurations are shown in Figure 5.41C/D. By placing the oxygen flowmeter nearest the manifold outlet, a leak upstream from the oxygen results in loss of nitrous oxide rather than oxygen.

Before discovering that flowmeter sequence was important in preventing hypoxia, there was no consensus on where the oxygen flowmeter should be in relation to the flowmeters for other gases. To avoid confusion, the ASTM workstation standard requires that the oxygen flowmeter be placed on the right side of a group of flowmeter as viewed from the front (7). It should be noted that having the oxygen flowmeter on the right is specific to North America. In many countries, the oxygen flowmeter is on the left with the outlet also on the left. This sets the stage for potential operator error if a user administers anesthesia in a country other than where he or she was trained. There is no consensus on the location of the air or nitrous oxide flowmeters as long as they do not occupy the location next to the manifold outlet.

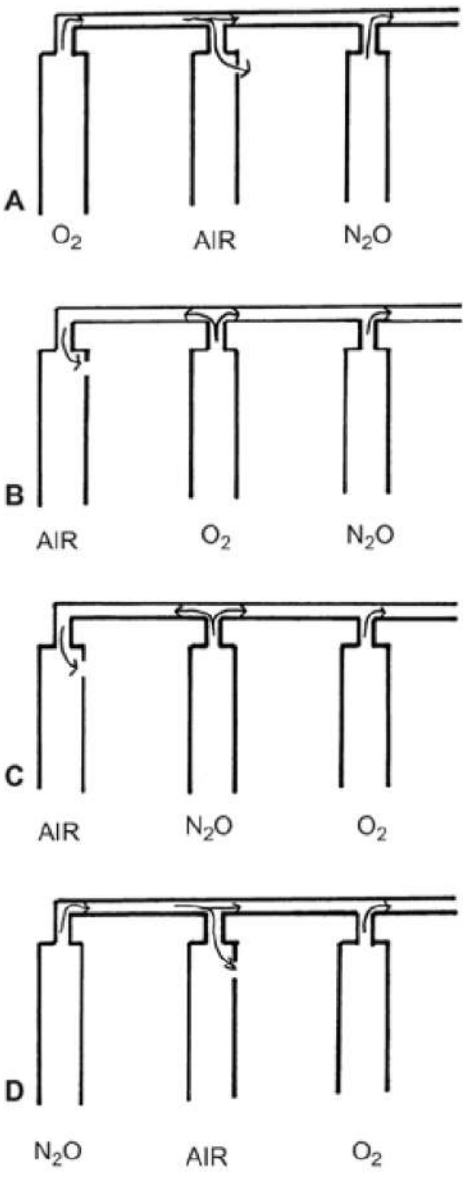


Figure 5.41 Flow indicator sequence. **A,B:** Potentially dangerous arrangements, with the oxygen flow indicator upstream. If a leak occurs, oxygen will be selectively lost. **C,D:** Oxygen is downstream from other gases, which is a safer situation because anesthetic gas rather than oxygen will be lost. *Arrows* represent flows of gases. (Redrawn from Eger EI, Hylton RR, Irwin RH, et al. Anesthetic flow meter sequenceÏ€"a case for hypoxia. Anesthesiology 1963;24:396Ï€"397).

Auxiliary Oxygen Flowmeter

An auxiliary (courtesy) oxygen flowmeter (Fig. 5.42) is a self-contained flowmeter with its own flow control valve, flow indicator, and outlet. It usually has a short tube with a maximum flow of 10 L/minute and a barbed fitting on the outlet. It is usually mounted on the left side of the machine. This can be used to supply oxygen to the patient without turning ON the anesthesia machine.

On some older machines, this flowmeter will work only on pipeline gas. On newer machines, it will work on both cylinder and pipeline supplies.

Figure 5.42 Courtesy (auxiliary) oxygen flowmeter.

A case has been reported where a courtesy flowmeter had a leaky valve that allowed a continuous low flow of oxygen despite the oxygen being turned OFF (61). This resulted in a serious fire.

Problems with Flowmeters

Inaccuracy

The flowmeter scale, tube, and indicator must be regarded as an inseparable unit. Should any one of the components need replacement, a complete new set must be obtained. If there is mixing between any of the components of the flowmeter assembly, the flowmeter will be inaccurate.

The tube assembly calibrated for one gas cannot be used for a different gas. In one instance, when the entire assembly of indicator scales and tubes were used for a gas other than the one for which they were calibrated, inaccuracy resulted (62,63). The degree of inaccuracy that will occur if flowmeters are transposed depends on the gases for which the flowmeters were intended. If a carbon dioxide flowmeter is transposed with a nitrous oxide flowmeter, the difference in accuracy will be minimal because both gases have similar densities and viscosities (64). Using heliox in place of air will result in delivery of a flow higher than that set (65).

The greatest accuracy in flowmeter tubes is in the middle half of the tube. Having one tube in the series arrangement for low flows (less than 1 L/minute) and one for high flows (1 to 10 L/minute) will result in greater accuracy.

Indicator Problems

Damage to the flow indicator can result from a sudden projection to the top of the tube when a cylinder is opened or a pipeline hose is connected with the flow control valve open. Flow indicators can become worn or distorted by handling (66). The stop at the top of the flowmeter tube can become dislodged and rest on top of the indicator.

Leaks

A leak in a flowmeter downstream of the indicator but upstream of the common manifold will result in a lower than expected concentration of that gas in the fresh gas (67,68,69,70,71). A leak may occur if a flow control valve is left open and there is no cylinder or yoke plug in the yoke (18,53,71A). The indicator at the bottom of the tube will not prevent gas backflow.

Using the Wrong Flowmeter

Anesthesia providers are accustomed to a certain flowmeter sequence. When this sequence is altered, there frequently are mistakes that result in an unintended gas being administered (72,73). The problem is most likely to occur between air and nitrous oxide, as the position of oxygen is generally fixed by national custom or standards.

Mechanical flowmeters should be protected by turning each flow control valve OFF when a cylinder valve is opened or a pipeline hose is connected to the machine. This prevents the indicator from suddenly rising to the top of the tube, which might damage the indicator or allow it to go unnoticed.

Electronic Flowmeters

Most of the electronic anesthesia machines available at this time use a conventional flow control valve and an electronic flow sensor. The flow measured by the sensor is then represented digitally and/or by a simulated flowmeter on the anesthesia machine screen (Fig. 5.43). An advantage of electronic flow measurement is that this information is available in a form that can be sent to a data management system.

Different technologies are used to measure gas flow. They are discussed in Chapter 23.

Hypoxia Prevention Safety Devices

One of the hazards associated with flow indicators is the possibility that the operator will set the flows so that a hypoxic mixture will be delivered. Various devices have been developed to prevent this.

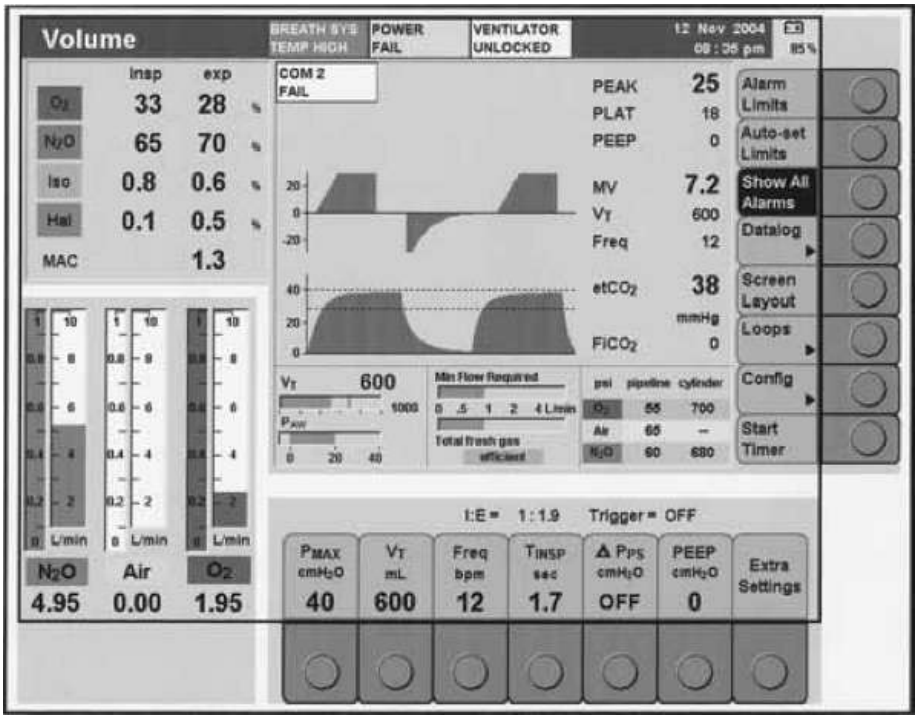


Figure 5.43 The flowmeters are represented electronically at the lower left part of the screen. The flows are set by using conventional flow control valves, then the flows are measured electronically. Note that the simulated flowmeter tubes are in series. At the top are a series of messages, including ones showing that there is no mains power and the battery has 85% of its charge. This screen also shows the pipeline and cylinder pressures. (Courtesy of Drager Medical.)

Mandatory Minimum Oxygen Flow

Some anesthesia machines require a minimum (50 to 250 mL/minute) flow of oxygen before other gases will flow. This is preset by the manufacturer (sometimes to the customer's specification). On some machines, the minimum flow may be deleted at the user's request. Some machines activate an alarm if the oxygen flow goes below a certain minimum, even if no other gases are being used.

The minimum flow is activated when the master switch is turned ON. On some machines, it is disabled when air is used. It may be provided by a stop on the oxygen flow control valve or a

resistor that permits a small flow to bypass a totally closed oxygen flow control valve (33,59).

The minimum oxygen flow does not in itself prevent a hypoxic gas concentration from being delivered. A hypoxic gas mixture can be delivered with only modest anesthetic gas flows.

Minimum Oxygen Ratio

The anesthesia workstation standard requires that an anesthesia machine be provided with a device to protect against an operator-selected delivery of a mixture of oxygen and nitrous oxide having an oxygen concentration below 21% oxygen (V/V) in the fresh gas or the inspiratory gas (7).

Mechanical Linkage

A mechanical linkage between the nitrous oxide and oxygen flow control valves is shown in Figure 5.44. There is a 14-tooth sprocket on the nitrous oxide flow control

valve and a 29-tooth sprocket on the oxygen flow control valve. If the flow control valves are adjusted so that a 25% concentration of oxygen is reached, a pin on the oxygen sprocket engages a pin on the oxygen flow control knob. This causes the oxygen and nitrous oxide flow control valves to turn together to maintain a minimum of 25% oxygen. This minimum oxygen ratio device (proportioning system) permits independent control of each gas as long as the percentage of oxygen is above the minimum. If the operator attempts to increase the nitrous oxide flow beyond that ratio, the oxygen flow is automatically increased. If the operator attempts to lower the oxygen flow too much, the nitrous oxide flow is lowered proportionally. It should be noted that these devices only link two gases, normally nitrous oxide and oxygen. Administering a third gas such as helium can result in a hypoxic mixture.

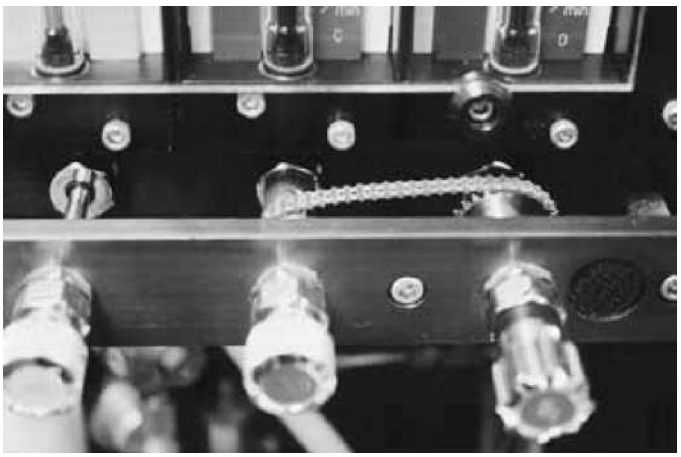


Figure 5.44 Mechanically linked flow control valves. Sprockets are secured to the stems of the oxygen and nitrous oxide flow control valves. A chain linking the sprockets limits the minimum oxygen concentration that can be set. Either nitrous oxide or oxygen flow can be adjusted independently, but the minimum oxygen concentration is maintained. If the nitrous oxide flow is increased beyond the maximum allowed, there is a proportional increase in oxygen flow. If the oxygen flow is lowered, there is a proportional decrease in nitrous oxide flow.

Problems have been reported with these devices (74,75,76,77,78,79,80,81,82,83,84,85).

Electronic Linkage

An electronic system can be used to provide a minimum ratio of oxygen to nitrous oxide flow. An electronic proportioning valve controls the oxygen concentration in the fresh gas. A computer continuously calculates the maximum allowable nitrous oxide flow given the oxygen flow. If the nitrous oxide flow control valve is opened sufficiently to cause a flow higher than the maximum allowable, the proportioning valve reduces the nitrous oxide flow to supply a minimum of 25% oxygen.

Alarms

Alarms are available on some machines to alert the operator that the oxygen:nitrous oxide flow ratio has fallen below a preset

value.

Unidirectional (Check) Valve

When ventilation is controlled or assisted, positive pressure from the breathing system can be transmitted back into the machine. Using the oxygen flush valve may also create a positive back pressure. This pressure can affect flowmeter readings and the concentration of volatile anesthetic agents delivered from the vaporizers on the machine. Some machines have a unidirectional (check) valve to minimize these effects. This valve is located between the vaporizers and the common gas outlet, upstream of where the oxygen flush flow joins the fresh gas flow. This valve will lessen the pressure increase but not prevent it, because gas will be continually flowing from the flowmeters.

These check valves are of great importance when checking the machine for leaks. Testing the breathing system for leaks will not detect a leak upstream of the check valve in a machine equipped with a check valve (86,87). This is discussed further in Chapter 33.

Pressure Relief Device

Some machines have a pressure relief device near the common gas outlet to protect the machine from high pressures. This valve opens to atmosphere and vents gas to atmosphere if a preset pressure is exceeded.

A pressure relief device may limit the ability of an anesthesia machine to provide adequate pressure for jet ventilation through a catheter inserted through the cricothyroid membrane (88). Anesthesia machine manufacturers do not recommend that the common gas outlet be used to provide jet ventilation. Some machines offer a connection from the pipeline or intermediate pressure system for a jet ventilation device.

Low-pressure Piping

Low-pressure gas piping has a large number of connections. Components located within this area are subject to breakage and leaks.

Common (Fresh) Gas Outlet

The common (fresh) gas outlet receives all of the gases and vapors from the machine and delivers the mixture to the breathing system. Some outlets have a 15-mm female slip-joint fitting (that will accept a tracheal tube connector), with a coaxial 22-mm male connector. They may also have a manufacturer-specific fitting. Because the common gas outlet is a common location for a disconnection, the machine standard mandates that it be difficult to accidentally disengage the delivery hose from the outlet (Fig. 5.45). The fresh gas supply tube, which conveys gas to the fresh gas inlet in the breathing system, attaches to the common gas outlet.

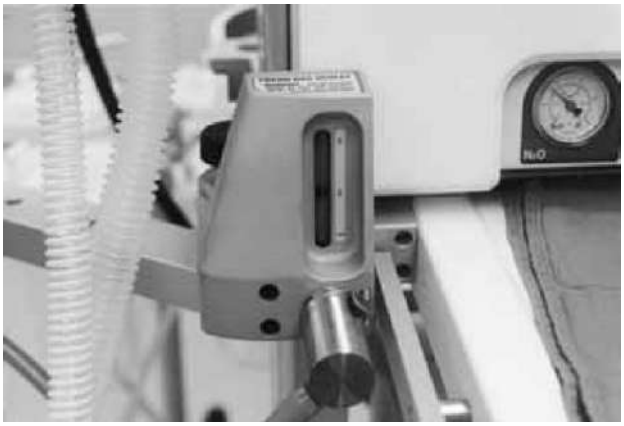


Figure 5.45 Common gas outlet with retaining device to prevent a disconnection. The flowmeter indicates the total fresh gas flow.

Some new anesthesia machines provide two common gas outlets. A hazard with this arrangement is that the fresh gas may be directed to the wrong outlet (89). The anesthesia workstation standard states that there shall be only one functional common gas outlet at a time (7). An interlock prevents both outlets from being inadvertently operative at the same time (90,91).

Many new anesthesia machines have internal connections to the breathing system. These machines may not have the conventional common gas outlet described previously.

The common gas outlet should not be used to administer

supplemental oxygen to a patient (92,93,94,95,96). This will delay use of the breathing system if an emergency arises. Another potential problem is that a vaporizer on the back bar may be accidentally left ON, leading to undesired administration of inhalational agent. Either the auxiliary oxygen flowmeter or a separate flowmeter should be used to supply oxygen.

Alternative Oxygen Control

When using an anesthesia machine, there is always the possibility that the electronics will fail. There needs to be a mechanism to deal with this problem. Different machines deal with this problem in different ways. As shown in Figures 5.14 and 5.46, some machines provide an alternative means to administer oxygen. This is separate from the auxiliary (courtesy) flowmeter. If there is a mechanical total flow flowmeter, it can be used to measure the delivered oxygen. Anesthesia can be administered with intravenous agents.

Figure 5.46 Alternative oxygen source. This can be used to supply oxygen in case of total loss of electrical power.

Power Failure

Power failure is addressed first by equipping the anesthesia machine with a battery that will supply power for 30 minutes or

more, depending on the battery charge and the electrical load. A noninterruptible power supply (Fig. 5.4) can be added to prolong the backup period. Anesthesia machines usually have a means to test the backup supply and give a reading of the battery charge (Fig. 5.5). Messages are provided to tell the anesthesia provider that battery power is in use as well as when the backup power is nearly exhausted (Fig. 5.43).

Older anesthesia machines that were pneumatically driven used electrical power for monitors and alarms. If the power failed and the battery was exhausted, the monitors would be lost, but the machine could carry on its pneumatic functions. With electronic computer-driven anesthesia machines, the need for a dependable and continuous power supply increased. Various machines deal with this problem in different ways. In most cases, there is a way of bypassing the electronic functions that allows the breathing system to be used in the manual/spontaneous mode. It may still be possible to deliver oxygen, especially from machines that have conventional mechanical flowmeters. If the vaporizers are mechanical, it may be possible to deliver volatile agent. If nitrous oxide or air is also being delivered, some manufacturers recommend that they be discontinued because monitoring will be lost.

Service

There are three options for machine servicing. These include the manufacturer's service organization, independent service organizations, and in-house trained personnel. Independent service organizations will often service machines from several different manufacturers. If the health care facility is large and has a number of machines from one manufacturer, it may be efficient to train biomedical personnel to service the equipment in-house. No matter which option is used, it is important that the technician be trained and certified for the particular machine being serviced. Manufacturers offer training for their equipment and certification upon successful completion of the course. The facility should retain a copy of the technician's certification.

Manufacturers and independent service organizations offer service contracts for their machines. With such a contract, a service representative will inspect and perform routine maintenance (including testing, cleaning, lubrication, adjustments, and replacement of worn or damaged parts) on the

machine at regular intervals, usually two to four times a year. Software upgrades that offer new features can often be made. If the upgrade is used to correct a problem, it likely will not be at extra cost. The quality of service varies. It should not be taken for granted that the work has been performed correctly. Whenever a machine has been serviced, it should be thoroughly checked before use (Chapter 33). Most service personnel will leave a message on the machine indicating that recent service has been performed, the date of service, and when the next service should be performed This can be removed after the machine has been found to be in working order. These notes may be checked by accreditation agencies.

Records must be kept on each machine, including problems that occur, service performed, date performed, and by whom. Records on equipment are required by the Joint Commission on Accreditation of Healthcare Organizations, and they can be very helpful in the event of legal action. It should be noted, however, that routine servicing does not relieve the user of the responsibility for checking the machine before each use.

Choosing an Anesthesia Machine

Only machines that meet all the requirements of the applicable ASTM standard (7) should be considered for purchase (97,98,99). Several criteria should be considered when choosing an anesthesia machine.

Service

All machines that comply with the ASTM standard should perform well when new. All machines, however,

will require servicing. Service quality varies among companies and from area to area within the same company. If one company is providing satisfactory service, it makes sense to consider purchasing models of that company's machines. If this is not the case, it is advisable to inquire about the experiences of colleagues in the area. Important considerations include whether there are long down times waiting for repairs, whether machines are available for loan, and whether service contracts are honored.

Cost

Both the purchase cost and the ongoing cost of maintenance should be considered. Some machines require that many expensive parts be replaced on a regular basis. This increases the cost. It may be possible to get concessions for maintenance costs as part of a purchase contract. Existing problems should be fixed without additional cost unless new features (upgrades) are performed (98).

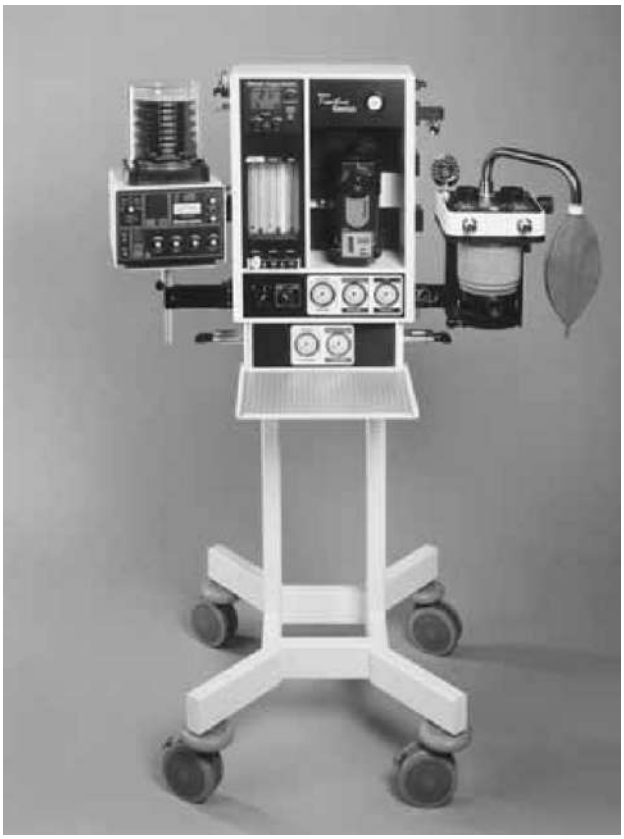


Figure 5.47 A small anesthesia machine may be a good choice for a small room or when it is necessary to transport the machine. (Courtesy of Blease.)

Many health care facilities have contracts with buying groups. If a particular anesthesia machine is part of this contract, there may be a considerable cost saving compared with machines not covered in this contract. The health care facility may pressure

the department to purchase machines under that contract.

Size

Some manufacturers offer compact machines. A small machine will fit better in a small room and will be easier to move (Fig. 5.47). Larger machines usually offer more drawers, vaporizers, and a larger worktop.

Suitability for Intended Use

Certain machines offer special features that may make them particularly desirable. Some ventilators may fit the institution's needs better than others. The ability to add on or incorporate additional equipment is important. One machine may be more user-friendly than another.

Since data management systems are likely to be used in the future, the ability to automatically gather data from a machine is important. In general, the more electronic the machine, the more data will be available for the data management system.

Equipment Standardization

If all anesthesia machines are the same, there may be fewer accidents related to operator error and training is easier. If the machines are purchased for a new facility, standardization is easily accomplished. There might be considerable cost savings in purchasing a large number of machines at one time from one vendor. Some institutions lease their machines, and when the lease runs out, they may trade them for new machines.

Standardization is difficult if anesthesia machines are replaced gradually. A machine that had been purchased in the past may no longer be available or suitable for the practice. This results in a number of different machines in the department. Even if the same model machine is purchased, there will usually be different features or different software. It may be possible to upgrade software in existing machines so that some uniformity is achieved.

Box 5.1 Guidelines for Obsolescence

American Society of Anesthesiologists Guidelines for

Determining Anesthesia Machine Obsolescence*

This document has been developed by the ASA Committee on Equipment and Facilities and has not been reviewed or approved as a practice parameter or policy statement by the ASA House of Delegates (1).

The following guidelines have been developed to assist anesthesia providers and other health care personnel, administrators, and regulatory bodies in determining when an anesthesia machine is obsolete. Anesthesia equipment can become obsolete if essential components wear out and cannot be replaced. The equipment may also become obsolete as a result of changes in medical practices, changes in the training and experience of anesthesia providers, and/or development of new safety features.

An anesthesia machine should not be considered obsolete solely because it has reached an arbitrary age. Furthermore, a machine should not be expected to meet all of the performance and safety requirements specified in international or U.S. equipment standards published after the machine was manufactured. It is the responsibility of the anesthesia provider to determine if a machine's failure to meet newer standards represents a sufficient threat to patient safety to render the machine obsolete.

The ASA Standards for Basic Anesthetic Monitoring (2) apply to all anesthesia care. The equipment necessary to accomplish this monitoring may be integral to the anesthesia machine or separate from it. The criteria for defining obsolescence that are described in this document relate only to the gas and vapor delivery portion of the machine. Integral monitors (e.g., electrocardiograph, oxygen monitor, blood pressure monitor, pulse oximeter, carbon dioxide monitor) should be considered separately and are not addressed in these guidelines.

These guidelines apply only to existing machines and are not intended to unduly restrict the design of machines in the future. It is recognized that future machines may incorporate different safety mechanisms than those in use today to accomplish the same goals.

Absolute Criteria

An anesthesia machine shall be considered to be obsolete if any of the following criteria apply.

I. **Lack of Essential Safety Features**

A. Minimum oxygen ratio device (O_2/N_2O proportioning system) on a machine that can deliver nitrous oxide

Rationale: Hypoxia has been a major cause of patient death or severe brain injury during anesthesia. An anesthesia machine that cannot deliver oxygen must automatically be rendered incapable of delivering nitrous oxide as well.

B. Oxygen failure safety (ĺ€fail-safeĺ€) device

Rationale: One of the most serious mishaps that occurred with anesthesia machines in the past was depletion of the oxygen supply (usually from an exhausted cylinder) without the user being aware. The result was delivery of a hypoxic mixture. This mishap can occur even with piped gas supplies. An oxygen failure safety device prevents this hazard by stopping the flow of nitrous oxide when there is a loss of oxygen supply pressure.

C. Oxygen supply pressure failure alarm

Rationale: While the supply of oxygen from a pipeline system or cylinders is usually very reliable, interruptions in that supply can occur. Given the critical nature of oxygen delivery, the operator of an

anesthesia machine should be made aware immediately of the failure of the central oxygen supply so that appropriate remedial measures (e.g., opening a cylinder, reducing the use of oxygen, obtaining additional cylinders) can be taken.

D. Vaporizer interlock device

Note 1: This does not apply to an anesthesia machine that allows only one vaporizer to be mounted at a time.

Note 2: It may be possible to add a vaporizer interlock device to a machine.

Rationale: Turning on two vaporizers at the same time can result in dangerously high anesthetic vapor concentrations being delivered and contamination of the downstream vaporizer.

E. Pin Index Safety System

Rationale: This system is needed to prevent mounting a cylinder on an incorrect yoke.

F. Noninterchangeable, gas-specific (e.g., Diameter Index Safety System [DISS]) connectors on the gas pipeline inlets

Rationale: These connectors are needed to prevent attachment of an incorrect gas delivery hose to the machine.

II. **Presence of Unacceptable Features**

A. Measured flow (flowmeter-controlled) vaporizers (e.g., Copper Kettle, Verni-trol)

Rationale: These vaporizers have not been manufactured for some time, and servicing for them is no longer available. Many anesthesia providers are not sufficiently familiar with them to use them correctly, which may result in delivery of inadequately low or dangerously high anesthetic vapor concentrations. Some of these vaporizers lack the side-fill feature needed to prevent accidental overfilling and spilling of liquid anesthetic into the breathing system.

B. More than one flow control knob for a single gas delivered to the common gas outlet of the machine

Note: This does not include the flow control knob for an auxiliary oxygen flowmeter.

Rationale: Having more than one flow control knob for a gas may result in an unintended high or low flow of gas being delivered. Parallel flowmeters may cause ambiguity because on all recently manufactured machines, flowmeters are in series with one flow control knob for each gas delivered to the machine's common gas outlet.

C. Vaporizer with rotary concentration dial such that the anesthetic vapor concentration increases when

the dial is turned clockwise

Note: It may be possible to replace an unacceptable vaporizer without replacing the entire machine.

Rationale: All vaporizers manufactured in recent years are designed to deliver increased vapor concentration when the dial is turned counterclockwise. Uniformity in vaporizer controls will prevent errors and increase safety.

D. Connection(s) in scavenging system of the same (i.e., 15 mm or 22 mm) diameter as a breathing system connection

Note: It may be possible to replace an unacceptable scavenging connection without replacing the entire machine.

Rationale: Having 15- or 22-mm diameter connections in the scavenging system can result in incorrect connections between the breathing system and the scavenging system, potentially resulting in negative or high pressure in the breathing system. Current standards mandate 30-mm (preferred) or 19-mm connections in the scavenging system.

III. **Adequate Maintenance No Longer Possible**

The manufacturer or certified service personnel will not or cannot service the machine with acceptable replacement parts so that it performs within the tolerances to which it was originally designed.

Note 1: Although a manufacturer may declare that its own subsidiaries will no longer service, support, or certify a particular machine, the essential core components of the machine may still be serviceable.

Note 2: Obtaining acceptable replacement parts can be a problem. In some cases, it may be possible to obtain the parts from the party who supplied them to the machine manufacturer. Alternatively, such parts may be obtained from machines that have already been taken out of service.

Note 3: When a manufacturer declares that it will no longer provide support for a machine, responsibility is typically transferred to the user (health care facility) and/or the third party who services the machine.

Rationale: A machine that cannot be serviced or for which replacement parts are not available cannot be maintained according to the standards and specifications to which it was originally designed and is dangerous.

Relative Criteria

Consideration should be given to replacing an anesthesia machine if any of the following apply:

I. **Lack of Certain Safety Features**

A. Means to isolate the APL (adjustable pressure limiting) valve during mechanical ventilation

Note: Isolation of the APL valve can be done in a number of ways (e.g., mechanically,

electronically).

Rationale: The APL valve is designed for use with manual, not mechanical, ventilation. If an APL valve is left open and is not isolated from the breathing system during mechanical ventilation, a portion of the inspired tidal volume may be lost.

B. Oxygen flow control knob that is fluted and larger than the other flow control knobs

Rationale: Current standards mandate that the oxygen flow control knob be larger than other flow control knobs and fluted. Alterations to gas flows may be performed during low light conditions or when the anesthesia provider is not looking directly at the machine. Tactile identification of the oxygen flow control knob should reduce errors.

C. Oxygen flush control protected from accidental activation

Note: Protection can be either by placement or design of the control.

Rationale: Accidental activation of the oxygen flush can result in barotrauma.

D. Main ON/OFF switch for electrical power to integral monitors and alarms

Rationale: Current standards mandate that the main power

switch, when turned ON, enables integral monitors and alarms. Operators unfamiliar with older anesthesia machines may not appreciate that monitors and alarms are not automatically enabled and may neglect to turn on one or several of them if they are not activated by a single switch.

E. Antidisconnection device at the fresh gas outlet

Rationale: Disconnection of the fresh gas inflow to the breathing system might lead to undesirable anesthetic or oxygen concentrations delivered to the patient or create a significant leak in the breathing system with rapid loss of gas. Depending on the mode of ventilation (spontaneous or controlled), disconnection of the fresh gas hose may not be immediately apparent.

F. Airway pressure alarm (for detecting sustained positive pressure, negative pressure, and high peak pressure)

Note: An alarm for detecting disconnections (low-pressure alarm) is a criterion of the ASA Standards for Basic Anesthetic Monitoring.

Rationale: These pressure conditions represent an immediate threat to patient safety and need to be brought to the immediate attention of

the anesthesia provider.

II. **Problems with Maintenance** The maintenance history indicates that problems with the machine (e.g., increasing frequency of service calls, machine frequently not available for use) are impacting clinical service in a manner that is unacceptable to the institution or which threatens patient safety

Note: Maintenance records or logs should be kept for all anesthesia machines in clinical use and problems documented. These records should be reviewed regularly to determine what type of problems are occurring with each machine, how often they occur, and their effect on the anesthesia practice.

III. **Potential for Human Error** Differences between older and newer machines can be a source of confusion and error if certain features (e.g., automatic activation of monitors and alarms by a main ON-OFF switch) are present on some machines but not on others or are in different locations on the machines.

Rationale: Having certain machine features in different locations on different machines can create confusion and increase the likelihood of operator error. Anesthesia providers who are more familiar with anesthesia machines manufactured recently may mistakenly expect that certain features are present on older machines, and it may not be readily apparent that they are different. Standardization of anesthesia machines throughout an institution should be considered.

IV. ***Inability to Meet Practice Needs*** *Examples:*

A. The machine cannot accept vaporizers for newer potent inhaled volatile agents

> *Note:* A vaporizer should never be placed downstream of the common gas outlet. This is a dangerous practice.

B. The machine cannot deliver fresh gas flows that are low enough for current anesthetic techniques.

C. The integral anesthesia ventilator is incapable of safely and effectively ventilating the lungs of the target patient population.

> *Rationale:* New agents, techniques, and/or ventilators may not be compatible with older anesthesia machines. If their use is considered to be necessary for optimal patient management, a new anesthesia machine should be obtained.

When it has been determined that a machine is obsolete, it should not be placed somewhere in the facility where it might be used clinically (e.g., as an oxygen delivery device). A machine that has been determined to be obsolete should either be destroyed or donated to a worthy party (e.g., a developing country, zoo, or laboratory). If the latter course is followed, it would be prudent to obtain legal advice about potential liability relating to the donation. Also, it is prudent to ensure that the recipient possesses the infrastructure (e.g., electrical power, medical gases), access to drugs and supplies (e.g., volatile anesthetics, circuits, replacement parts), technical expertise, and training to safely use the machine.

> *Rationale:* Placing an obsolete machine where it might be used involves many hazards.

Many of the hazards noted previously are related to the possible misuse of an older anesthesia machine by personnel who are unfamiliar with its idiosyncrasies and deviations from more modern machines. Placement of an obsolete anesthesia machine in a location where it would be used only infrequently during high-acuity situations, possibly by personnel without anesthesia training, can only magnify these risks. User expectationsÏ€”that it is a Ï€modernÏ€ machine with Ï€modernÏ€ safety featuresÏ€”will still be present. The presence of an anesthesia machine in an atypical location may tempt personnel unfamiliar with the machine to modify it. Nonanesthesia personnel may avoid using it because they are not familiar with it. The need to provide positive-pressure ventilation with oxygen in remote locations can be met by using an oxygen cylinder or flowmeter connected to a pipeline outlet and a nonrebreathing bag. This is inexpensive, easy to use, and can easily be made available in remote locations.

1. Variances from the recommendations contained in this document may be acceptable based on the judgment of the responsible anesthesiologist. The recommendations are designed to encourage quality patient care and safety

in the workplace but cannot guarantee a specific outcome. They are subject to revision from time to time as warranted by the evolution of technology and practice. Posted June 22, 2004

2. Standards for Basic Anesthetic Monitoring Approved by House of Delegates and last amended on October 21, 1998. Available from the American Society of Anesthesiologists, 520 N. Northwest Highway, Park Ridge, IL 60068-2573. http://www.ASAhq.org

If the institution is teaching anesthesia residents or student nurse anesthetists, different machines add to the diversity of their experience. However, trainees will need to be monitored more closely if they use a variety of different machines.

Guidelines for Determining Anesthesia Machine Obsolescence

Replacing outdated equipment is a necessary, ongoing process. Apparatus that was the best available at one time may become unacceptable as improved models become available.

A questionnaire sent to anesthetists selected from National Health Service hospitals from all regions of the United Kingdom in 2001 found that 27% of anesthesia machines did not have an antihypoxic device that could prevent administration of hypoxic gas mixtures (100). Most were in little-used operating theaters, emergency departments, and radiology, which made their presence even more likely to present a problem, because users may not suspect that they lack these safety devices.

The Equipment and Facilities Committee of the American Society of Anesthesiologists (ASA) has developed guidelines to assist anesthesia providers and other health care personnel, administrators, and state regulatory bodies in determining when an anesthesia machine is obsolete. The guidelines are shown in Box 5.1.

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Questions

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

1. The high pressure system of the anesthesia machine

includes

A. The oxygen flush

B. Flowmeters

C. The pipeline inlet

D. The hanger yokes

View Answer

2. The Pin Index Safety System

A. Consists of two pins on the cylinder valve that fit two corresponding holes in the yoke

B. Is located above the nipple on the yoke

C. Makes it impossible to place an incorrect cylinder in a yoke

D. Has specific locations for pins and holes for each gas

View Answer

3. When placing a cylinder in the yoke,

A. The first step is to fully retract the retaining screw

B. The washer should be placed on the cylinder valve

C. The Pin Index Safety System components must be mated

D. The screw is tightened into the cylinder relief valve

View Answer

4. The pressure regulator

A. Reduces cylinder pressure to below 345 kPa

B. Supplies a relatively constant outlet pressure while the source pressure is reduced

C. Will not work properly if gas is being removed from the low-pressure side

D. Can be either direct or indirect acting

View Answer

5. The intermediate pressure system includes

A. The pipeline pressure gauge

B. The flowmeter manifold

C. The oxygen flush

D. Vaporizer(s)

View Answer

6. The oxygen failure safety valve

A. Will prevent a hypoxic gas mixture from being delivered

B. Will cut off the flow of oxygen should the nitrous oxide supply fail

C. Prevents the user from dialing a hypoxic mixture on the flowmeters

D. May or may not cut off the flow of air if the oxygen supply fails

View Answer

7. The oxygen supply pressure alarm will

A. Be activated by a disconnected oxygen pipeline hose

B. Help prevent delivery of a hypoxic mixture

C. Be activated if the oxygen pipeline pressure is low

D. Protect the patient from hypoxia due to leaks in the machine

View Answer

8. The oxygen flush valve

A. Will deliver oxygen at between 30 and 60 L/minute

B. Can be locked in the ON position

C. May increase the pressure in vaporizers up to 200 cm H_2O when activated

D. Must be protected against accidental activation

View Answer

9. Which of the following statements about flowmeters are correct?

A. Parallel flowmeters are used in new anesthesia machines

B. Flowmeter tubes work on the principle of the variable orifice

C. The inside of a flow tube containing a ball is smooth

D. The pressure drop across the indicator is constant for all positions in the tube

View Answer

10. The rate of flow through a flowmeter tube depends on

A. The pressure drop across the constriction

B. The size of the annular opening

C. The physical properties of the gas

D. The length of the tube

View Answer

11. If a flowmeter tube is broken

A. Only the tube needs to be replaced

B. The indicator can be used in the new tube if it is a ball

C. The scale must be replaced if it is integral to the tube

D. The tube, indicator, and scale must be replaced as a unit

View Answer

12. Effects of the physical characteristics of the gas passing through the flowmeter include

A. At low flows, flow is a function of the viscosity of the gas

B. Viscosity of the gas is more important with a longer and narrower constriction

C. With high flows, flow depends more on the density of the gas

D. The density of the gas is more important with a shorter and wider constriction

View Answer

13. Correct statements concerning the order of flowmeter tubes include

A. The left tube should be either oxygen or air

B. A leak in the flowmeter that is farthest from the manifold outlet may result in loss of gas from the middle flowmeter

C. A small leak in the middle flowmeter will cause loss of gas from the flowmeter next to the manifold

D. The oxygen flowmeter should be next to the manifold outlet

View Answer

14. Concerning mandatory minimum oxygen flow,

A. It will prevent delivery of a hypoxic mixture

B. It cannot be removed

C. The amount of flow is user adjustable

D. It is sometimes associated with an alarm

View Answer

15. Correct statements concerning the minimum oxygen ratio control include

A. If the flow of nitrous oxide is increased, the oxygen flow is automatically increased with a mechanical linkage

B. The gases are independently controlled when the oxygen percentage is above the minimum

C. It can be a mechanical or pneumatic link

D. It is usually set at 25% nitrous oxide

View Answer

16. What are the functions of the hanger yoke?

A. Ensuring a unidirectional gas flow into the anesthesia machine

B. Providing a gas-tight seal

C. Orienting and supporting the cylinder

D. Providing a cylinder connection for each gas used in the machine

View Answer

17. Gas cylinder valves on the anesthesia machine with a pipeline supply should be kept closed for the following reasons:

A. So that a pipeline pressure failure will be recognized early

B. To prevent gas from flowing retrograde into the pipeline system

C. To prevent pressure alterations in the pipeline from drawing down the cylinder contents

D. To prevent fires

View Answer

18. Which physical principles govern the gas flow through a mechanical flowmeter?

A. The elevation of the indicator is a measure of the annular area for flow

B. Temperature changes affect the density and viscosity of gases and thus significantly alter the accuracy of flowmeters

C. Short, wide constrictions cause more turbulent flow

D. The pressure drop as gas flows around the indicator varies with the diameter of the inside of the flow tube

View Answer

Chapter 6
Vaporizers

Most of the inhalational anesthetic agents in use today are liquids at atmospheric pressure and room temperature and must be converted into vapors before they can be used. A vaporizer (anesthetic agent or vapor delivery device) is a device that changes a liquid anesthetic agent into its vapor and adds a controlled amount of that vapor to the fresh gas flow or the breathing system. Up to three vaporizers are commonly attached to an anesthesia machine.

Physics

Vapor Pressure

Figure 6.1A shows a volatile liquid inside a container that is closed to atmosphere. Molecules of liquid break away from the surface and enter the space above, forming a vapor. If the container is kept at a constant temperature, a dynamic equilibrium is formed between the liquid and vapor phases so that the number of molecules in the vapor phase remains constant. These molecules bombard the walls of the container, creating a pressure. This is called the *saturated vapor pressure* and is represented by the density of dots above the liquid.

If heat is supplied to the container (Fig. 6.1B), the equilibrium will be shifted so that more molecules enter the vapor phase and the vapor pressure will rise. If heat is taken away from the system (Fig. 6.1C), more molecules will enter the liquid state, and the vapor pressure will be lower. It is meaningless, therefore, to talk about vapor pressure without specifying the temperature. Vapor pressures of some anesthetic agents at 20ยฐC are shown in Table 6.1. Vapor pressure depends only on the liquid and the temperature. It is not affected by ambient pressure within the range of barometric pressures encountered in anesthesia.

Boiling Point

A liquid's boiling point is the temperature at which its vapor pressure is equal to the atmospheric pressure. The boiling point will be lower with lower atmospheric pressure. Anesthetic agents with low boiling points are more susceptible to variations in barometric pressure than agents with higher boiling points. The boiling points for some anesthetic agents are shown in Table 6.1.

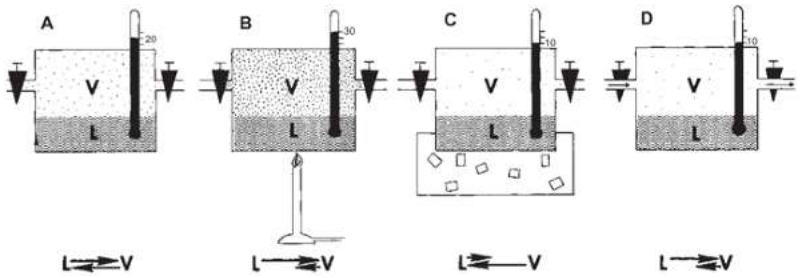

Figure 6.1 Vapor pressure changes with varying temperature. **A:** The liquid and vapor are in equilibrium. **B:** The application of heat causes the equilibrium to shift so that more molecules enter the vapor phase, as illustrated by the increased density of dots above the liquid. **C:** Lowering the temperature causes a shift toward the liquid phase and a decrease in vapor pressure. **D:** Passing a carrier gas over the liquid shifts the equilibrium toward the vapor phase. The heat of vaporization is supplied from the remaining liquid. This causes a drop in temperature.

Gas Concentration

Two methods are commonly used to express the concentration of a gas or vapor: Partial pressure and volumes percent (vol %).

Partial Pressure

A mixture of gases in a closed container will exert a pressure on the walls of the container. The part of the total pressure due to any one gas in the mixture is called the partial pressure of that gas. The total pressure of the mixture is the sum of the partial pressures of the constituent gases. The partial pressure exerted by the vapor of a liquid agent depends only on the temperature of that agent and is unaffected by the total pressure above the liquid. The highest partial pressure that can be exerted by a gas at a given temperature is its vapor pressure.

TABLE 6.1 Properties of Common Anesthetic Agents

Agent	*Trade Name*	*Boiling Point (ยฐC, 760 mm Hg)*	*Vapor Pressure (torr, 20ยฐC)*	*Density of Liquid (g/mL)*	*Heat of Vaporization*		*Specific Heat of Liquid*		*MACa in O_2 (%)*
					cal/g	*cal/mL*	*cal/mL*	*cal/g*	
Halothane	Fluothane	50.2	243	1.86 (20ยฐC)	35 (20ยฐC)	65 (20ยฐC)	0.35	0.19	0.75
Enflurane	Ethrane	56.5	175	1.517 (25ยฐC)	42 (25ยฐC)	63 (25ยฐC)			1.68
Isoflurane	Forane	48.5	238	1.496 (25ยฐC)	41 (25ยฐC)	62 (25ยฐC)			1.15
Desflurane	Suprane	22.8	669	1.45 (20ยฐC)					6.4

Sevoflurane	Ultane	58.6	157						2.0

[a]Minimum anesthetic concentration.
Adapted with permission from Quasha AL, Eger EL, Tinker JH. Determinaion and applications of MAC. Anesthesiology 1980;53:315Ī€“334.

Volumes Percent

The concentration of a gas in a mixture can also be expressed as its percentage of the total volume. Volumes percent is the number of units of volume of a gas in relation to a total of 100 units of volume for the total gas mixture. In a mixture of gases, each constituent gas exerts the same proportion of the total pressure as its volume is of the total volume. Volumes percent expresses the relative ratio of gas molecules in a mixture, whereas partial pressure expresses an absolute value.

Partial Pressure/Total pressure = Volumes percent

Although gas and vapor concentrations delivered by a vaporizer are usually expressed in volumes percent, patient uptake and anesthetic depth are directly related to

partial pressure but only indirectly to volumes percent. While a given partial pressure represents the same anesthetic potency under various barometric pressures, this is not the case with volumes percent (1).

Heat of Vaporization

It takes energy for the molecules in a liquid to break away and enter the gaseous phase. A liquid's heat of vaporization is the number of calories necessary to convert 1 g of liquid into a vapor. Heat of vaporization can also be expressed as the number of calories necessary to convert 1 mL of liquid into a vapor. The heats of vaporization of some anesthetic agents are shown in Table 6.1.

Liquid temperature decreases as vaporization proceeds. As the temperature falls, a gradient is created so that heat flows from the surroundings into the liquid. The lower the liquid temperature, the greater the gradient and the greater the flow of heat from the surroundings. Eventually, equilibrium is established so that the heat lost to vaporization is matched by the heat supplied from the surroundings. At this point, the temperature ceases to drop.

In Figure 6.1D, a flow of gas (carrier gas) is passed through the container and carries away molecules of vapor. This causes the equilibrium to shift so that more molecules enter the vapor phase. Unless some means of supplying heat is available, the liquid will cool. As the temperature drops, so does the vapor pressure of the liquid, and fewer molecules will be picked up by the carrier gas so that there is a decrease in concentration in the gas flowing out of the container.

Specific Heat

A substance's specific heat is the quantity of heat required to raise the temperature of 1 g of the substance by 1ยฐC. The

higher the specific heat, the more heat that is required to raise the temperature of a given quantity of that substance. A slightly different definition of specific heat is the amount of heat required to raise the temperature of 1 mL of the substance by 1°C. Water is the standard with a specific heat of 1 cal/g/°C or 1 cal/mL/°C.

Specific heat is important when considering the amount of heat that must be supplied to a liquid anesthetic to maintain a stable temperature when heat is lost during vaporization. Specific heats for some anesthetic agents are given in Table 6.1.

Specific heat is also important for choosing the material to construct a vaporizer. Temperature changes more gradually for materials with a high specific heat than for those with a low specific heat.

Thermal Conductivity

Another consideration in choosing material from which to construct a vaporizer is thermal conductivity. This is a measure of the speed with which heat flows through a substance. The higher the thermal conductivity, the better the substance conducts heat.

Thermostabilization is achieved by constructing a vaporizer of a metal with high thermal conductivity (copper, bronze) to minimize temperature changes when the vaporizer is in use. In a vaporizer containing a wick, it is important that the wick be in contact with a metal part so that heat lost as a result of vaporization can be quickly replaced.

Vaporizer Design

Concentration Calibration

Nearly all the vaporizers in use today in the United States are calibrated by agent concentration as expressed in percentage of vapor output. They are known as *concentrated-calibrated vaporizers*.

They are also called *direct-reading*, *dial-controlled*, *automatic plenum*, *percentage-type*, and *tec-type* vaporizers. Vaporizer output is controlled by a single knob or dial that is calibrated in volumes percent.

Concentration-calibrated vaporizers are designed to be located between the flowmeters and the common gas outlet on the anesthesia machine. They are not designed to be used between the common gas outlet and the breathing system or in the breathing system, because they are not calibrated for the high gas flows that occur with the oxygen flush in these locations and offer too much resistance.

Variable Bypass Vaporizers

The vapor pressures of most anesthetic agents at room temperature are much greater than the partial pressure required to produce anesthesia. To produce clinically useful concentrations, a vaporizer dilutes saturated vapor. This can be accomplished by splitting the gas flow that passes through the vaporizer (Fig. 6.2). Some of the gas flows through the

vaporizing chamber (the part containing the liquid anesthetic agent), and the remainder goes through a bypass to the vaporizer outlet. Both gas flows join downstream of the vaporizing chamber, where gas exits the vaporizer at the desired concentration.

The ratio of bypass gas to gas going to the vaporizing chamber is called the *splitting ratio* and depends on the ratio of resistances in the two pathways (2,3). This in turn depends on the variable (adjustable) orifice. This orifice may be in the inlet to the vaporizing chamber but is in

the outlet in most modern vaporizers. The splitting ratio may also depend on the total flow to the vaporizer.

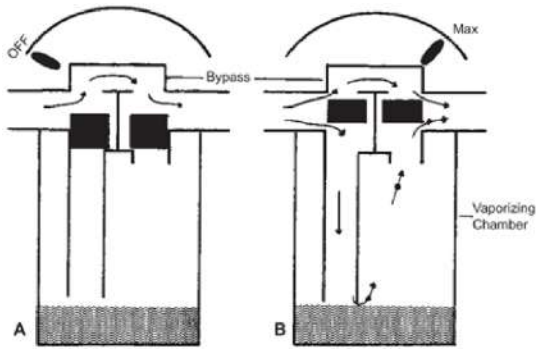

Figure 6.2 Concentration-calibrated vaporizer. **A:** In the OFF position, all of the inflowing gas is directed through the bypass. **B:** In the ON position, gas flow is divided between the bypass and the vaporizing chamber. In the MAX position, all of the gas flow allowed by the vaporizer goes to the vaporizing chamber.

Electronic Vaporizers

In an electronic vaporizer, the volume of carrier gas necessary to produce the desired agent concentration may be determined by a computer that calculates the carrier gas flow that needs to pass through the vaporizing chamber in order to produce the desired anesthetic agent concentration.

Another type of electronic vaporizer withdraws a calculated amount of liquid agent from the agent bottle and injects that liquid into the breathing system or fresh gas flow. The amount of liquid that is injected is adjusted to achieve the desired anesthetic agent concentration.

Vaporization Methods

Flow-over

In a flow-over vaporizer, a stream of carrier gas passes over the surface of the liquid. Increasing the area of the carrier gas-liquid interface can enhance the efficiency of vaporization. This can be done by using baffles or spiral tracks to lengthen the gas

pathway over the liquid. Another method is to employ wicks that have their bases in the liquid. The liquid moves up the wick by capillary action. Most of the vaporizers used in anesthesia employ this vaporization method.

Injection

Certain vaporizers control the vapor concentration by injecting a known amount of liquid anesthetic into a known volume of gas.

Temperature Compensation

As a liquid is vaporized, energy in the form of heat is lost. As the liquid temperature decreases, so does the vapor pressure. Two methods have been employed to maintain a constant vapor output with fluctuations in liquid anesthetic temperature.

Mechanical Thermocompensation

Most concentration-calibrated vaporizers compensate for changes in vapor pressure with temperature changes by altering the splitting ratio so that the percentage of carrier gas that is directed through the vaporizing chamber is increased or decreased. As the vaporizer cools, the thermal element restricts the bypass flow, causing more carrier gas to pass through the vaporizing chamber. The opposite can occur if the vaporizer becomes too warm.

Supplied Heat

An electric heater can be used to supply heat to a vaporizer and maintain it at a constant temperature.

Computerized Thermocompensation

Thermocompensation may be accomplished by computer control. Two methods have been used. The amount of agent injected into the breathing system or fresh gas flow may be altered. If the vaporizer withdraws an amount of liquid from a bottle and injects it, the heat loss due to vaporization may not be important. The second method is computerized control of the amount of carrier gas that flows through the vaporizing chamber.

Effects of Altered Barometric Pressure

Most vaporizers are calibrated at sea level (4). Because they are sometimes used in hyperbaric chambers or at high altitudes where atmospheric pressure is low, it is important to have some knowledge of how they

will perform when the barometric pressure is changed. The American Society of Testing and Materials (ASTM) anesthesia workstation standard (5) requires that the effects of changes in ambient pressure on vaporizer performance be stated in the accompanying documents.

Effects of Intermittent Back Pressure

When assisted or controlled ventilation is used, the positive pressure generated during inspiration is transmitted from the breathing system back to the machine and the vaporizers. Back pressure also occurs when the oxygen flush is activated. Back

pressure may either increase (pumping effect) or decrease (pressurizing effect) the vaporizer output.

The ASTM anesthesia workstation standard (5) limits the changes in concentration from intermittent back pressure. Manufacturers are required to state in operators' manuals the extent to which back pressure affects a vaporizer's performance.

Pumping Effect

Factors

Studies have shown that concentrations delivered by some vaporizers during controlled or assisted ventilation are higher than when the vaporizer was used with free flow to atmosphere (6). This change is most pronounced when there is less agent in the vaporizing chamber, when carrier gas flow is low, when the pressure fluctuations are high and frequent, and when the dial setting is low.

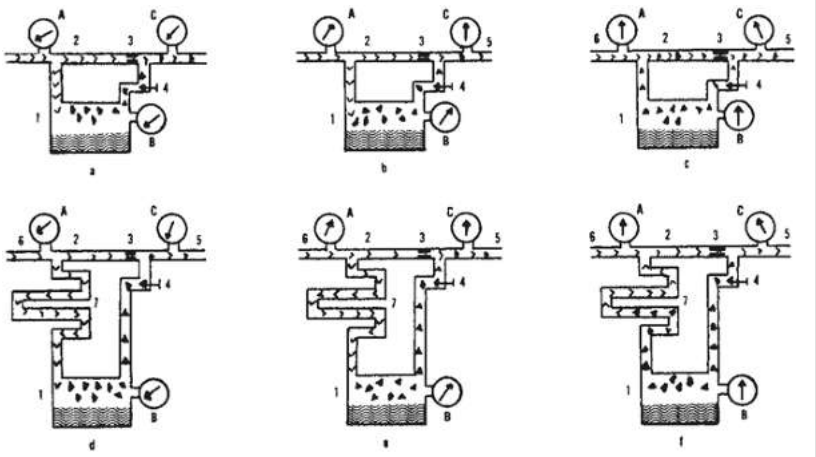

Figure 6.3 The pumping effect in a concentration-calibrated vaporizer. (See text for details.) (From Hill DW. The design and calibration of vaporizers for volatile anesthetic agents. Br J Anaesth 1968;40:656.)

Mechanisms

A proposed mechanism for the pumping effect in the concentration-calibrated variable-bypass vaporizers is shown in Figure 6.3AÎ€“C. Figure 6.3A shows the vaporizer during exhalation. The relative resistances of the outlets from the bypass and vaporizing chamber determine the flows to each (items 3 and 4 in the figure).

Figure 6.3B shows inspiration. Positive pressure at point C prevents gas and vapor outflow. Pressure is transmitted to points A and B. This results in gas being compressed in the vaporizing chamber and bypass. Because the bypass has a smaller volume than the vaporizing chamber, more gas enters the vaporizing chamber so that the normal ratio between the flow to the vaporizing chamber and that through the bypass is disturbed. The result is an increased flow to the vaporizing

chamber, which then picks up additional anesthetic vapor.

Figure 6.3C shows the situation just after the beginning of exhalation. The pressure at point C falls rapidly, and gas flows from the vaporizing chamber and the bypass to the outlet. Because the bypass has less resistance than the vaporizing chamber outlet, the pressure in the bypass falls more quickly than that in the vaporizing chamber, and gas containing vapor flows from the vaporizing chamber into the bypass. Because the gas in the bypass (which dilutes the gas from the vaporizing chamber) now carries vapor and the gas flowing from

the vaporizing chamber is still saturated, the concentration in the vaporizer output is increased.

Modifications to Minimize the Pumping Effect

Alterations to the Vaporizer

Because the increased output is related to the relative sizes of the space above the liquid in the vaporizing chamber and the space in the bypass, keeping the vaporizing chamber small or increasing the size of the bypass will decrease the effects of back pressure (2). Another method is to employ a long, spiral or large-diameter tube to lead to the vaporizing chamber (Fig. 6.3D–F). The extra gas forced into this tube and subsequently returned to the bypass does not reach the vaporizing chamber. Another method is to exclude wicks from the area where the inlet tube joins the vaporizing chamber. Finally, an overall increase in resistance to gas flow through the vaporizer may be used.

Alterations to the Anesthesia Machine

These devices (pressurizing valve, unidirectional valve, and pressure relief device) were discussed in Chapter 5. A check valve near the machine outlet but upstream of the junction with the oxygen flush offers less protection from the pumping effect than a check valve at the outlet of a vaporizer (7).

Pressurizing Effect

Factors

The output of some vaporizers used in conjunction with automatic ventilators has been found to be lower than during free flow to atmosphere (8). The effect is greater with high flows, large pressure fluctuations, and low vaporizer settings.

Mechanisms

The explanation for the pressurizing effect is shown in Figure 6.4. Figure 6.4A shows a vaporizer flowing free to atmosphere. The pressure in the vaporizing chamber and the bypass is P. As gas flows to the outlet, the pressure is reduced to R. The number of molecules of anesthetic agent picked up by each milliliter of carrier gas depends on the density of the anesthetic vapor molecules in the vaporizing chamber. This, in turn, depends on the agent's vapor pressure. The vapor pressure depends solely on the temperature and is not affected by alterations in the atmospheric pressure.

Figure 6.4B shows the situation when an increased pressure is applied to the vaporizer outlet and transmitted to the vaporizing chamber. The increased pressure will compress the carrier gas so that there will be more molecules per milliliter. The number of anesthetic vapor molecules in the vaporizing chamber will not be increased, however, because this depends on the saturated vapor pressure of the anesthetic and not on the pressure in the container. The net result is a decrease in the concentration of anesthetic in the vaporizing chamber and the vaporizer outlet.

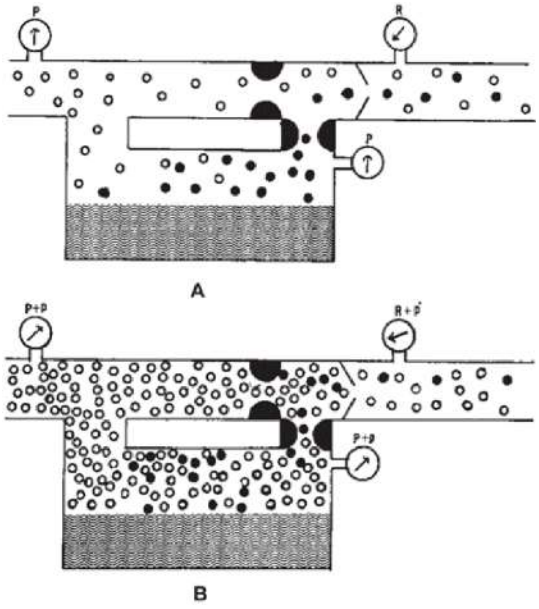

Figure 6.4 The pressurizing effect. An increase in pressure (p increase) causes an increase in pressure (p) inside the vaporizer. The vapor pressure of the volatile anesthetic is unaffected by changes in the total pressure of the gas mixture above it. As a result, the concentration is reduced.

Interplay between Pressurizing and Pumping Effects

The changes in vaporizer output caused by the pumping effect usually are greater than those associated with the pressurizing effect. The pressurizing effect is seen with high gas flows and the pumping effect at low flows.

Effects of Rebreathing

The vaporizer dial setting reflects the concentration of inhalational agent delivered to the breathing system. When the fresh gas flow is high, there may be little, if any, exhaled gas rebreathed, and the inspired concentration should be close to the vaporizer setting. As the fresh gas flow is lowered, exhaled gases contribute a more significant portion of the inspired gases. Rebreathing causes a difference between the vaporizer setting

and the inspired concentration. Also, if minute volume is

increased, there will be more rebreathing and a greater effect. With significant rebreathing, only an agent analyzer can provide an accurate value for the inspired agent concentration.

Vaporizers and Standards

An international standard covers vaporizers (9). The ASTM anesthesia workstation standard (5) contains the following provisions regarding vaporizers:

1. The effects of variations in ambient temperature and pressure, tilting, back pressure, and input flow rate and gas mixture composition on vaporizer performance must be stated in the accompanying documents.
2. The average delivered concentration from the vaporizer shall not deviate from the set value by more than ยฑ20% or ยฑ5% of the maximum setting, whichever is greater, without back pressure.
3. The average delivered concentration from the vaporizer shall not deviate from the set value by more than +30% or -20% or by more than +7.5% or -5% of the maximum setting, whichever is greater, with pressure fluctuations at the common gas outlet of 2 kPa with a total gas flow of 2 L/minute or 5 kPa with a total gas flow of 8 L/minute.
4. A system that prevents gas from passing through the vaporizing chamber or reservoir of one vaporizer and then through that of another must be provided.
5. The output of the vaporizer shall be less than 0.05% in the ĺ€OFFĺ€ or ĺ€zeroĺ€ position if the ĺ€zeroĺ€ position is also the ĺ€OFFĺ€ position.
6. All vaporizer control knobs must open counterclockwise.
7. Either the maximum and minimum filling levels or the actual usable volume and capacity shall be displayed.
8. The vaporizer must be designed so that it cannot be overfilled when in the normal operating position.
9. Vaporizers unsuitable for use in the breathing system must have noninterchangeable proprietary or 23-mm fittings. Conical fittings of 15 mm and 22 mm cannot be used. When 23-mm fittings are used, the inlet of the vaporizer must be male and the outlet female. The direction of gas flow must be marked.
10. Vaporizers suitable for use in the breathing system must have standard 22-mm fittings or screw-threaded, weight-bearing fittings with the inlet female and the outlet male. The direction of gas flow must be indicated by arrows and the vaporizer marked ĺ€for use in the breathing system.ĺ€

Concentration-calibrated Vaporizers

Tec 5

Tec 5 vaporizers are designed for use with halothane, enflurane,

isoflurane, and sevoflurane.

Construction

Tec 5 vaporizers are shown in Figure 6.5. The control dial is at the top. A release button located at the rear of the dial must be pushed in before the vaporizer can be turned ON. At the rear is a locking lever that is connected to the control dial so that the vaporizer cannot be turned ON until it is locked on the manifold. At the bottom right front is a sight glass that shows the liquid agent level in the vaporizing chamber.

Tec 5 vaporizers are available with either of two filling devices. One is a keyed system (Fig. 6.5). The filling/draining port is at the front of the vaporizer on the left near the bottom. A locking lever to secure the filler block is located on the left side of the vaporizer. A small lever at the base allows liquid to be added to or drained from the vaporizer. The other filling device is a funnel fill that has a drain plug that can be loosened to drain the vaporizer.

A schematic diagram of a Tec 5 vaporizer is shown in Figure 6.6. The internal baffle system is designed to keep liquid from reaching the outlet if the vaporizer is tipped or inverted.

When the concentration dial is in the zero position, all of the gas from the flowmeters bypasses the vaporizer through the Select-a-tec bar (Fig. 6.74). When the dial is turned past zero, inflowing gas is split into two streams by the rotary valve. One stream is directed to the vaporizing chamber, the other through the bypass.

Gas flowing through the bypass flows down one side of the vaporizer and past the thermostat, which is a bimetallic strip in the base. As the temperature in the vaporizer decreases, the thermostat permits less gas flow through the bypass so that more gas passes through the vaporizing chamber. From the thermostat, gas flows up the other side of the vaporizer and near the outlet joins the gas that has passed through the vaporizing chamber.

The gas flowing to the vaporizing chamber first passes through the central part of the rotary valve, after which it is directed through a helical channel then past a spiral wick that is in contact with the wick skirt, which dips into the liquid agent. Gas with vapor leaves the vaporizing chamber via a channel in the concentration dial rotary valve and flows to the outlet.

Evaluation

The manufacturer's performance curves are shown in Figure 6.7. Greatest accuracy is at a fresh gas flow of

P.129
P.130
P.131
P.132

less than 5 L/minute and dial settings less than 3%. At higher flows and higher dial settings, there is a decrease in output (10).

Figure 6.5 Tec 5 vaporizers. The locking lever for the filling device is on the lower left side of each vaporizer. The lever for filling-draining is at the base, below the sight glass. To fill, the bottle adaptor is inserted into the port and clamped in place by pulling the locking lever down. The bottle is then lifted up, and the filling-draining lever is pulled forward. When filling is completed, the filling-draining lever is returned to the closed position, the bottle is lowered, the clamping lever is pushed upward, and the bottle is removed. Draining of the vaporizer is accomplished by using the same levers but by lowering the bottle rather than lifting it. Behind each control dial is a locking lever in the locked position. (Courtesy of Ohmeda, a division of BOC Health Care, Inc.)

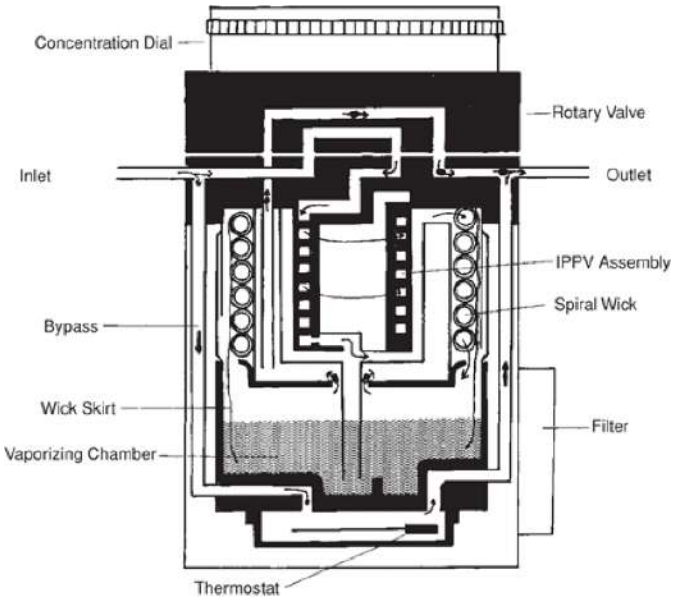

Figure 6.6 Diagram of Tec 5 vaporizer in the ON position. (See text for details.) (Redrawn from a drawing furnished by Ohmeda, a division of the BOC Health Care, Inc.)

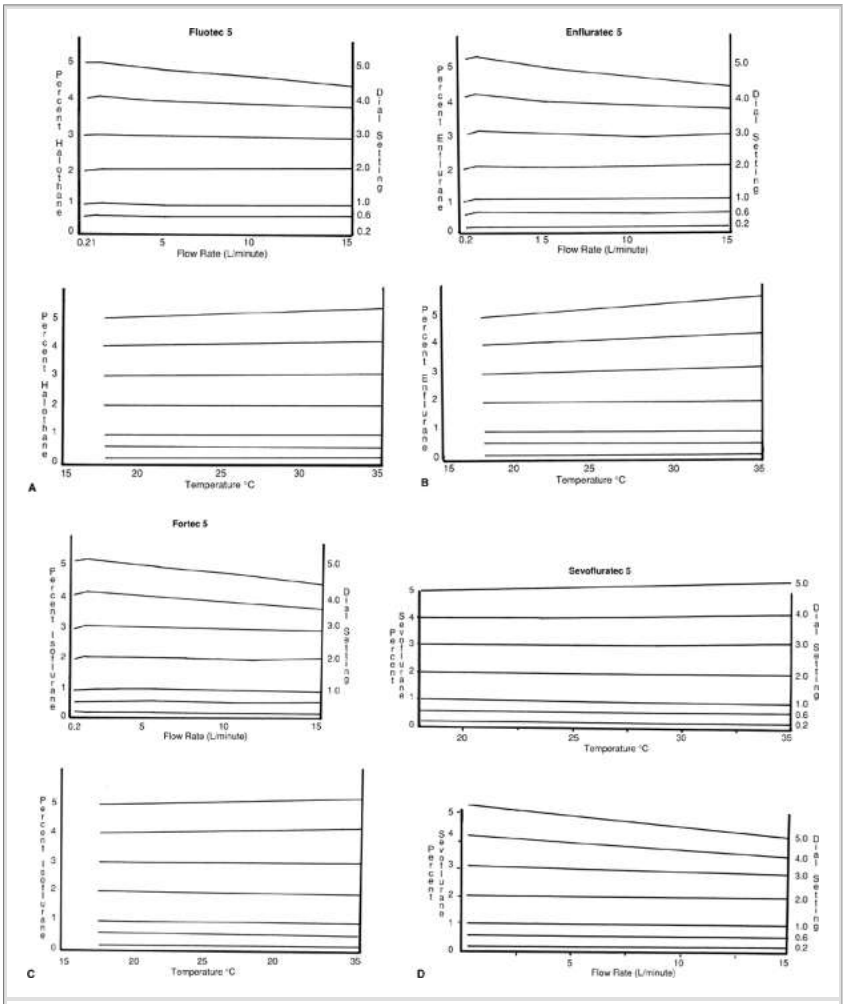

Figure 6.7 Performances of four Tec 5 vaporizers. (Redrawn from drawings furnished by Ohmeda, a division of the BOC Health Care, Inc.)

The greatest accuracy is between 15ยฐC and 35ยฐC. The thermostat does not respond to temperatures below 15ยฐC, and the output will be less than indicated on the dial. If the temperature is above 35ยฐC, the output will be unpredictably high.

The Tec 5 is prone to increases in output from the pumping effect (11). Carrier gas composition affects the output of the Tec 5 vaporizers. At low flows, the output is less when air or nitrous oxide is used than when oxygen is the carrier gas. At high flows, a small increase in output will occur.

Hazards

If the locking lever is partially loose or the filling port open, there will be a gas leak (12,13,14,15). Liquid agent may be lost if the vaporizer is fairly full.

These vaporizers can be overfilled if the bottle adaptor is loose and the control dial is in the ON position (16,17,18). Tilting the vaporizer can result in overfilling (19). This will cause the vapor output to be elevated. Reversed flow through the vaporizer results in increased output (20).

Maintenance

The exterior of the vaporizer may be wiped with a damp cloth. No other cleaning or disinfection should be attempted.

The manufacturer recommends that if the agent contains additives or stabilizing agents, the vaporizer should be drained every 2 weeks or when the level is low. If there are no additives or stabilizing agents, the vaporizer can be drained at less frequent intervals. The vaporizer should be returned to a service center every 3 years. There may be some flexibility in the recommended service frequency when agent analysis is used.

Tec 6

The Tec 6 vaporizer is designed for use only with desflurane (21,22,23).

Construction

The Tec 6 vaporizer is shown in Figure 6.8. It is somewhat larger than the Tec 5 vaporizers. The concentration dial at the top is calibrated from 1% to 18% in gradations of 1% up to 10% and 2% between 10% and 18%. A dial release at the back of the dial must be depressed to turn the dial from the standby position or to dial concentrations over 12%. This release cannot be depressed unless the operational light-emitting diode (LED) is illuminated.

The filler port is at the front on the left. It is designed so that only a desflurane-specific bottle can be inserted into it. The power cord attachment and battery case are on the bottom. The battery provides power for the alarms and liquid crystal level indicator during mains power failures. The power cord exits at the side. The vaporizer casing is warm to the touch when it is connected to the electrical supply, which will cause slight heating of adjacent equipment (24). The drain plug is located at the base. A special kit is required to drain the vaporizer.

Figure 6.8 Tec 6 vaporizer. The filler port is at the bottom left. At the bottom right are the liquid level indicator and the visual signals for monitors of

vaporizer function. A bottle of desflurane with the protection cap in place is to the left of the vaporizer. The locking lever behind the control dial is in the unlocked position. (Courtesy of Ohmeda, a division of BOC Health Care, Inc.)

On the front lower right of the vaporizer is the display panel, which has visual indicators for vaporizer functions (Fig. 6.8). With the exception of the tilt condition, there is a 10-second delay between detecting a malfunction and alarm activation. An auditory alarm is mounted behind the upper part of the display panel. An audio OFF (mute) button is located above the display panel.

The amber *warm-up* LED indicates an initial warm-up period after the vaporizer is first connected to the mains power. Once warm-up is complete, the green *operational* LED is illuminated, indicating that the vaporizer has reached its operating temperature and the concentration dial can be turned ON. A short tone sounds at the transition from warm-up to operational.

The red *no output* LED flashes and an auditory alarm of repetitive tones sounds if the vaporizer is not able to deliver vapor. This can be caused by an agent level less than 20 mL, tilting the vaporizer more than 10 degrees, power failure, or an internal malfunction. Turning the concentration dial to standby will mute this alarm and illuminate the red light.

The amber *low agent* LED accompanied by an audible alarm is illuminated if there is less than 50 mL of agent in the vaporizer. This alarm can be audio paused (muted) for 120 seconds. If less than 20 mL remain in the vaporizer, the *no output* alarm is activated.

The amber *alarm battery low* LED illuminates to indicate that a new battery is required. There is no auditory signal for this condition.

The liquid level indicator has a liquid crystal display (LCD) that indicates the amount of liquid in the vaporizer between 50 and 425 mL. The LCDs are visible whenever the vaporizer is powered. There are 20 bars. A single bar corresponds to a volume of approximately 20 mL. An arrow on the side indicates the 250 mL refill mark. If the level is below this mark, the vaporizer will accept a full bottle (240 mL) of desflurane.

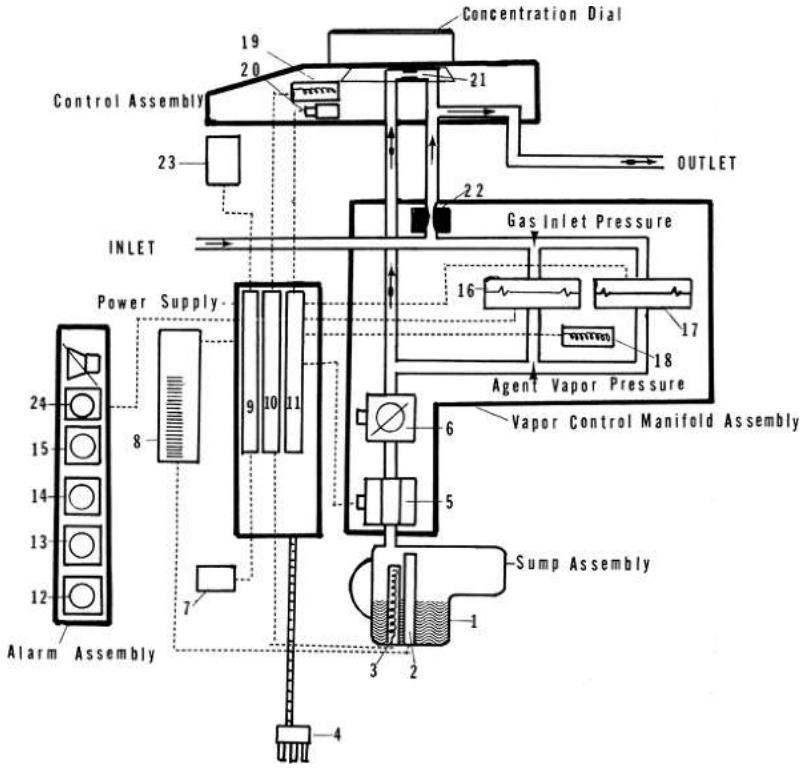

Figure 6.9 Diagram of Tec 6 vaporizer. (***1***) agent, (***2***) level sensor, (***3***) sump heaters, (***4***) electrical mains, (***5***) shut-off valve, (***6***) agent pressure-regulating valve, (***7***) battery for alarms, (***8***) LCD level display, (***9***) alarm electronics, (***10***) heater electronics, (***11***) control electronics, (***12***) alarm battery low LED, (***13***) warm-up LED, (***14***) low agent LED, (***15***) no output LED, (***16***) pressure transducer, (***17***) pressure monitor, (***18***) heater in vapor manifold, (***19***) heater in valve plate, (***20***) solenoid interlock, (***21***) variable resistor (controlled by rotary valve), (***22***) fixed restrictor, (***23***) tilt switch, (***24***) operational LED. (See text for details.) (Redrawn from a diagram furnished by Ohmeda, a division of BOC Health Care, Inc.)

When the unit is plugged in, the electronics go through a self-test. For 2 seconds, the alarm sounds, and each LED and LCD illuminates. This self-test can be repeated at any time by pressing the mute button for 4 seconds or more. Once the vaporizer is plugged in, the power is always ON, and the sump heaters are operational. Initially, the vaporizer will take 5 to 10 minutes to reach operating temperature.

The internal construction is shown in Fig. 6.9. Desflurane is heated to 39ยฐC (102ยฐF), which is well above its boiling point, by two heaters in the base. An external heat source is needed, because the potency of desflurane requires that large amounts be vaporized. In addition, the desflurane boiling point is near room temperature and depending on ambient temperature would make the output unpredictable. These factors make

thermocompensation using the usual mechanical devices impossible. A transformer and alternating current (AC) to direct

current (DC) converter provide DC power for the vaporizer.

The sump assembly holds the agent and includes the filling port, drain, heaters, and agent level sensor. It has a capacity of 425 mL. The temperature is monitored, and the associated electronics act as a thermostat. Two heaters in the upper part of the vaporizer prevent agent condensation where the warm vapor meets the cold gas from the common manifold.

The liquid agent level is sensed by a probe and sheath in the sump assembly. These measure the capacitance by using the agent as a dielectric. The display is on the front of the vaporizer.

When the proper temperature is reached, the green operational LED illuminates. A signal from the control electronics operates the solenoid interlock, allowing the dial and rotary valve to be turned. When the dial and rotary valve are turned, the shut-off valve opens.

Fresh gas flow enters the vaporizer and encounters a fixed resistor that creates back pressure. The higher the fresh gas flow, the greater the back pressure generated. Electromechanical devices maintain the agent vapor pressure at the variable resistor in the rotary valve at the same level as the fresh gas pressure at the fixed restrictor. This pressure balance between the desflurane and the diluent flow compensates for changes in temperature, vapor pressure, or diluent flow rate. The pressures are sensed by a transducer that sends a signal to the control electronics, which in turn alters the agent pressure at the variable resistor by opening or closing the agent pressure-regulating valve to balance the pressures. With this balance of pressures maintained, the concentration delivered by the vaporizer depends only on the ratio of fresh gas flow through the fixed restrictor and agent vapor flow through the variable resistor, which depends on the concentration dial setting. When the concentration dial is turned to a higher value, resistance to desflurane flow decreases and the flow of desflurane increases. With an increase in diluent flow, the electronics will increase the flow in the desflurane limb to maintain the pressure balance. The vapor mixes with fresh gas just before the latter exits the vaporizer.

The filling system is discussed later in the chapter under Desflurane Filling System (see Fig. 6.73). The vaporizer can be filled while in use, but the fresh gas flow should be less than 8 L/minute, the concentration dial set at no more than 8%, and the vaporizer should not be subjected to high back pressure. The vaporizer can be filled while it is in its warm-up cycle.

Evaluation

The manufacturer's data are shown in Figure 6.10. The vaporizer is calibrated for flows from 0.2 to 10 L/minute. The output is almost linear at the 3%, 7%, and 12% settings, with slightly lower outputs at flows less than 5 L/minute and slightly greater outputs at higher flows. The vaporizer is designed to be used at ambient temperatures between 18ยฐC and 30ยฐC. Studies have shown that the output is within ยฑ15% of the dial setting. Tilting does not render the vaporizer inoperative or dangerous to operate (25). Nitrous oxide in the carrier gas decreases the output slightly.

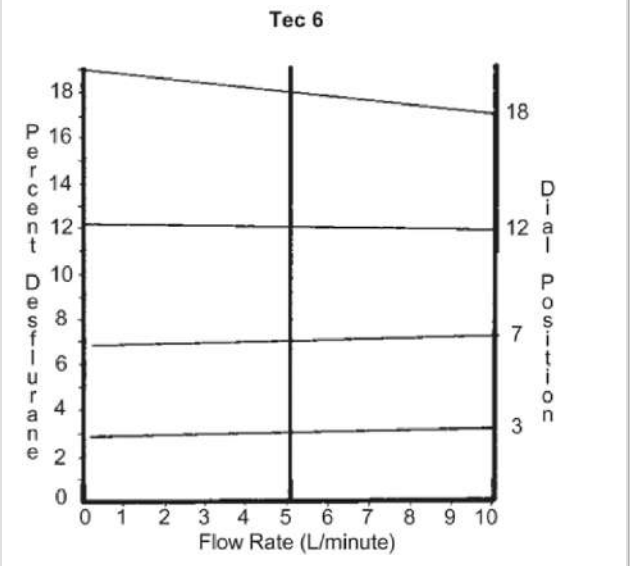

Figure 6.10 Performance of Tec 6 vaporizer, with oxygen as the carrier gas. (From a graph furnished by Ohmeda, a division of BOC Health Care, Inc.)

Fluctuating back pressure does not significantly affect the Tec 6 vaporizer output. Carrier gas composition affects vaporizer output (25,26,27,28). The output is decreased with air or nitrous oxide as the carrier gas.

Electricity consumption by the vaporizer is low (29). The battery must be replaced annually.

Hazards

Vapor can leak into the fresh gas with the vaporizer turned OFF.

When filling the vaporizer, the bottle must be gripped tightly when it is rotated downward. If not gripped tightly, the bottle may be dropped when it is released under pressure at the lower position.

A case has been reported where a valve piston in the attachment stuck in the depressed position, causing a large leak of fresh gas (30). Other vaporizers mounted on the machine could not be turned ON.

If the Tec 6 is used on an anesthesia machine that turns OFF the fresh gas flow during inspiration (fresh gas decoupling; Chapter 12), the intermittent flow will trigger an alarm if the software to avoid this problem is not in place (31,32,33).

Cases of sparks and smoke around the connection between the mains power cord and the socket have been

reported (34). This was believed to be the result of a loose plug.

The Tec 6 should be mounted on the far right-hand side on the back bar of the anesthesia machine (35). In other positions, the

power cord may interfere with the vaporizer interlock mechanism for the other vaporizers (36,37).

Leaks have been reported with this vaporizer (38).

Two cases of cardiac arrest secondary to a massive overdose caused by a defective control valve have been reported (39).

Maintenance

This vaporizer requires servicing every year at an authorized center. The external surface may be wiped by using a cloth slightly dampened with a cleaning agent. No other cleaning or disinfection should be attempted.

Tec 7

There are Tec 7 vaporizers for halothane, enflurane, isoflurane, and sevoflurane.

Construction

A Tec 7 vaporizer is shown in Figure 6.11. On top is the concentration control dial. At the rear of the dial is a release button that must be pushed in before the vaporizer can be turned ON. At the rear is a locking lever that is connected to the control dial so that the vaporizer cannot be turned ON until it is locked on the manifold. At the bottom right front of each vaporizer is a sight glass that indicates the liquid level in the vaporizing chamber.

Figure 6.11 Tec 7 vaporizer with Easy-Fil system. Note the locking lever behind the control dial. The interlock device can be seen near the back on the right of the vaporizer. (Courtesy of Datex-Ohmeda, a division of General Electric.)

Figure 6.12 Back of Tec 7 vaporizer. The rectangle at the lower right is the identification label. At the top is the locking lever. Note the interlock connectors at either side.

The back of the vaporizer is shown in Figure 6.12. A vaporizer identification label is affixed to the back. An anesthesia system fitted with a vaporizer identification unit uses this label to identify the vaporizer.

Although there are a number of improvements in this vaporizer compared with the Tec 5, the schematic diagram of the Tec 7 vaporizer is essentially the same as for the Tec 5 (Fig. 6.6). Tec 7 vaporizers are available with three filling devices: a funnel filler, the Quik-Fil, or the Easy-Fil system (Fig. 6.11).

Approximately 300 mL of liquid is needed to fill a vaporizer with dry wicks. Approximately 75 mL is retained in the wicks when the vaporizer is drained.

Evaluation

The manufacturer's performance curves are similar to those of the Tec 5 (Fig. 6.7). Greatest accuracy is at a fresh gas flow of 5 L/minute and dial settings less than 3%. At higher flows and higher dial settings, there is a decrease in output below the set value.

The greatest accuracy is between 15ยฐC and 35ยฐC. The thermostat does not respond to temperatures below 15ยฐC, and the output will be less than indicated on the dial. If the temperature is above 35ยฐC, the output will be unpredictably high.

Changes in barometric changes are compensated for automatically. Fluctuating back pressure can affect the vaporizer and increase the delivered concentration.

When air or nitrous oxide is part of the carrier gas, the output is lowered compared with the output when oxygen is the carrier gas. The effect is greatest during low flow rates and low dial

settings. The effect is greatest (up to 20% of setting) at low flows when nitrous oxide is used.

If the anesthesia machine and vaporizer are out of service for a period of time without gas flowing, low concentrations of the agent may be detected at the machine outlet immediately after the gas flow is turned ON. When the vaporizer is turned ON after a period of nonuse, a high concentration of agent may be delivered for approximately 10 seconds.

Hazards

The Tec 7 vaporizers are intended to be operated in the upright position. If a vaporizer is inverted, it should be connected to a scavenging system, the dial set to 5%, and the vaporizer purged with carrier gas at 5 L/minute for 5 minutes.

Figure 6.13 Aladin cassette vaporizer in place. The cassette fits into a recess on the front of the anesthesia machine. It can be removed by squeezing the handle. The concentration dial is to the left of the cassette. The wheel on the left of the cassette is used to lock the keyed filler in place and open the inlet to the vaporizer. The liquid level indicator is at the bottom near the center of the cassette. To its left is the keyed filling receptacle.

The vaporizer could be overfilled if it is not filled in the upright position. The dial must not be turned ON during filling to prevent overfilling.

Maintenance

The halothane vaporizer should be drained every 2 weeks when the level is low and the liquid discarded if there are additives or stabilizing agents. Other vaporizers should be drained once a year. Three years from the date of purchase and every 6 months thereafter, the vaporizers should undergo a safety inspection and the output checked.

The external surfaces can be cleaned with a moist cloth and neutral detergent. The cleaning agent must not be allowed to accumulate in the filler, the gas inlet, or outlet ports or around the control dial.

Aladin Vaporizer

The Aladin vaporizer is designed for desflurane, isoflurane,

sevoflurane, halothane, and enflurane.

Construction

The vaporizer consists of two parts. The electronic control mechanism is in the anesthesia machine. The agent is in a portable cassette that is inserted into a slot in the anesthesia machine.

The concentration dial is on the anesthesia machine next to where the cassette is placed (Fig. 6.13). A magnetic sensor identifies the cassette. A green LED on the front panel beside the agent wheel is used to indicate that the vaporizer is turned ON. On the display screen (Fig. 6.14), the agent is identified by name and color code and the setting in numbers and on a triangular graph.

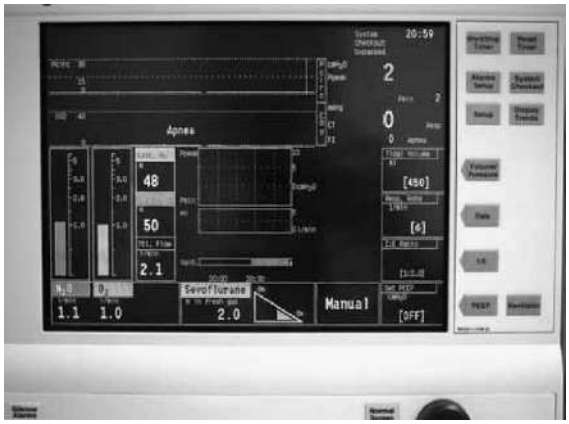

Figure 6.14 Display screen showing the agent and setting at the bottom in the center. The agent is identified in text and color code. The setting is in numerals and a triangular graph.

The cassette is shown in Figures 6.15 and 6.16. It is color coded for the agent that it is designed to contain and is magnetically coded so that the machine can automatically identify which cassette has been inserted. A handle on the front is used to carry the cassette and to insert it into and remove it from the machine. There is a release on the inside of the handle that when squeezed releases the cassette from the machine. It can be transported and stored in any position.

The cassettes for halothane, enflurane, and isoflurane have keyed fillers or the Easy-fil system. Sevoflurane cassettes may be equipped with either a keyed filler or the Quik-Fil system. A lock-and-fill wheel on the left locks the keyed filler in place and opens the air vent and liquid filling channel. The desflurane cassette has a filling system similar to the one on the Tec 6 vaporizer (Fig. 6.17). The liquid level indicator and the filling port are located on the front. The cassette holds up to 250 mL when full. When the ball in the sight tube is at the bottom, the cassette contains 80 mL or less. The liquid level may also be

displayed on the machine. When only 10% of liquid remains in the cassette, an alarm message appears.

The internal construction is shown in Figure 6.18. Fresh gas enters the vaporizer and is split between the bypass flow that is in the machine and the vaporizing chamber. Sensors in the vaporizing chamber outlet and bypass monitor the flow through each. Wicks in the vaporizing chamber increase the surface area. A check valve in the inlet to the vaporizing chamber protects against agent backflow into the bypass. The flow at the outlet of the vaporizing chamber is controlled by the central processing unit (CPU) in the anesthesia machine. This receives information, including the fresh gas composition, anesthetic agent, dial setting, temperature in the rear of the cassette, and flow. This information is used to determine the ratio of gas flow through the bypass and the vaporizing chamber. A mixing chamber stabilizes the output and reduces the effects of back pressure fluctuations.

Inside the vaporizing chamber, metal plates increase heat capacity, heat conductivity, and vaporizing surface, all of which improve temperature stability and vaporization. When cassette temperature decreases to less than 18ยฐC, a fan below it is activated to facilitate heat transfer to the vaporizer.

When the cassette is removed, two spring-loaded valves automatically close the channels to and from the vaporizer. When the cassette is inserted into the machine, these valves open to make the connections with the inflow and outflow channels. In error situations, the

valves operate to cut off anesthetic agent delivery. A pressure relief valve opens to the scavenging line if a high pressure is detected in the cassette or the liquid level measuring device detects overfilling.

Figure 6.15 Aladin cassette vaporizer. The handle is used to transport the vaporizer, which can be held in any position. Inside the handle is a release that when squeezed will release the cassette from the machine. The cassette is color coded for the agent contained.

If the cassette pressure is higher than the pressure distal to the cassette outflow, the vaporizer starts to work as an injector.

A locking mechanism holds the cassette in the slot on the machine. The connection is automatic when the cassette is pushed into position. The cassette is unlocked by squeezing the

handle.

The control dial (Fig. 6.13) is turned to set the concentration. The setting is displayed on the anesthesia machine screen (Fig. 6.14).

During filling, the cassette must be on a level surface or in its slot without being locked. The keyed filler is screwed firmly onto the bottle and then inserted into the filling port. The filler is locked in place by turning the lock-and-fill wheel on the left fully clockwise (Fig. 6.15). There will be a slight resistance when the filling port is opened. The bottle is turned upside down. Liquid should then flow into the cassette. When the vaporizer is filled, the bottle is rotated downward and the keyed filler released by turning the lock-and-fill wheel counterclockwise. The filler is then removed from the filling port.

Figure 6.16 Back of Aladin cassette vaporizer. A magnetic identification system is used by the anesthesia machine to determine which cassette is in place.

Figure 6.17 Aladin cassette vaporizer for desflurane.

Evaluation

The manufacturer indicates that the accuracy for all agents is ยท10% of the setting or ยท3% of the maximum dial setting (whichever is greater) with fresh gas flows from 200 mL/minute to 8 L/minute. Figure 6.19 shows variations in output with changes in fresh gas composition. One study found that the

output remained within 10% of the dial concentration with most commonly used fresh gas flows (40). Desflurane vaporizer accuracy was slightly less and accuracy with all anesthetics decreased at the extremes of fresh gas flow. The effects of sudden changes in fresh gas flow or carrier gas composition, back pressure, and tipping were minimal. If the temperature falls below 20ยฐC or the fresh gas flow is over 8 L/minute, the vaporizer may be unable to produce high concentrations and the messages *insufficient agent* and *decreased flow* will appear on the machine.

The delivered concentration will increase with a decrease in ambient pressure. Inaccurate output may occur briefly if the temperature of the liquid agent added to the cassette is considerably lower than the normal operating temperature.

Hazards

The cassette is fitted with an overfill protection mechanism. If air is allowed into the agent bottle, this mechanism is deactivated. This may result in overfilling and anesthetic overdose.

Turning the vaporizer ON while filling may pressurize the cassette and cause liquid to leak at the filling port.

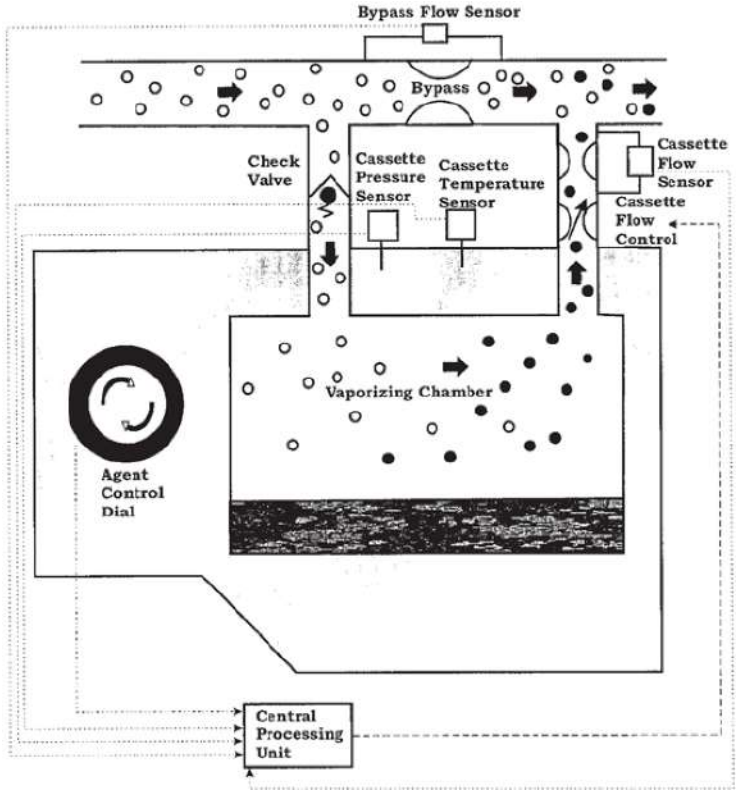

Figure 6.18 Diagram of Aladin cassette vaporizer. (See text for details.)

When the fresh gas flow is lowered, the one-way valve that prevents backflow of saturated vapor from the cassette toward the bypass channel may fail to close, resulting in high delivered concentrations (41). This problem may be more significant when desflurane is used.

Maintenance

The cassette surface can be cleaned with a cloth moistened in a mild soap solution. The cassette should be emptied before sending it to a service center.

Vapor 19.1, 19.3

The Vapor 19.1 vaporizors are designed for halothane, isoflurane, sevoflurane, and enflurane.

Construction

The Vapor 19.1 is shown in Figure 6.20. The ĺ€0ĺ€ must be depressed before the concentration dial can be turned. A filling spout, sight glass, and drain are located at the bottom.

The Vapor 19.1 is shown schematically in Figure 6.21. In the OFF position, the vaporizing chamber inlet and outlet are interconnected and vented to the outside. This prevents anesthetic agent from leaking into the fresh gas. Fresh gas passes directly through the inlet port and ON-OFF switch to the outlet port without entering the interior of the vaporizer (42).

In the ON position, at dial settings above 0.2%, incoming gas is diverted past the bypass cone to the lower vaporizing section. Part of the fresh gas flows through a pressure compensator that is designed to prevent

pressure fluctuations upstream or downstream of the vaporizer from affecting the output. Part of the fresh gas then flows to the vaporizing chamber, where it becomes saturated. The gas that passes through the vaporizing chamber exits past a control cone that is controlled by the concentration dial. As the concentration is increased or decreased, the space between the cone and its housing increases or decreases, allowing more or less gas-containing agent to leave the vaporizing chamber. The gas not flowing to the vaporizing chamber is routed past the bypass cone, where it mixes with gas from the vaporizing chamber and flows to the vaporizer output. The brass shell around the bypass cone contracts and expands with changes in temperature. If the vaporizing chamber cools, the shell will contract and the bypass cone will move upward, reducing the flow through the bypass and increasing the flow through the vaporizing chamber (42A,43).

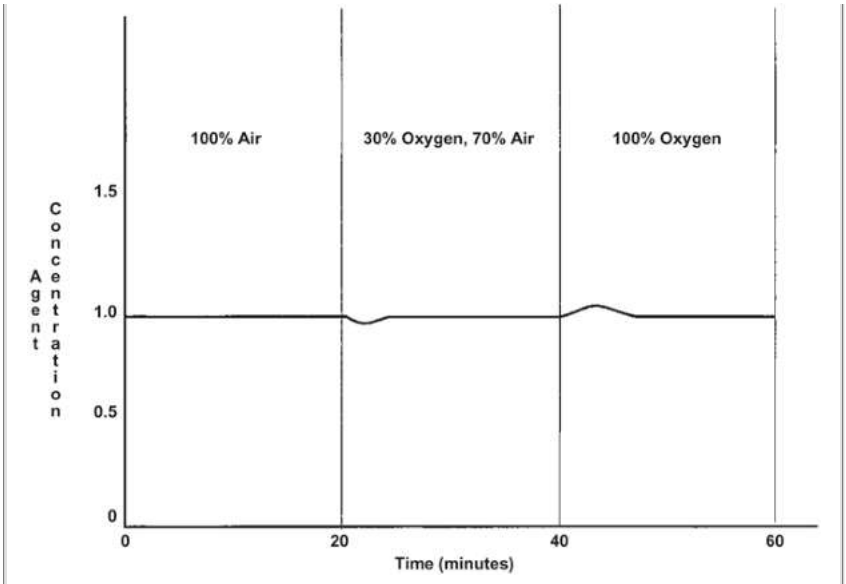

Figure 6.19 Output of Aladin cassette vaporizer with changes in fresh gas composition. The electronic control unit in the machine makes adjustments for changes in fresh gas composition to maintain a steady output.

Figure 6.20 Vapor 19.1 vaporizer. (Courtesy of North American Drager.)

The 19.3 version of this vaporizer is similar to the 19.1 but has a mounting adapter that will attach to a plug-in system. This is a quick release device similar to, but not interchangeable with, the Select-a-tec mounting system.

Evaluation

The manufacturer's data for the Vapor 19.1 are shown in Figure 6.22. Output is independent of fresh gas flow in the range of 0.3 to 15 L/minute with lower dial settings, but

with high gas flows output falls. An accuracy of ยฑ10% can be expected between 10ยฐC and 40ยฐC. At temperatures outside this range, the vaporizer will be less accurate. Investigations of Vapor 19.1 vaporizers for isoflurane, enflurane, sevoflurane, and halothane with high and low flows found that they perform accurately (44,45).

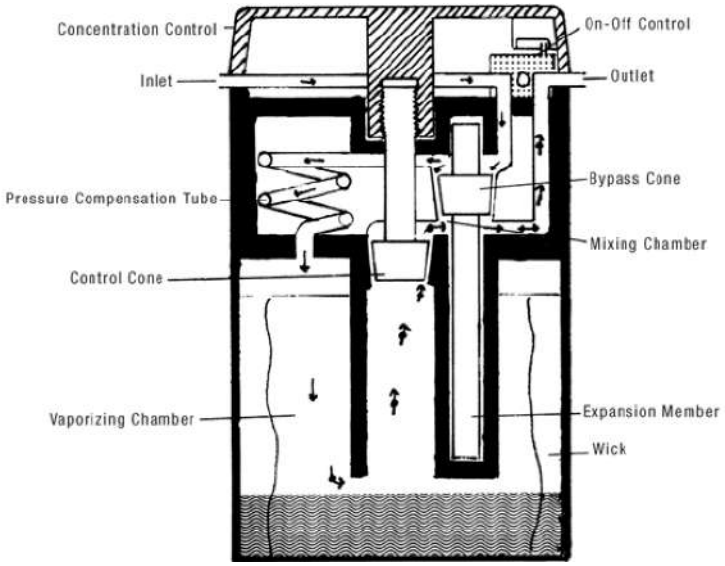

Figure 6.21 Vapor 19.1 vaporizer in the ON position. (See text for details.) (Redrawn from a drawing furnished by North American Drager.)

The Vapor 19.1 is calibrated by using air as the carrier gas. With 100% oxygen, the delivered concentration is 4% to 10% higher than the set concentration (44,46). When operated with 30% oxygen and 70% nitrous oxide, the delivered concentration is 5% to 10% lower. Changing from 66% nitrous oxide in oxygen to 100% oxygen results in an increase in output followed by a decrease (47). If helium is in the carrier gas, the output does not vary by more than ยฑ10% (48,49).

When the vaporizer was exposed to pressures up to 4 atm, the output decreased with increasing pressure but remained within 20% of setting (50).

Mounting the vaporizer on a moving trolley or reversed flow through it has no effect on output (20,51).

The Vapor 19.1 with a keyed filler will not overfill, even when the vaporizer is in the ON position and the bottle adaptor is loosened (52).

Hazards

If a filled Vapor 19.1 is tilted, liquid agent may spill into the control device whether the vaporizer is turned ON or OFF. This can result in either an increase or decrease in delivered concentration. If the vaporizer is tipped more than 45ยฐ, it

should be flushed with a flow of 10 L/minute with the concentration dial at the highest setting for at least 20 minutes.

A case has been reported where a rubber fragment obstructed the liquid level indicator (53). This gave the appearance of a liquid level although the vaporizer was empty.

When this vaporizer is equipped with a keyed filling device, a metal plug is used to seal the filling port (Fig. 6.62). There is also a vent on the top of the filler block. If the vent is not closed or the plug is not securely placed in the key filler, there will be a significant gas leak when the vaporizer is turned ON. Unlike some other vaporizers that fill below the liquid level, there will not be an escape of liquid anesthetic.

Maintenance

The outer part of the vaporizer can be cleaned with a damp cloth soaked with detergent. The manufacturer recommends that the halothane vaporizer be rinsed with fresh halothane when the liquid in the sight glass shows discoloration or particles.

The vaporizer should be inspected by trained personnel every 6 months. The vaporizing chamber should be cleaned and the wicks changed every 2 years.

Vapor 2000

The Vapor 2000 is designed for isoflurane, sevoflurane, halothane, and enflurane.

Construction

Vapor 2000 vaporizers are shown in Figures 6.23 and 6.24. The ĺ€0ĺ€ button on the handwheel (control dial) must be depressed to turn the vaporizer ON. To the right of the

OFF position is the ĺ€Tĺ€ (transport) position. This is used when the vaporizer is to be removed from the anesthesia machine. When the handwheel is turned to this position, the button locks in place.

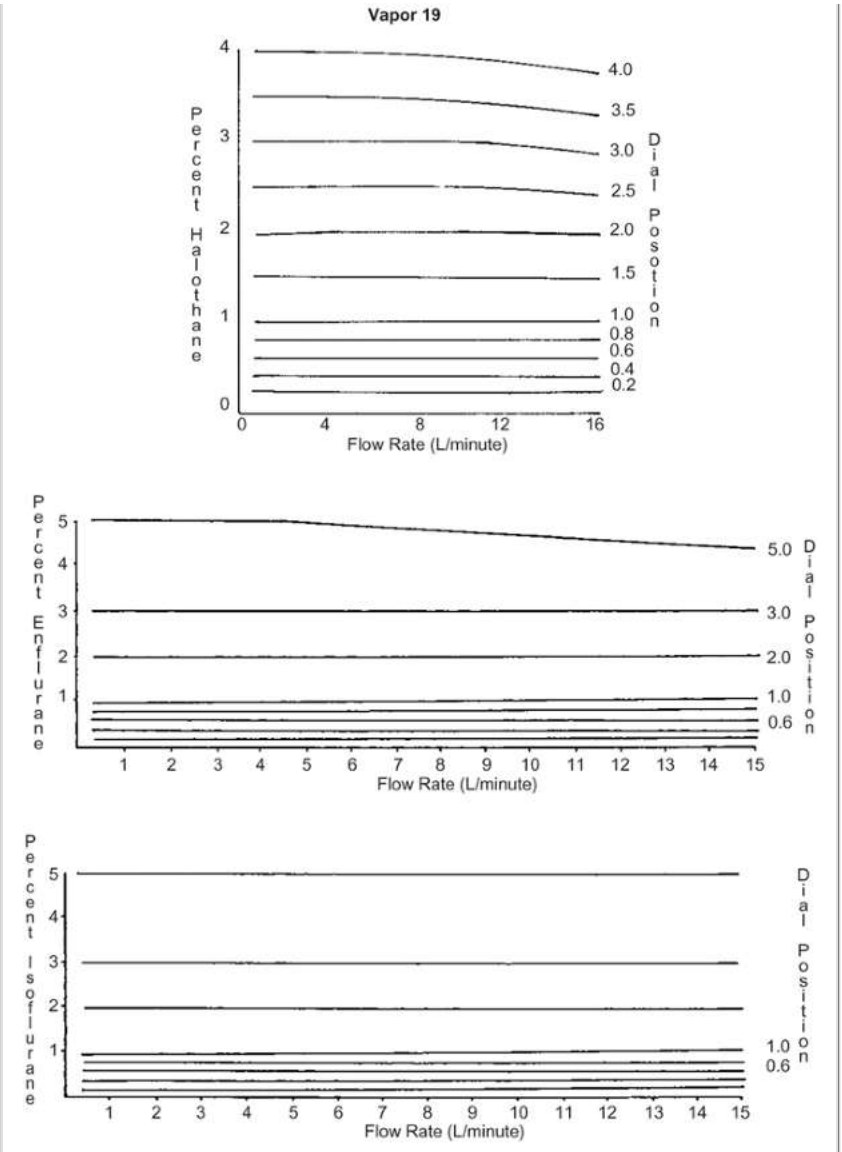

Figure 6.22 Output of Vapor 19.1 vaporizers at an ambient temperature of 22ยฐC. (Redrawn from graphs furnished by North American Drager.)

An adapter at the back of the vaporizer has holes that match pins on the anesthesia machine. The vaporizer is secured/released by turning the locking lever at the top. A pin on the locking lever must engage a groove in the top of the handwheel to release the vaporizer. This can be done only when the handwheel is at the โ€Tโ€ setting.

There are two interlock systems to prevent more than one vaporizer being turned ON at the same time. For systems in which the vaporizer is easily removable, there is a slide lever that causes a shaft to engage a hole in the

unused vaporizer handwheel that then cannot be used (Figs. 6.23, 6.24). For permanently mounted vaporizers, there is a rocker-style lever that engages a groove in the back of the handwheel. If one end is in this groove, the handwheel cannot be rotated and the vaporizer cannot be used (see Figs. 6.77, 6.78).

Figure 6.23 Vapor 2000 vaporizers. The left vaporizer has a funnel filler. The right vaporizer has a keyed filling system. Note the locking levers at the top. An interlock mechanism is between the two vaporizers at the top. The lever is turned toward the vaporizer in use.

Figure 6.24 View of Vapor 2000 vaporizers from the top. The ſ€0ſ€ button on the handwheel (control dial) must be depressed to turn the vaporizer ON or to put it into the transport position. To the right of this is the ſ€Tſ€ (transport) mark. When the handwheel is turned to this position (left vaporizer), the lever at the back of the vaporizer fits into the groove on the top of the dial so that the dial cannot be moved. The vaporizer can then be removed.

Three different filling systems are available. A simple funnel is available (Fig. 6.23, left vaporizer). There is also a keyed filling device similar to that available on other vaporizers (Fig. 6.23, right vaporizer). Sevoflurane vaporizers may have a Quik-Fil system. A drain is located under the vaporizer. The Quik-Fil system has a drain under the filler. The drain valve is opened by inserting a 2.5-mm Allen key and turning it counterclockwise.

The Quik-Fil system is discussed later in this chapter (see Figs. 6.66,6.68,6.69)

The internal vaporizer construction is shown in Figures 6.25, 6.26, and 6.27. When the vaporizer is turned OFF (Fig. 6.25), the inflowing gas passes through two bypasses. Part of the gas flows around the flow control cone. Two isolation valves (A and B) separate the vaporizing chamber from the bypass gas stream. The vaporizing chamber is vented to the outside through isolation valve A to prevent pressure buildup, thus preventing a vapor surge when the vaporizer is turned ON.

When the handwheel is turned to the transport position (Fig. 6.26), isolation valves A and B seal the vent channel as well as both channels to the vaporizing chamber. Another isolation valve (C) seals the bypass channel around the concentration cone.

When the handwheel is turned ON and set to a concentration greater than 0.2% (Fig. 6.27), isolation valve C closes one bypass and isolation valves A and B are opened, allowing a stream of gas to pass through the vaporizing chamber. The vent is closed. The stream of gas that passes through the vaporizing chamber bypass passes the temperature-compensation mechanism. As the vaporizer cools, the bypass channel is narrowed and more gas passes through the vaporizing chamber. The remainder of the gas passes through the vaporizing chamber. An elongated channel to the vaporizing chamber

reduces the pumping effect. The vapor-saturated carrier gas then passes through the isolation valve and past the flow control cone, where it joins the bypass gas and flows to the vaporizer outlet.

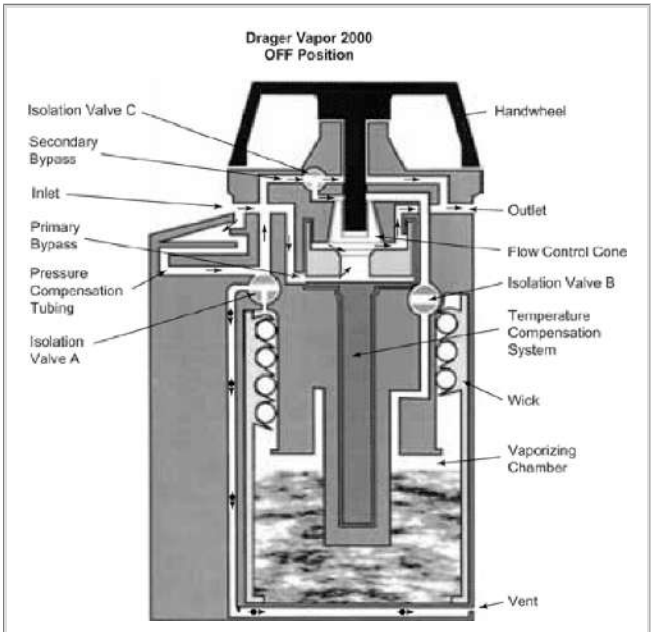

Figure 6.25 Vapor 2000 vaporizer in OFF position. (Redrawn from graphs furnished by Drager Medical.)

Evaluation

The performance data supplied by the manufacturer are illustrated in Figures 6.28 to 6.31. Some variation in vaporizer output occurs, mostly at higher settings, higher flows, and temperature extremes. While the vaporizer can compensate for cooling that occurs as the vaporizer is used, after a certain running time, the vaporizer stabilizes at a slightly lower temperature and delivers concentrations that deviate slightly from the set value. Altitude changes between 700 and 1100 mbar will cause only minor deviations in output.

The Vapor 2000 is calibrated by using air. One hundred percent oxygen will cause an increase in the output by a maximum of 10% but no more than 0.4 vol % (Fig. 6.32). A 30:70 ratio of oxygen and nitrous oxide will lower the output by the same amount.

Hazards

The vaporizer must be upright and secured while being filled. Overfilling can occur if the vaporizer is tilted during filling. If this happens, the vaporizer may deliver concentrations that are too high or too low. If the vaporizer is tilted more than 30ยฐ, anesthetic agent may escape into the fresh gas, causing a high concentration to be delivered.

The output is not defined in the area between 0% and 0.2%. The handwheel should not be set in this area.

The vaporizer should not be left in the ON position with no gas flow through it, because agent may accumulate in the anesthesia machine.

Leakage in the keyed filling system has been reported (54,55). This was thought to be the result of using oversized filling adaptors that damaged the sealing component or excessive pressure on the filling device lever that brought the lever mechanism out of alignment. When this problem occurs, there is a strong smell of agent near the vaporizer and reduced or no output from the vaporizer. This problem may be corrected on more recent versions of the vaporizer.

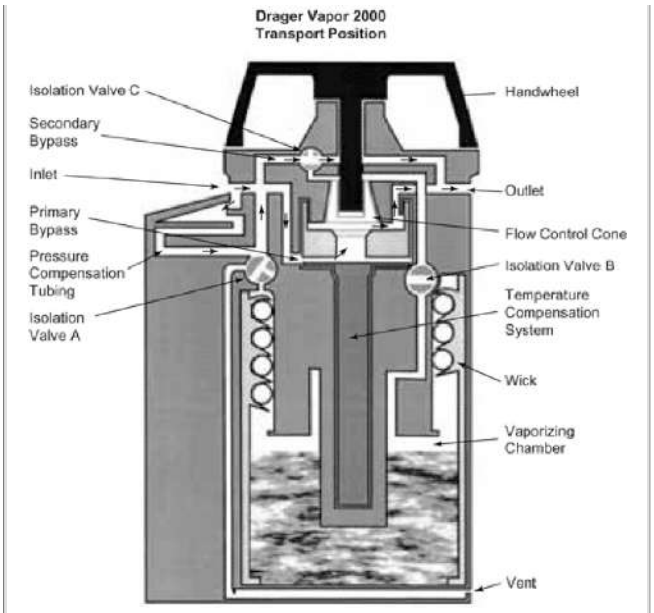

Figure 6.26 Vapor 2000 vaporizer in transport position. (Redrawn courtesy of Drager Medical.)

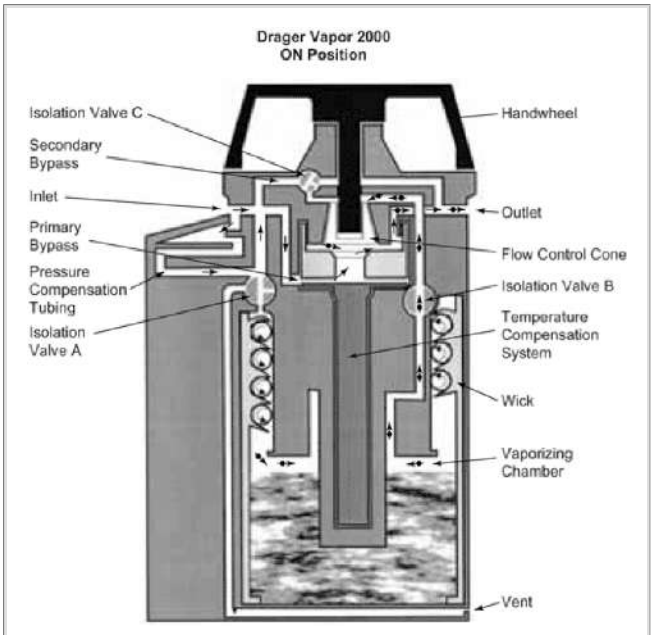

Figure 6.27 Vapor 2000 vaporizer in ON position. (Redrawn courtesy of Drager Medical.)

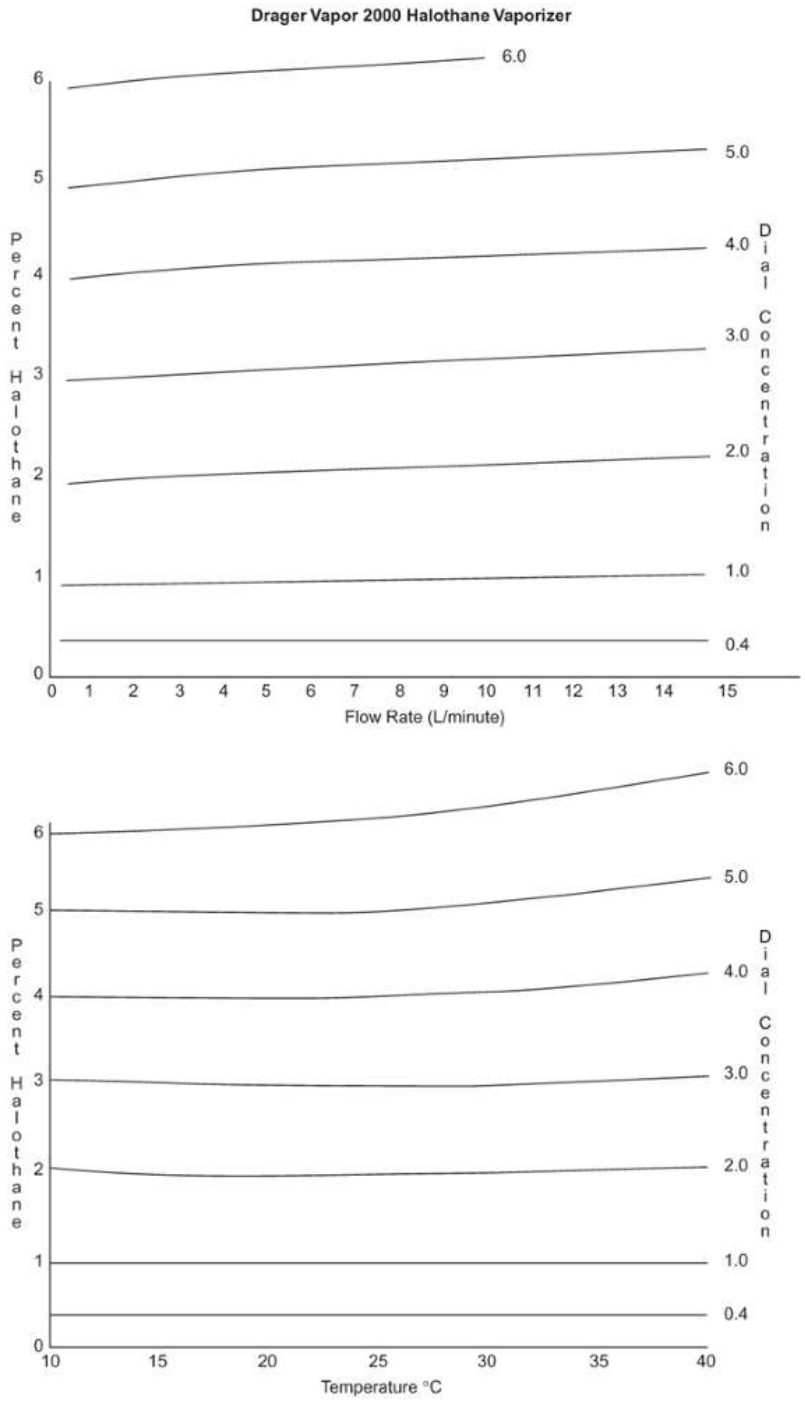

Figure 6.28 Performance of halothane Vapor 2000 vaporizer. (Redrawn from graphs furnished by Drager Medical.)

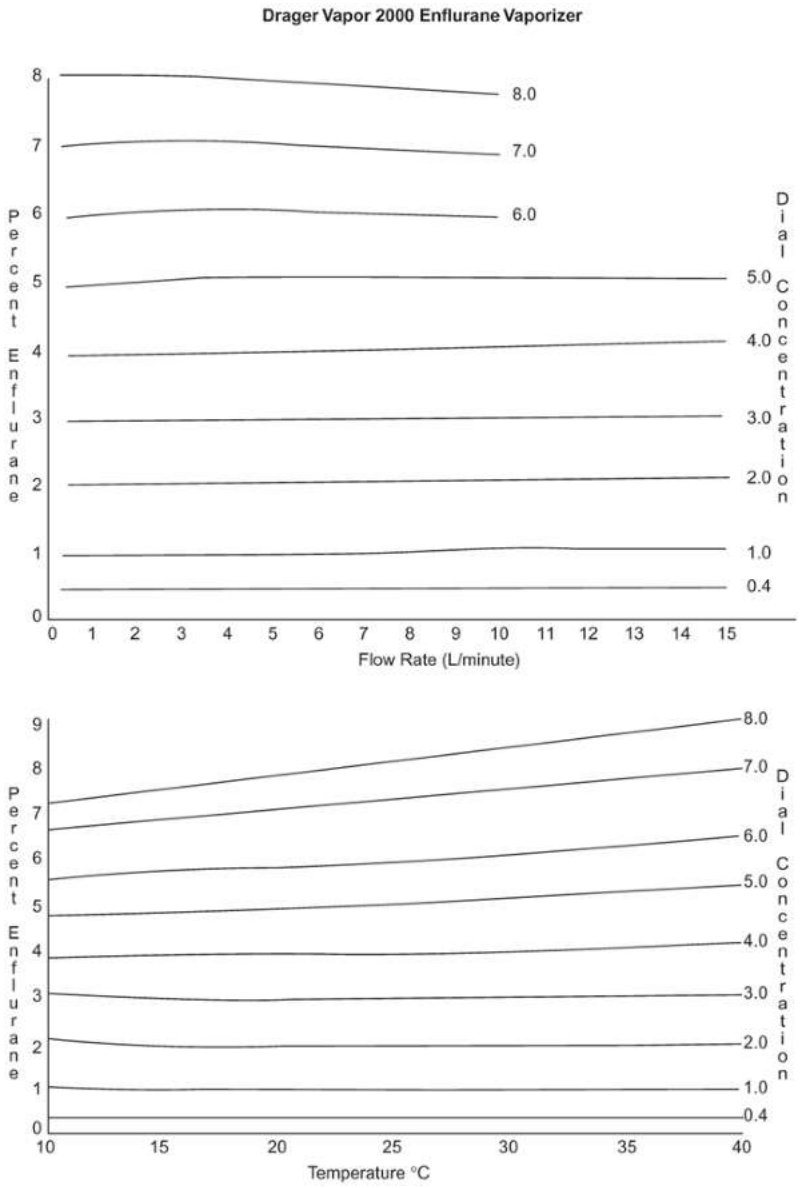

Figure 6.29 Performance of enflurane Vapor 2000 vaporizer. (Redrawn from graphs furnished by Drager Medical.)

If the connection between the filling adapter and the agent bottle is not leak tight, the vaporizer can be overfilled and anesthetic agent vapor can escape.

If flow through the vaporizer is reversed, the delivered concentration will be incorrect and often too high.

Maintenance

The external parts of the vaporizer can be wiped with a disposable cloth soaked with cleaning solution. Halogen-

releasing compounds, strong organic acids, and oxygen-releasing compounds are not suitable.

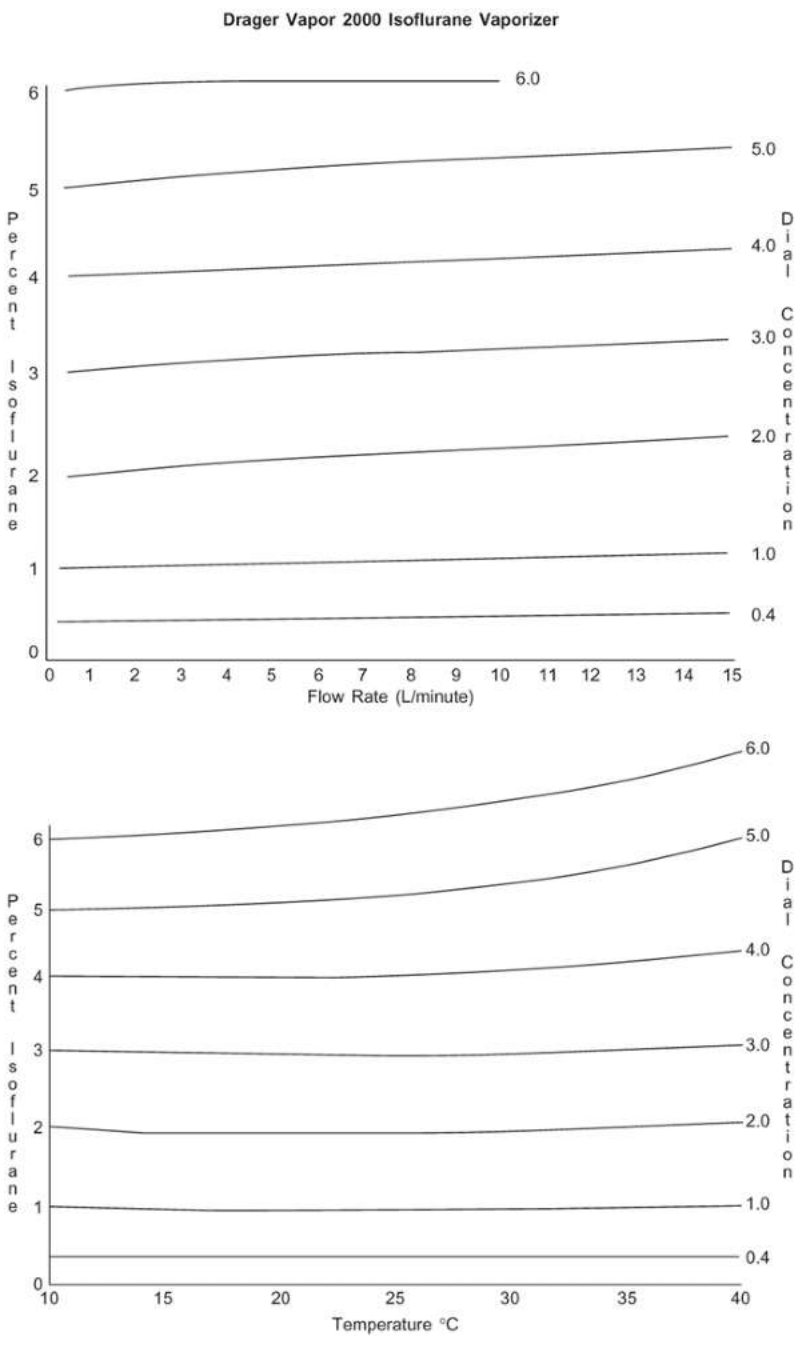

Figure 6.30 Performance of isoflurane Vapor 2000 vaporizer. (Redrawn from graphs furnished by Drager Medical.)

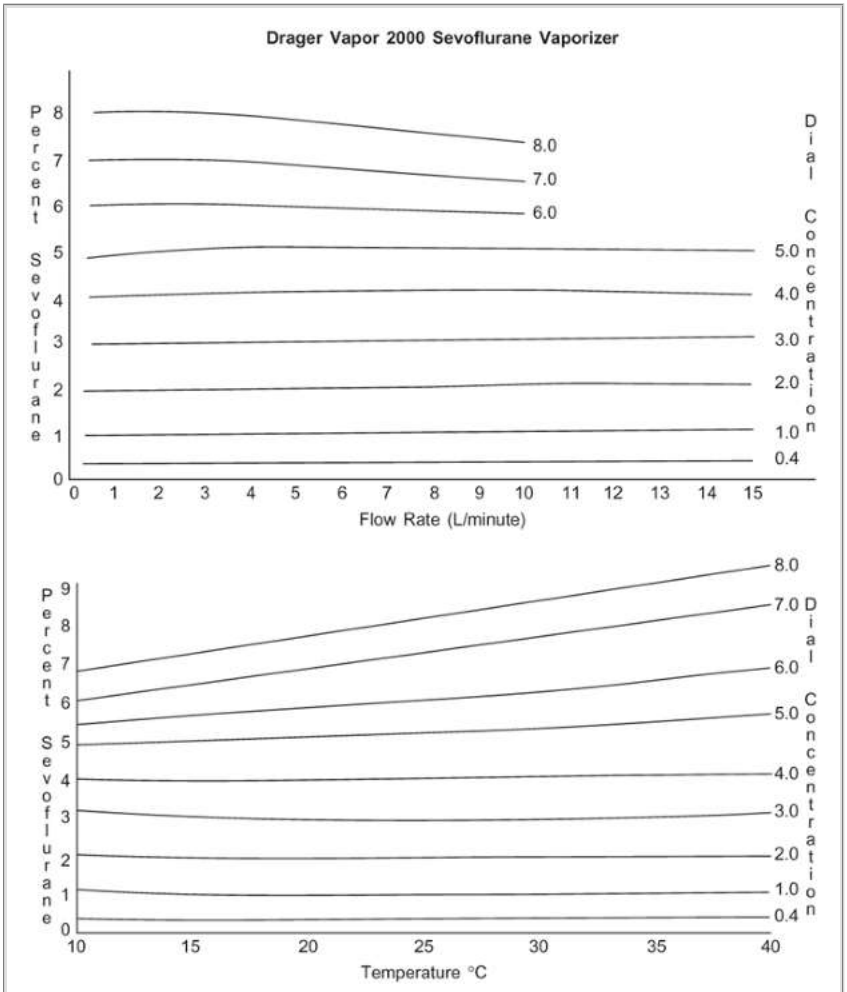

Figure 6.31 Performance of sevoflurane Vapor 2000 vaporizer. (Redrawn from graphs furnished by Drager Medical.)

The vaporizer should be inspected every 6 months by trained service personnel. The calibration should be checked weekly if the concentration is not continuously monitored.

Drager D-Vapor

The Drager D-Vapor is only for desflurane.

Construction

The D-Vapor is shown in Figure 6.33. The power cable is connected to the vaporizer at the rear. The control dial on the top is used to switch the vaporizer ON or OFF, put it in the transport position, and adjust the delivered agent concentration. Pushing the ĺ€0ĺ€ button on the front of the dial allows the dial to be rotated. The control dial locks in the zero (ĺ€0ĺ€) and transport (ĺ€Tĺ€) positions.

The concentration range is 2% to 18%. Concentrations higher than 12% are shown in inverted order. The ‵€0‵€ button on the control dial must be depressed to allow access to this high concentration range.

When the vaporizer must be removed from the anesthesia machine, the ‵€0‵€ button is depressed, and the concentration dial is moved to the ‵€T‵€ position. This allows the vaporizer to be transported in any position. A locking lever at the rear of the vaporizer is used to disengage the vaporizer from its mounting.

The D-Vapor filling system (Saf-T-Fil System) (Fig. 6.33) is located on the front of the vaporizer. A sealing plug closes the filling system when the vaporizer is not

being filled. To fill the vaporizer, the button on the right side of the vaporizer is depressed to allow the sealing plug to be removed. The desflurane bottle is inserted into the filling mechanism. When it is locked in place, an audible click is heard. Pressing the bottle downward will allow the agent to fill the vaporizer. When the vaporizer is full, the bottle retracts, stopping the agent flow. After waiting 2 to 3 seconds to allow all of the agent to enter the vaporizer, the button is depressed to release the bottle from the filling device. The sealing cap is pressed into the filler until it locks in place, as determined by an audible click.

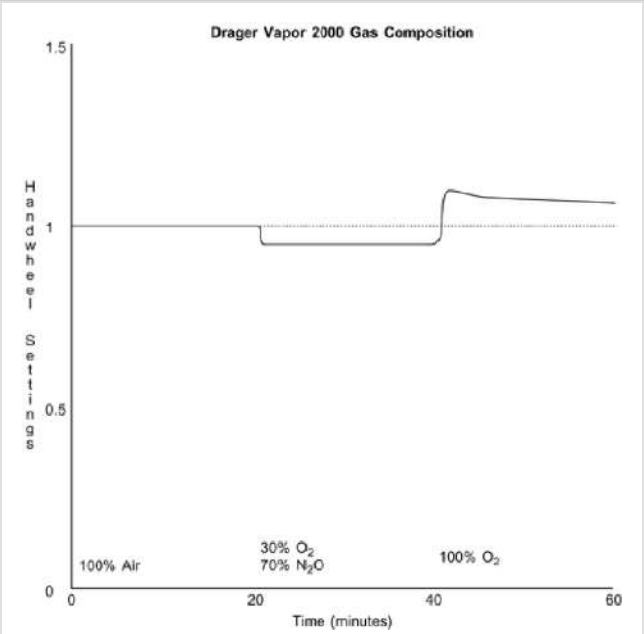

Figure 6.32 Effect of carrier gas composition on output of the halothane Vapor 2000 vaporizer. (Redrawn from graphs furnished by Drager Medical.)

The agent-level indicator is at the front on the right side. There are three horizontal lines. The top line indicates that the vaporizer is full. The second line, which is near the bottom, indicates when one complete bottle of desflurane (240 mL) will

be needed to fill the vaporizer. The bottom line indicates that there are only 30 mL of agent remaining in the vaporizer. The vaporizer has a capacity of 300 mL.

The D-Vapor can be filled when the device is switched OFF (no power to the vaporizer), during the heating phase, or during operation. If filled during operation, the filling process will be slower.

The display and alarm indicators are located on the front of the vaporizer to the left. For a high priority alarm, there is a red flashing LED accompanied by two groups of five tones, each emitted for 10 seconds. For a medium priority alarm, there is an amber flashing LED and one group of three tones emitted every 25 seconds. The indication alarm is a continuously glowing amber LED with a single tone every 1 to 2 seconds.

There is a button and LED at the top and five LEDs below. Pushing the button audio pauses (silences) the alarms for 2 minutes and causes the amber LED to illuminate. The second LED is green and indicates that the vaporizer is ‘operational.’ The third LED is red and indicates ‘no output.’ The fourth LED is amber and indicates ‘warm up.’ The fifth LED is amber and indicates that the vaporizer needs to be refilled (‘Fill UP’). The bottom LED is amber and indicates ‘Battery.’ In the event of a mains power failure, it will blink. If it glows continually, the battery should be changed. If there is an apparatus fault, all of the LEDs blink. The reader is referred to the user manual for further details.

If no power is supplied to the vaporizer, there will be no illuminated LEDs. When power is supplied to the vaporizer, a self-test is automatically performed. All six LEDs should light, and an audible alarm signal sounds. During the 5-minute heating phase, the green ‘operation’ LED flashes. When the heating phase is complete, this LED glows continuously, and an audible signal is emitted.

The vaporizer is then ready for use. The vaporizer must be set to ‘0’ at least every 24 hours for a total of 5 seconds. This will initiate a self-test.

Figure 6.33 Drager D-Vapor. (Courtesy of Drager

Medical.)

The D-Vapor has its own battery backup. If the battery is not sufficiently charged, the amber LED glows. The backup battery will last only 5 minutes. After 5 minutes, the vaporizer is switched OFF, and an alarm sounds. If power is restored in less than 5 minutes, there will be no interruption in output.

The internal construction is shown in Figure 6.34. The reservoir containing the liquid desflurane is heated to 40ยฐC and is at a constant pressure of 2 bar. This allows the desflurane that leaves the reservoir to be a fully saturated vapor. A shutoff valve prevents the reservoir from delivering vapor when the control dial is at the zero setting, during the heating phase, or in the event of vaporizer failure.

Fresh gas from the flowmeters is conducted through the bypass and on to the machine outlet. There is a flow resistance in the bypass that increases the pressure in the line and causes pressure to be applied to a diaphragm in the regulating sensor. This sensor causes the proportioning valve to deliver as much saturated desflurane vapor as is necessary to balance the pressures between the fresh gas flow and the desflurane flow. The delivered desflurane concentration is determined by the relationship between the bypass resistances and the flow control cone, which is determined by the control dial setting.

Evaluation

Carrier gas composition will affect vaporizer output. With air or nitrous oxide, the delivered concentration is reduced in comparison to that delivered when the carrier gas is oxygen. For air, the output is reduced approximately 10%. With a nitrous oxide:oxygen in a 70:30 ratio as the carrier gas, the output is reduced approxi-mately 20%.

Vaporizer performance is not substantially influenced by ambient temperature fluctuations within the range of 18ยฐC to 30ยฐC.

The D-Vapor is calibrated in volume percent. Since this calibration is independent of ambient pressure, the control dial settings need to be adjusted higher at higher altitudes to achieve the same concentration.

The output accuracy is related to the volume of gas that passes through the vaporizer (Fig. 6.35). The desflurane concentration is accurate for dial concentration and flows in the shaded areas of the graph. In the unshaded areas, the output is lower than the setting.

Hazards

Cellular phones should not be used within 10 m of the vaporizer.

The D-Vapor is not designed to be used at an angle of more than 10 degrees. At greater angles, an uncontrolled concentration of vapor may result, connections to the vaporizer may leak, and the level in the sight glass will not be correct. This could lead to overfilling.

Maintenance

Continuous agent monitoring is recommended. In the absence of this, a weekly check of vapor output is recommended. The manufacturer requires that the vaporizer be inspected and serviced by skilled personnel at yearly intervals.

Detergents must not be allowed to get under the control dial or into the inlet for gas flow or the filling system. Halogen-releasing compounds, strong organic acids, or oxygen-releasing compounds should not be used to clean the vaporizer.

Penlon Sigma PPV

The Penlon Sigma PPV vaporizer is designed to dispense halothane, enflurane, isoflurane, and sevoflurane.

Construction

The Penlon Sigma PPV vaporizer is shown in Figure 6.36. The upper part of the vaporizer and concentration dial are color coded. To set a concentration, the dial is pushed in and rotated. The filling device can be either a funnel fill, Quik-Fil, or keyed filler. The liquid level

indicator has lines for the minimum and maximum levels. The direction of gas flow is marked on the top.

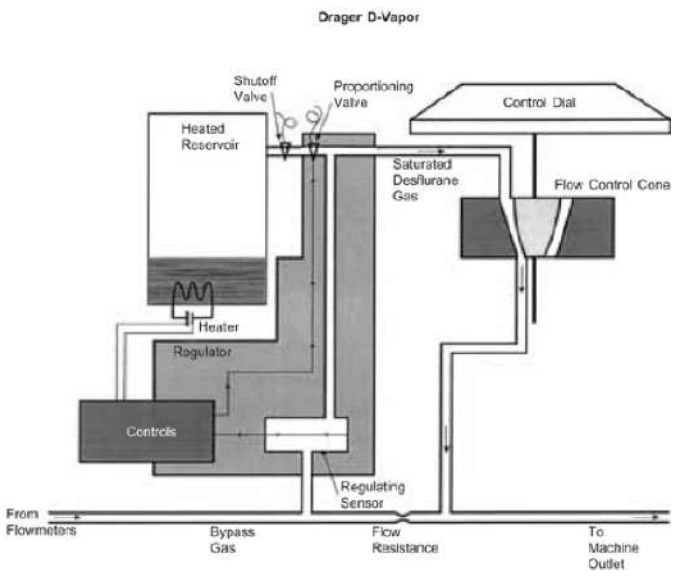

Figure 6.34 Internal construction of Drager D-Vapor. (Redrawn courtesy of Drager Medical.)

Internal vaporizer construction is shown in Figure 6.37. Gas enters the vaporizer and is split into two streams, one passing through the bypass and the other through the vaporizing chamber. In the zero lock position, the bypass remains open, but the vaporizing chamber is isolated. If the zero lock port is open, gas passes through a spiral tube into the vaporizing chamber, which contains a stainless-steel wick. Gas saturated with vapor

exits the vaporizing chamber through the vapor control orifice. The size of this orifice is controlled by the concentration dial setting. Gas saturated with vapor then joins the bypass gas and flows to the outlet.

Temperature compensation is provided by a liquid-filled expansion bellows controlling a variable resistance valve in the bypass. As the vaporizing chamber cools, the orifice becomes smaller so that a greater proportion of gas passes through the vaporizing chamber.

Evaluation

The performance characteristics supplied by the manufacturer are illustrated in Figure 6.38. The vaporizer is accurate at temperatures from 15ยฐC to 35ยฐC. At higher temperatures, output is increased. If nitrous oxide is in the carrier gas, the output will be slightly higher. Air or helium in the carrier stream causes the output to drop slightly. Intermittent back pressure may result in a small increase in output. Reversed gas flow results in increased output (20).

Hazards

If the vaporizer is transported while filled, the control must be in the zero position, and at least 2 minutes should elapse with the vaporizer in a secure upright position before use. If the vaporizer has been transported with the control in the open position, it should be flushed with gas at 4 L/minute for 2 minutes.

The concentration dial must be in the zero position during filling or draining. The vaporizer must be upright to avoid overfilling. A vaporizer that has been overfilled should be withdrawn from use.

Overfilling can occur if the vaporizer is turned ON and the bottle adaptor loosened (56). A high output will then occur when the vaporizer is used.

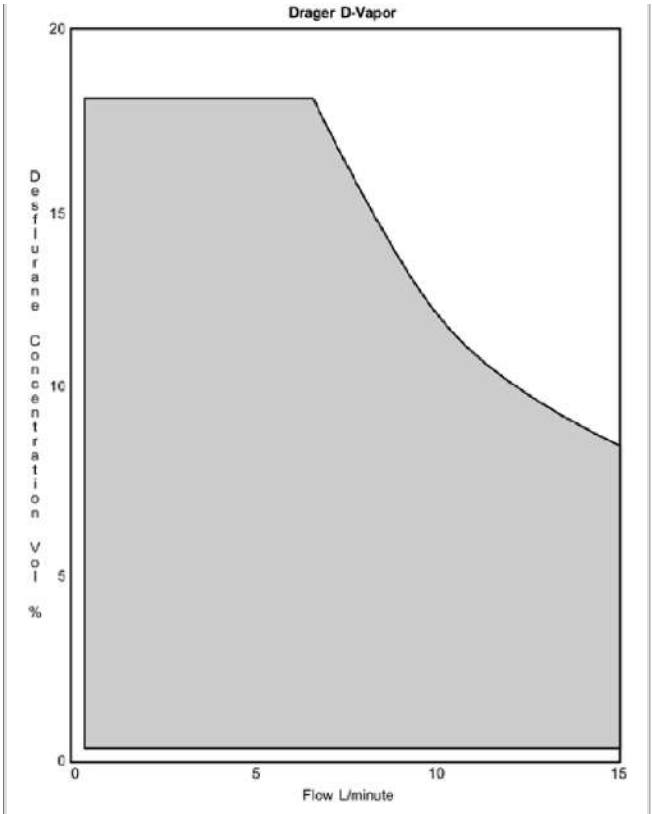

Figure 6.35 The desflurane concentration is accurate for dial settings and flows in the shaded areas of the graph. In the unshaded areas, the output is lower than the setting. (Redrawn from a graph furnished by Drager Medical.)

The key filler port is closed with a block that is shaped like the end of the keyed filler. If the block is not replaced or the screw not tightened, there will be a gas leak when the vaporizer is turned ON. This will result in loss of the gas that passes through the vaporizing chamber, and little or no vapor will reach the breathing system (57,58). Liquid agent will not be lost through a loose filler block.

Maintenance

The vaporizer should be calibrated every 3 to 6 months, with a major overhaul every 5 years. The exterior should be cleaned with a dry cloth. No liquids, including water, should be applied to the surface. The halothane vaporizer should be drained periodically and the liquid discarded to prevent thymol buildup.

Penlon Sigma Delta

The Sigma Delta vaporizer is used to dispense halothane, enflurane, isoflurane, and sevoflurane.

Construction

The Sigma Delta vaporizer is shown in Figure 6.39. The front has a color-coded control dial that locks in the ĩ€0ĩ€ position. To use the vaporizer, the dial is pushed inward and rotated counterclockwise to the desired concentration. When the control dial is turned

OFF, it will automatically spring outward to the locked position.

Figure 6.36 PPV Sigma vaporizer with screw cap filler and back entry connections. (Courtesy of Penlon, Ltd.)

At the bottom is the liquid level indicator, with maximum and minimum level marks. Three different filling devices are available: funnel fill, keyed fill, and Quik-Fil. The keyed filler utilizes a plug that is held in place by using a screw on the side.

At the base of the filling mechanism is a means of drainage. If a keyed filler is used, the same bottle adaptor that is used to fill the vaporizer is used to drain it. For the Quik-Fil and funnel-fill mechanisms, a screw at the base of the filler block opens the drain. The filler cap must be removed from the vaporizer to drain it. The liquid can drain directly into the bottle for the funnel fill. For the Quik-Fil, a receptacle is slid over the base of the filler mechanism and is used to catch the liquid (see Figs. 6.68, 6.69).

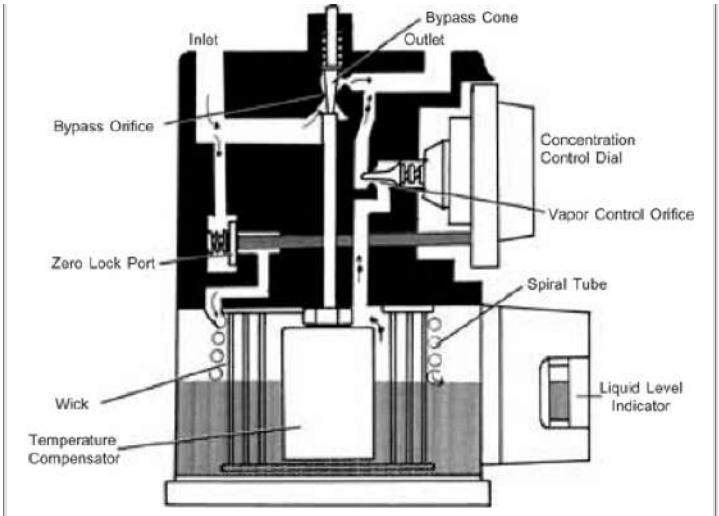

Figure 6.37 Diagram of PPV Sigma vaporizer. (See text for details.) (Redrawn from a drawing furnished by Penlon, Ltd.)

The vaporizer has a liquid capacity of 250 mL. At the MIN mark, the volume will be 35 mL. Approximately 60 mL of liquid will remain in the wick after the vaporizer is drained.

The internal construction is shown in Figure 6.40. The vaporizing chamber contains a wick. Temperature compensation is by means of a thermostat in the bypass. In the zero position, the bypass remains open, but the vaporizing chamber is isolated from the gas flow.

Evaluation

The operating temperature range is 15ยฐC to 35ยฐC. The temperature-compensating mechanism reacts slowly to room temperature changes and may need a minimum of 1 to 2 hours to compensate for a change in room temperature. The vaporizer is designed to operate between fresh gas flows of 0.2 and 15 L/minute. Graphs of

P.155
P.156
P.157

vaporizer output in relation to fresh gas flow and temperature are given in Figures 6.41 to 6.44.

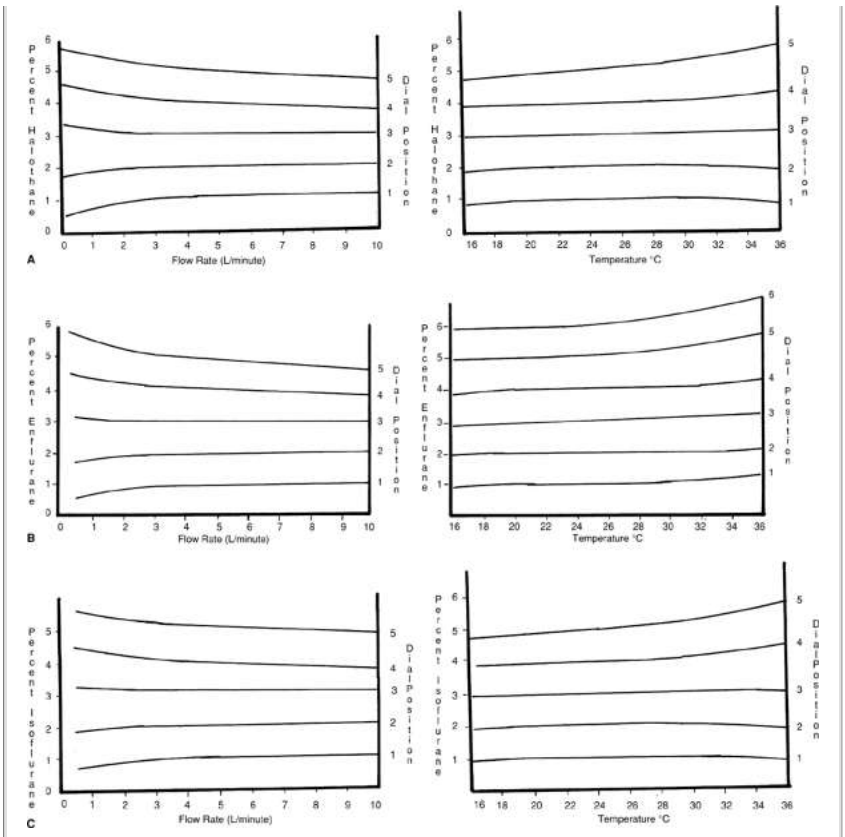

Figure 6.38 Performances of PPV Sigma vaporizers with oxygen as the carrier gas. (Redrawn from graphs furnished by Penlon, Ltd.)

Figure 6.39 Sigma Delta vaporizers. **Left:** With keyed filler. **Right:** With Quick-Fil. (Photo courtesy of Penlon Company UK.)

Barometric pressure effects are not usually clinically important.

A steady back pressure of 10 to 15 kPa (100 to 150 cm H_2O) will reduce the vaporizer output. Intermittent back pressure may result in some changes in output. The effect is greatest at low vaporizer settings and low flow rates.

The vaporizer is calibrated with 100% oxygen. Nitrous oxide in the carrier gas will produce a decrease in output. Air will reduce the vaporizer output by a maximum of 5%. Helium in the fresh gas will result in low concentrations.

Hazards

The Penlon Sigma Delta may malfunction if exposed to excessively high temperatures. This may affect the calibration. The vaporizer should be stored between -20ยฐC and 50ยฐC.

The vaporizer control dial should be at zero, and the vaporizer should be upright during filling. If it is not upright, there is a possibility of overfilling. An agent bottle that is cracked or a filler that is not tightly attached to the bottle or is broken should not be used because overfilling may occur or contaminated agent may enter the vaporizer. An overfilled vaporizer must be taken out of service and the manufacturer consulted.

If the vaporizer is transported while filled, the control dial should be in the โ€0โ€ position. The dial must remain in the โ€0โ€ position for at least 10 minutes after the vaporizer is attached to the anesthesia machine. Anesthetic agent overdose can occur if not enough time for any liquid to drain into the normal position has elapsed. If a vaporizer has been transported with the control dial in an open position, it must be flushed with a 5 L/minute flow of gas for at least 10 minutes before use. If a vaporizer has been tipped or inverted during transport, the control dial must be set to maximum output and run at 5 L/minute for 10 minutes prior to use.

This vaporizer is flow-direction sensitive. If the gas flow is reversed, the output will be inaccurate.

Maintenance

Calibration can be performed by using a suitable agent gas analyzer. If the calibration is outside the performance limits, the vaporizer must be serviced.

The manufacturer recommends that a major overhaul be performed every 10 years. Halothane models should have a major overhaul every 5 years. The halothane vaporizer should be drained periodically and the liquid discarded.

Penlon Sigma Alpha

The Penlon Sigma Alpha vaporizer is an electrically powered vaporizer designed for desflurane.

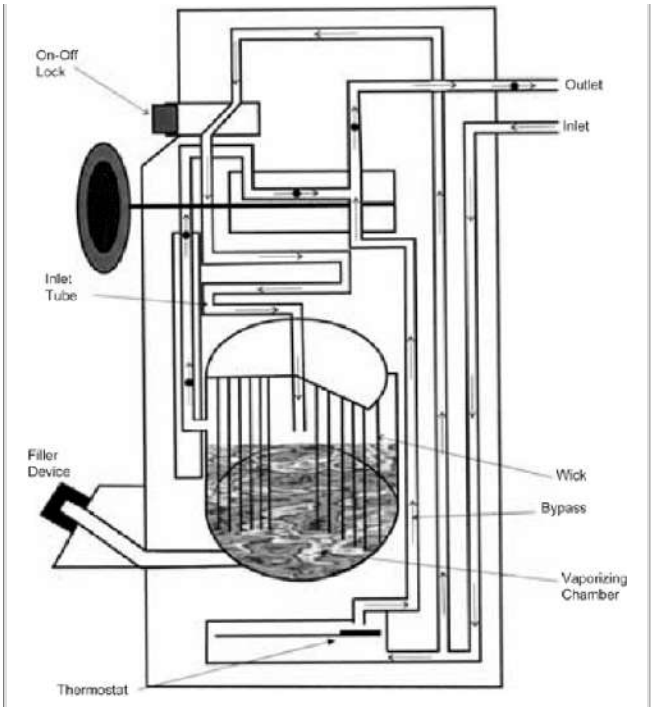

Figure 6.40 Internal construction of Sigma Delta vaporizer. (Redrawn courtesy of Penlon Company UK.)

Construction

The vaporizer is shown in Figure 6.45. The front has a control dial to set the concentration. The dial is locked at ‘0’ when not in use. To set a concentration, the dial is pushed in and rotated to the desired setting.

Below the control dial is a display screen. When the vaporizer is first turned ON, a ‘WARM-UP’ message appears. After warm-up is complete, a ‘STANDBY’ message is shown. When the control dial is turned ON, an ‘IN USE’ message appears. If mains electricity is lost, a ‘BATTERY IN USE’ message appears. Agent level is indicated vertically on the left side of the message window.

To the right of the message window are the ON-OFF switch, an ‘in-use’ indicator, and an ‘alarm mute/des used’ button. When connected to mains power, the amber power indicator to the left of the ‘in-use’ indicator will be illuminated. When the ON-OFF switch is activated, the green ‘in-use’ indicator at the right is illuminated and the power indicator extinguished. Warm-up takes approximately 2 minutes. No vapor output is possible during that period. After the warm-up period, the vaporizer switches to the standby mode. The ON-OFF button is pressed to switch OFF the vaporizer. If the vaporizer is still connected to mains electricity, the amber light will be illuminated.

Pressing the ‘alarm mute/des used’ control initiates an audio OFF state and activates the agent consumption mechanism. This

allows the user to quantify the volume of desflurane used.

The filling capacity at the maximum mark is 330 mL. When the ‘low agent’ message is displayed, the contents are 70 mL or less. At 50 mL, agent output is turned OFF.

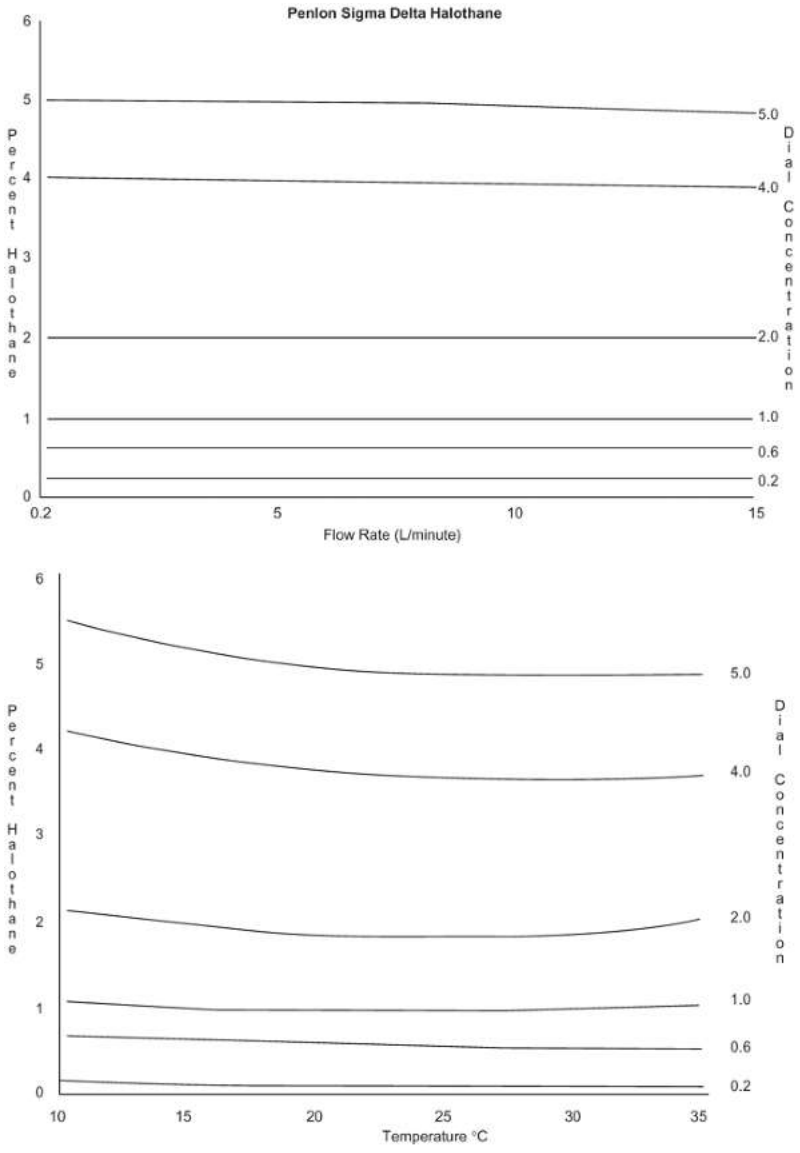

Figure 6.41 Performances of halothane Sigma Delta vaporizer. (Redrawn from graphs furnished by Penlon Company UK.)

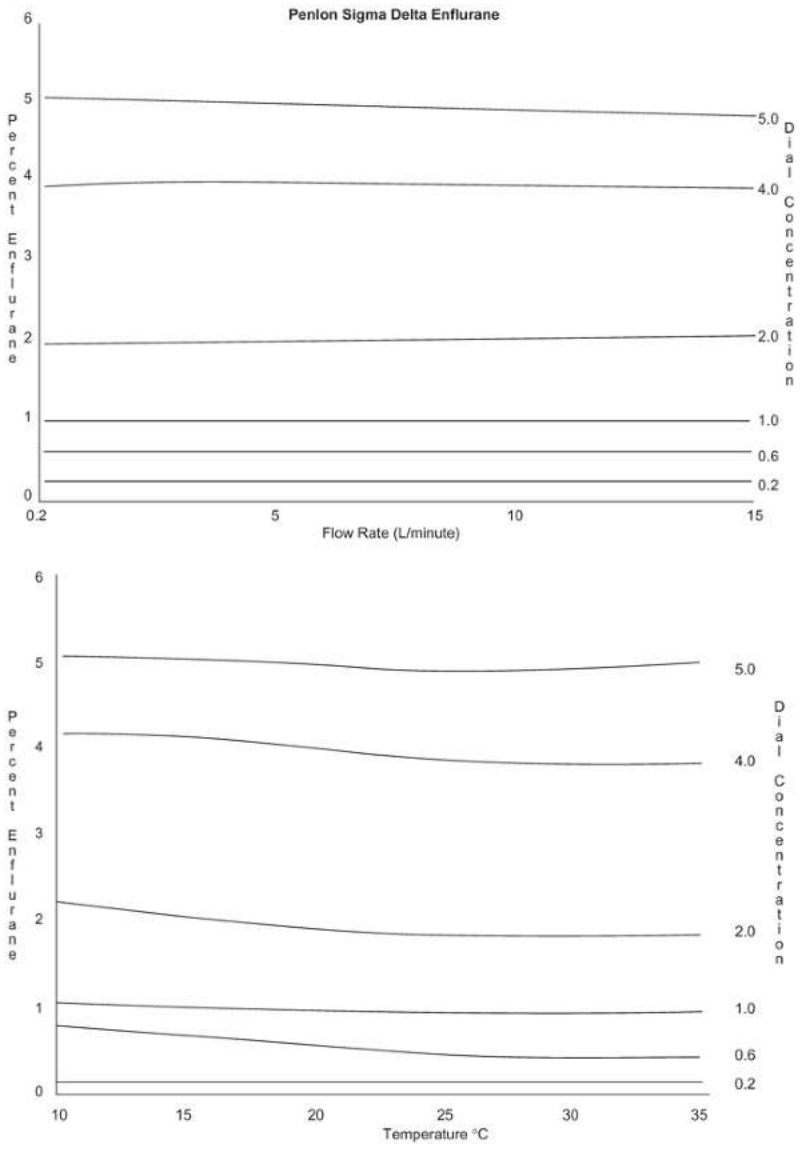

Figure 6.42 Performances of enflurane Sigma Delta vaporizer. (Redrawn from graphs furnished by Penlon Company UK.)

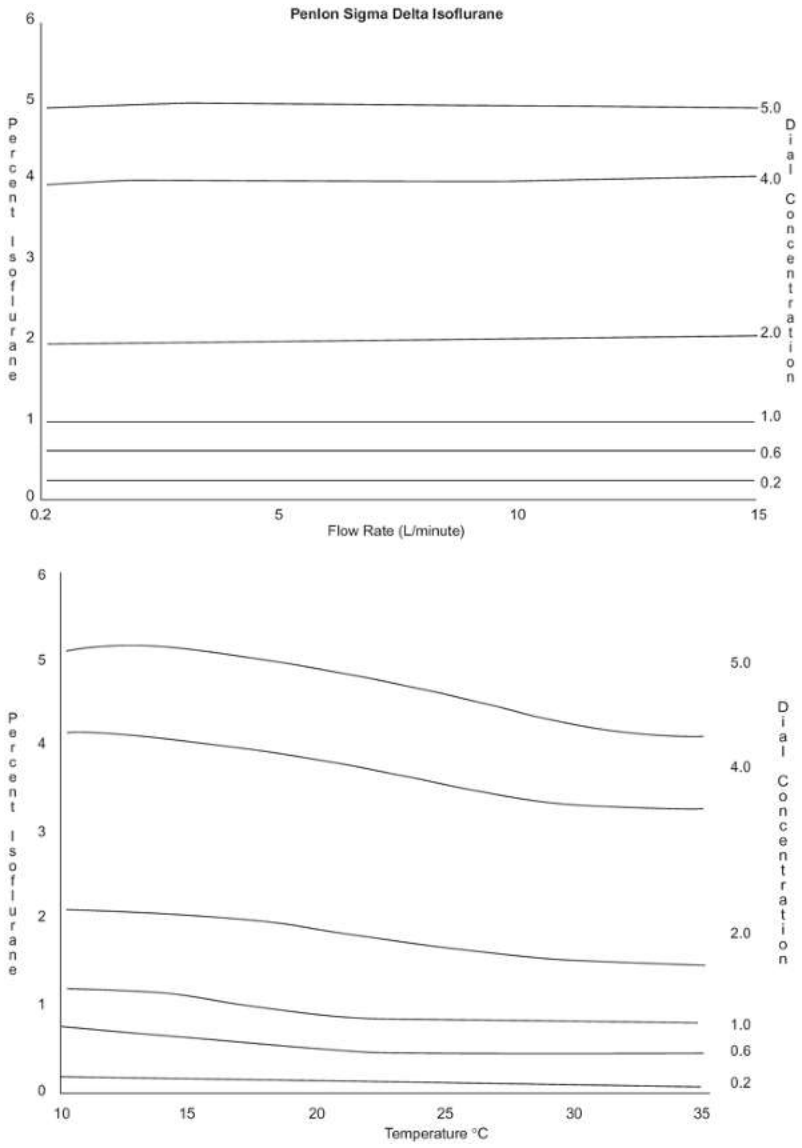

Figure 6.43 Performances of isoflurane Sigma Delta vaporizer. (Redrawn from graphs furnished by Penlon Company UK.)

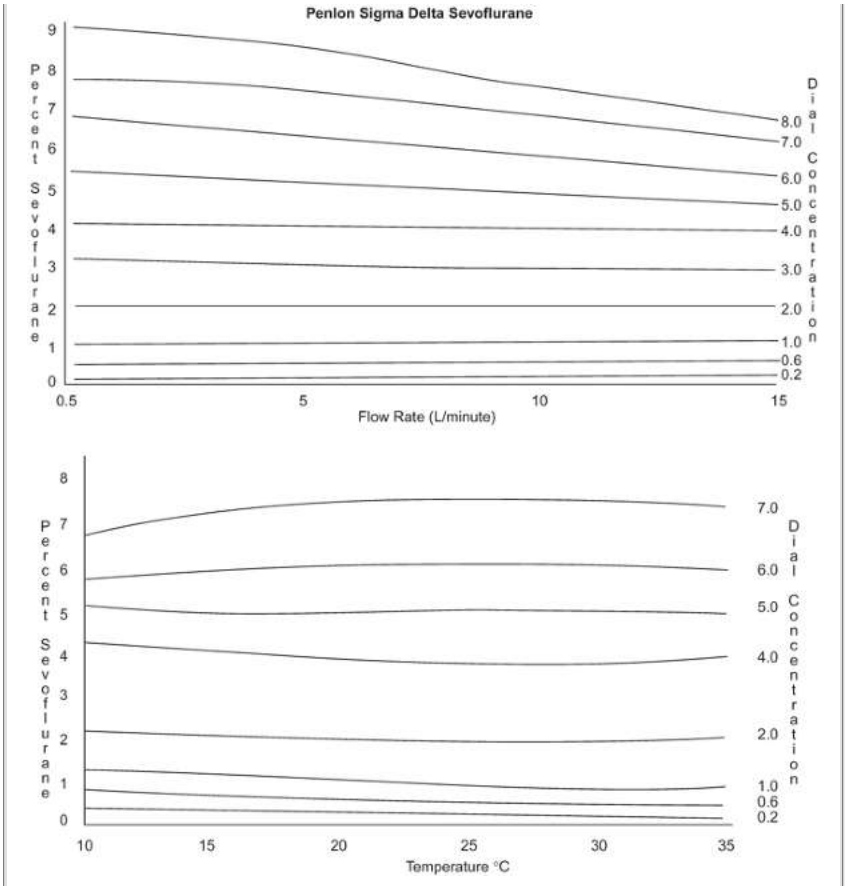

Figure 6.44 Performances of sevoflurane Sigma Delta vaporizer. (Redrawn from graphs furnished by Penlon Company UK.)

The filling system is at the front of the vaporizer near the bottom. To fill the vaporizer, the filter cover is lifted and the bottle aligned with the filler receiver. The bottle is inserted until it is fully engaged. The filler locking ring, which is just below where the bottle is inserted, is then rotated clockwise until it clicks into position. It is then rotated further clockwise until it again clicks into position. Liquid will then flow into the vaporizer until it is filled to the level desired on the LCD display or the flow of air bubbles into the bottle has stopped. After the vaporizer is filled, the locking ring is rotated counterclockwise until the bottle is released. The vaporizer may be filled while gas is flowing through the vaporizer.

The vaporizer is powered by mains electricity transformed down to a low voltage. It has a backup battery. It has a fast warm-up time and low power consumption. The vaporizer can calculate the amount of desflurane used for each case.

Figure 6.46 shows the internal construction. The filling device is used to add desflurane to the agent reservoir (cartridge). A sensor measures the liquid level, which is displayed on the front of the vaporizer. The vaporizer may be filled while mounted or

off of the

anesthesia machine. When the bottle is removed, the agent reservoir is automatically sealed and then pressurized above the vapor pressure of desflurane. This causes the desflurane to remain in the liquid state. Liquid desflurane is moved via a tube from the reservoir to the control part of the delivery device.

Figure 6.45 Sigma Alpha vaporizer. (Courtesy of Penlon Company UK.)

Gas flows are measured in the vaporizer inlet and outlet. Sensors can detect nitrous oxide in the fresh gas and calculate the concentrations of oxygen and nitrous oxide. With no desflurane being delivered, the inlet and outlet flow sensors will provide similar flow readings. Only with the addition of desflurane will there be a difference. The desflurane concentration is determined from the difference.

The liquid desflurane flow is measured by a liquid-flow sensor. The central processor calculates the flow of liquid desflurane needed for the set concentration and fresh gas flow and adjusts the proportional valve to deliver the required amount of agent. The liquid agent flows through a device that maintains a constant back pressure. It is then delivered via a shutoff (ON-OFF valve) into a heating device where it is vaporized. The heating element has a feedback control that ensures that the agent is heated according to the flow rate and its thermal properties. This arrangement means that the temperature and power are continually monitored and adjusted to minimize power consumption. The vaporized agent then passes through to the fresh gas supply. The second flow sensor monitors the increased flow resulting from the added vapor. In the event of a device failure, the system will stop delivery of desflurane and enter into a safe mode. It also generates visual and audible alarm signals.

Evaluation

The manufacturer's data for output are shown in Figure 6.47. The vaporizer is designed to be used at a temperature between 15ยฐC and 30ยฐC. The output is maintained within ยฑ20% of the

set concentration. The flow range is 0.5 to 12 L/minute. The maximum flow through the vaporizer is 20 L/minute. Above this flow, the vaporizer turns OFF.

The vaporizer is calibrated with pure oxygen. Adding nitrous oxide to the fresh gas will decrease the output by up to 15%. Air as the carrier gas will reduce the output below the set value by a maximum of 5%.

Hazards

Excessive electronic noise caused by a device such as an electrosurgery unit may adversely interfere with vaporizer function. To avoid this, the electrosurgery device should not be plugged into the same wall socket or outlet strip as the vaporizer. Electromagnetic interference may occur if the vaporizer is used with an extension cord.

Movement during transport can result in increased vapor output unless time is allowed for the liquid to drain into the normal area. If the vaporizer has been removed from the anesthesia machine and transported, it should be purged at 5 L/minute for 2 minutes before use.

Sudden inadvertent movement can cause an increased output unless the vaporizer is securely fixed to the anesthesia machine and in an upright position.

Maintenance

The manufacturer recommends a periodic service check by a manufacturer-trained engineer. A training course is available for those who wish to carry out routine maintenance.

Blease Datum

Blease Datum vaporizers are available for halothane, enflurane, isoflurane, and sevoflurane.

Construction

The vaporizer is shown in Figure 6.48. The agent-specific colored label is on the front of the vaporizer below the dial. The concentration control dial locks automatically in the OFF position. To set a concentration, the dial is pushed inward and rotated counterclockwise. The concentration dial should not be set between zero and the

first setting. The filling device can be either a funnel fill or a keyed filler mechanism. The sevoflurane vaporizer does not have a funnel fill but may have the Quik-Fil system (Fig. 6.48).

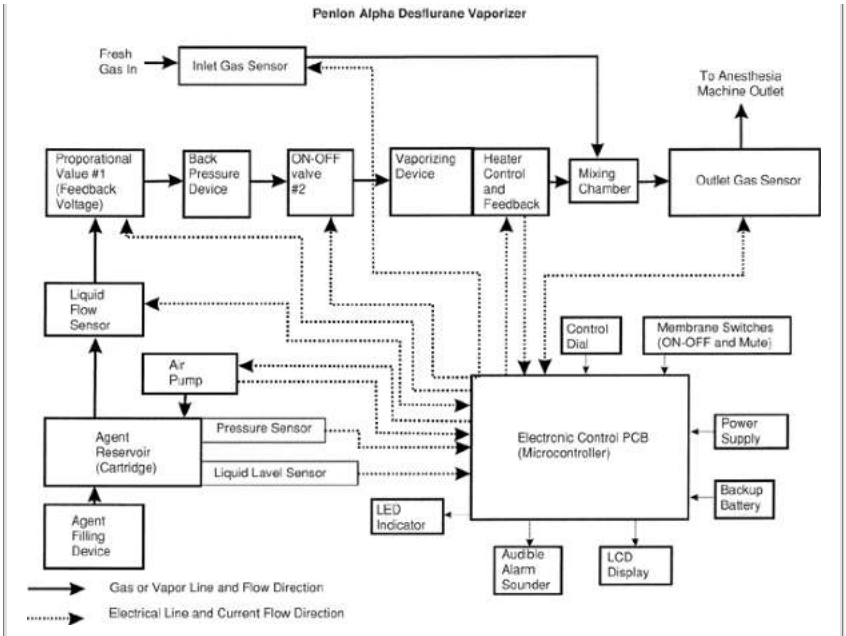

Figure 6.46 Internal construction of Sigma Alpha vaporizer. (Redrawn from a drawing furnished by Penlon Company UK.)

The internal vaporizer construction is shown in Figures 6.49 and 6.50. Gas enters the vaporizer and is split into two streams, one passing through the bypass and the other through the vaporizing chamber. In the zero lock position, the bypass remains open, but the vaporizing chamber is completely separated from gas flow by the closed zero lock valve. When the vaporizer is turned ON, the zero lock valve opens, and gas passes through a spiral tube to minimize the effects of intermittent positive pressure ventilation and then into the vaporizing chamber that contains a main and a coil wick. Gas saturated with vapor exits the vaporizing chamber through the vapor control valve. The concentration control dial setting controls the size of the orifice in this valve. Gas saturated with vapor then joins the bypass gas and flows on to the outlet.

Temperature compensation is provided by a mechanism with its base in the vaporizing chamber. It is connected to a variable bypass valve. As the vaporizing chamber cools, the orifice in the valve becomes smaller so that a greater proportion of gas passes through the vaporizing chamber.

Evaluation

The concentration dial must be in the zero position while draining or filling the vaporizer. The effect of altitude on the output is shown in Figure 6.51. Vaporizer output in relation to dial setting, flow, and temperature is shown in Figures 6.52 to 6.55.

Temperature compensation is in the range of 15ยฐC to 30ยฐC. Temperatures outside of this range will cause the output to vary. When the liquid level is below

the minimum marking on the sight glass, the output may fall.

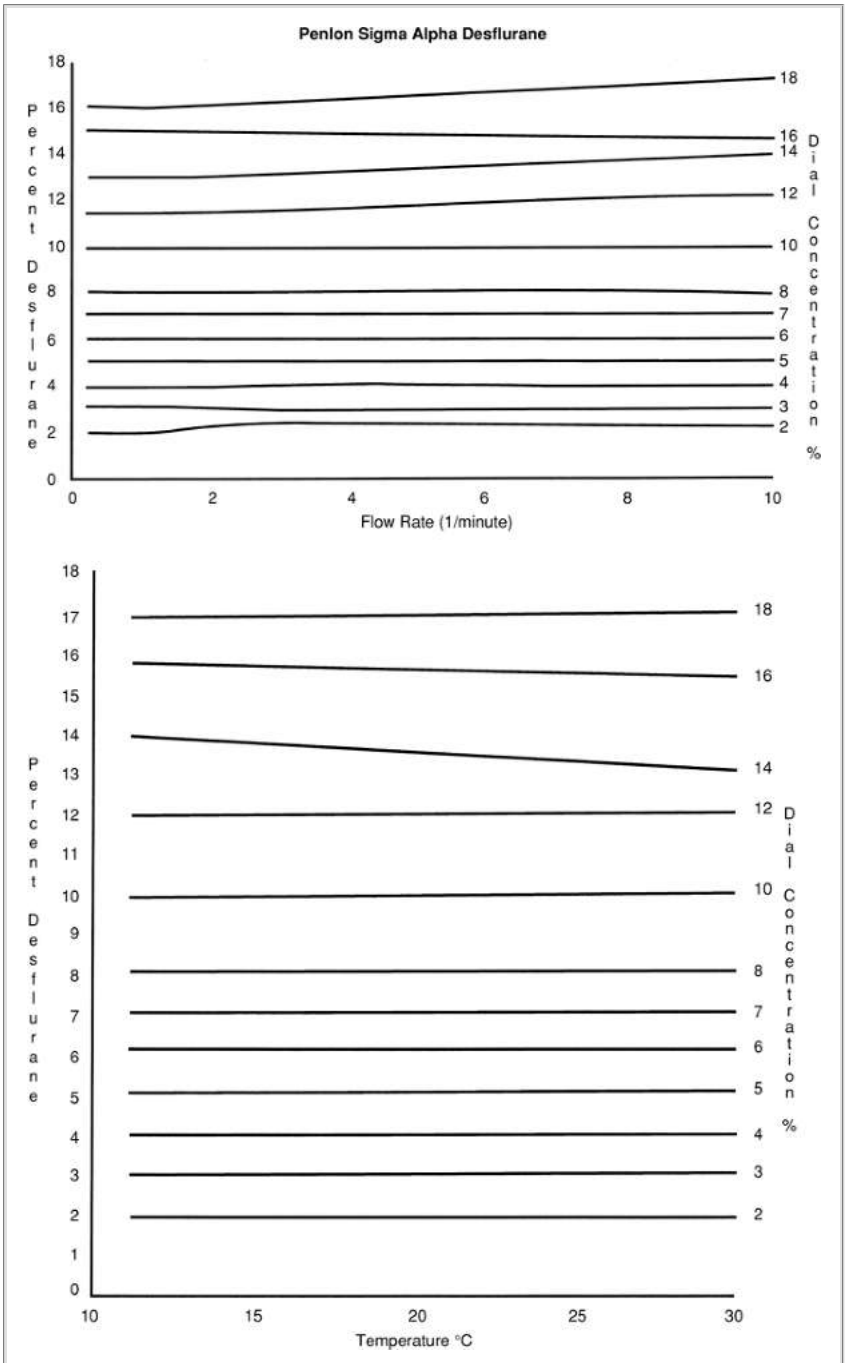

Figure 6.47 Output of Sigma Alpha vaporizer. (Redrawn from graphs furnished by Penlon Company UK.)

Figure 6.48 Blease Datum vaporizer with Quick-Fil system. (Photograph courtesy of Blease.)

Barometric pressure changes are normally not clinically significant. A small increase in output concentration can be produced by intermittent back pressure, most noticeably at low concentrations and low flow rates.

The output is affected by the gas composition. The variation is unlikely to be more than 10% of the set concentration. The vaporizer is calibrated by using air. Oxygen will produce a slight increase in output. This effect is greatest at low flows. Helium has negligible effects on the sevoflurane output (49). Reversed flow has a negligible effect on output (59,60).

Hazards

Excessive output may occur if the vaporizer is moved suddenly during use. The vaporizer should be drained prior to transport. If the vaporizer is transported with liquid agent, the control dial should be in the OFF position. The vaporizer must then be secured in the upright position for at least 1 hour before it is connected to a machine. It is then flushed with 4 L/minute of oxygen for 2 minutes before being used. If the vaporizer has been transported with the control dial in the ON position, the operator should contact the manufacturer for advice.

If the vaporizer is overfilled, it should not be used, and the manufacturer should be contacted for advice.

If the vaporizer is subjected to extremes in temperature, the temperature compensation mechanism may be damaged. The temperature range at which the vaporizer can be stored is -20ยฐC to 50ยฐC.

Changes in atmospheric pressure do not usually affect the output, but altitudes greater than 1500 m may require a correction factor.

Problems with mounting this vaporizer have been reported (61).

Maintenance

Maintenance includes cleaning the exterior of the vaporizer with a clean, damp cloth. The halothane vaporizer should be drained at regular intervals to prevent thymol buildup. Since some agents turn yellow or brown when exposed to light, this is not in itself a reason to change the agent.

In-system Vaporizers

Although in-system vaporizers are not often used in developed countries, their low cost, simple design, and portability have made them popular in developing countries and in the military (62). The availability of anesthetic agent monitors has sparked renewed interest in their use.

Characteristics of In-system Vaporizers

Often, the vaporizing chamber is a simple reservoir with a glass that allows the anesthesia provider to determine the amount of liquid present. There may or may not be a means of temperature compensation. The output depends on the vaporizer dial setting, fresh gas flow, and the composition and concentration of the gas entering the vaporizer, which in turn depends on the patient's minute volume, oxygen, and anesthetic agent uptake and the breathing system configuration (63,64,65).

Ambient air is often used as the principal carrier gas. Oxygen can be supplied through a T-piece that includes a reservoir tube (Fig. 6.56). The inspired oxygen concentration depends on oxygen flow, reservoir volume, and ventilatory volume. There are two ways that gas flows through a vaporizer: push through and draw over (Fig. 6.56) (66). Some vaporizers deliver higher outputs in the push-through configuration.

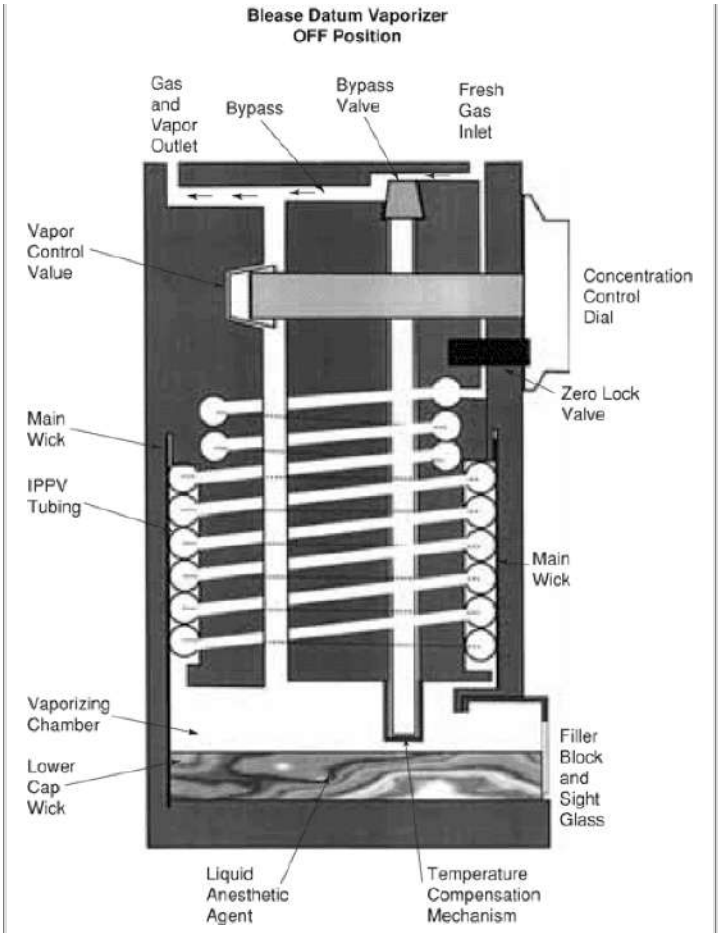

Figure 6.49 Internal construction of Blease Datum vaporizer in the OFF position. (Redrawn from information supplied by Blease.)

Significant water contamination may occur after prolonged closed-circle anesthesia (67).

Oxford Miniature Vaporizer

There are Oxford miniature vaporizers (OMVs) for halothane, enflurane, isoflurane, and sevoflurane.

Description

The vaporizer is shown in Figure 6.57. On the top is a control lever with a calibrated scale. There are calibrated scales for each agent, and only the agent marked on the vaporizer should be used. Each vaporizer can hold up to 50 mL. There are markings at 10 mL and 50 mL. An arrow indicates the correct direction of flow. Right-to-left flow vaporizers have 22-mm connectors for attachment to a breathing system. Left-to-right flow vaporizers have 23-mm connectors for use on the anesthesia machine between the flowmeters and the common gas outlet or attached to the fresh gas outlet. The scale is only

accurate if the marked direction of flow is used.

A sealed compartment in the base contains antifreeze, which acts as a temperature buffer. On the top of the vaporizer is a control lever with a calibrated scale that indicates the delivered concentration. With the control lever in the counterclockwise position, a sliding valve isolates the vaporizing chamber inlet and outlet. As the lever is rotated clockwise, the valve blocking the vaporizing chamber inlet and outlet is gradually opened to allow gas to enter that chamber.

The vaporizer can be filled or drained, even if gas is passing through the vaporizer, as long as the indicator is in the OFF position. The vaporizer is filled by removing the filler cap and pouring the liquid into the vaporizer. Since the top of the filler orifice is lower than the vaporizing chamber, it is not possible to overfill the vaporizer.

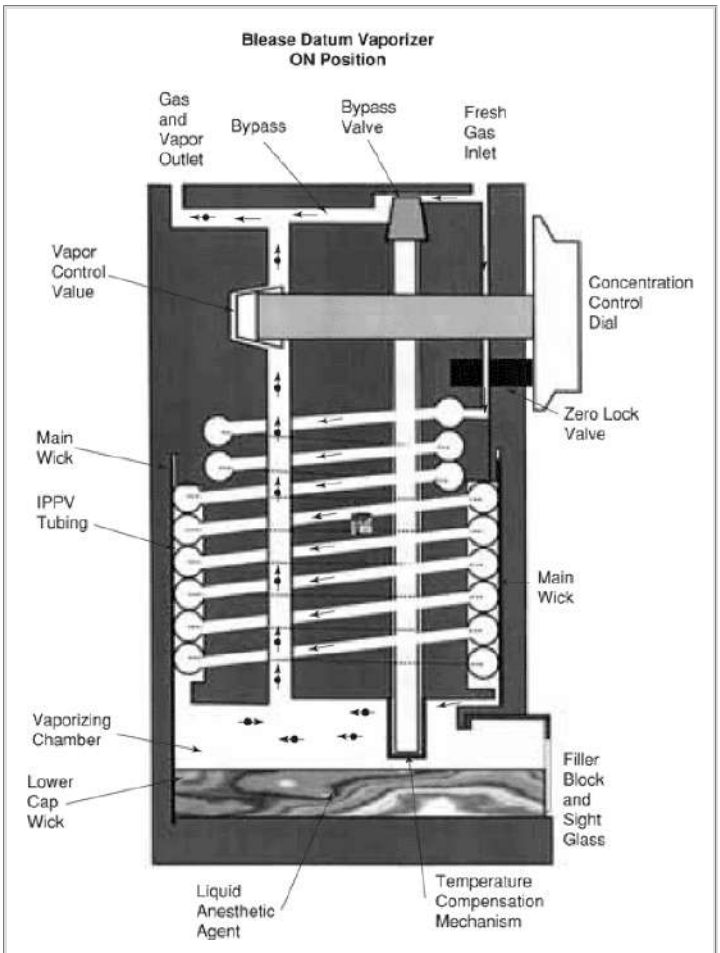

Figure 6.50 Internal construction of Blease Datum vaporizer in the ON position. (Redrawn from information supplied by Blease.)

The vaporizer is drained by inverting the cap that has a groove to fit the top of the drain screw. Loosening the drain screw will allow liquid to be drained from the vaporizer. All of the liquid will drain out except for the 2 to 4 cc that remain in the wicks.

Evaluation

The Oxford miniature vaporizer has a resistance to flow of less than 1 cm H_2O at a flow of 40 L/minute. It is designed to be used in an upright position but can be tilted up to 30 degrees. If it has been tilted more than this or has been transported full of liquid, 2 or 3 minutes should be allowed for liquid to drain back into the vaporizing chamber. The control pointer should be at zero during transport.

The Oxford miniature vaporizer is calibrated at a flow rate of 6 L/minute at 20ยฐC. The vaporizer does not have an active thermocompensating mechanism, so output is affected by ambient temperature changes (68). A plastic card that is supplied with the vaporizer indicates the output variation with temperature and flow rate.

The vaporizer is designed for continuous flow rates between 3 and 8 L/minute or drawover rates between 4 and 10 L/minute and ambient temperatures between 18ยฐC and 28ยฐC. Pressure fluctuations from controlled breathing have little effect on vaporizer output. The output is reduced at high minute volumes and with continuous carrier gas flow (69). Using a self-refilling bag (Chapter 10) with the Oxford miniature vaporizer in the pushover configuration may cause a higher output than some mechanical ventilators (62).

These vaporizers are not recommended for use within a closed system. Rapid anesthetic overdose may result because of their high efficiency. Their

performance will deteriorate with time because water condenses on the wick.

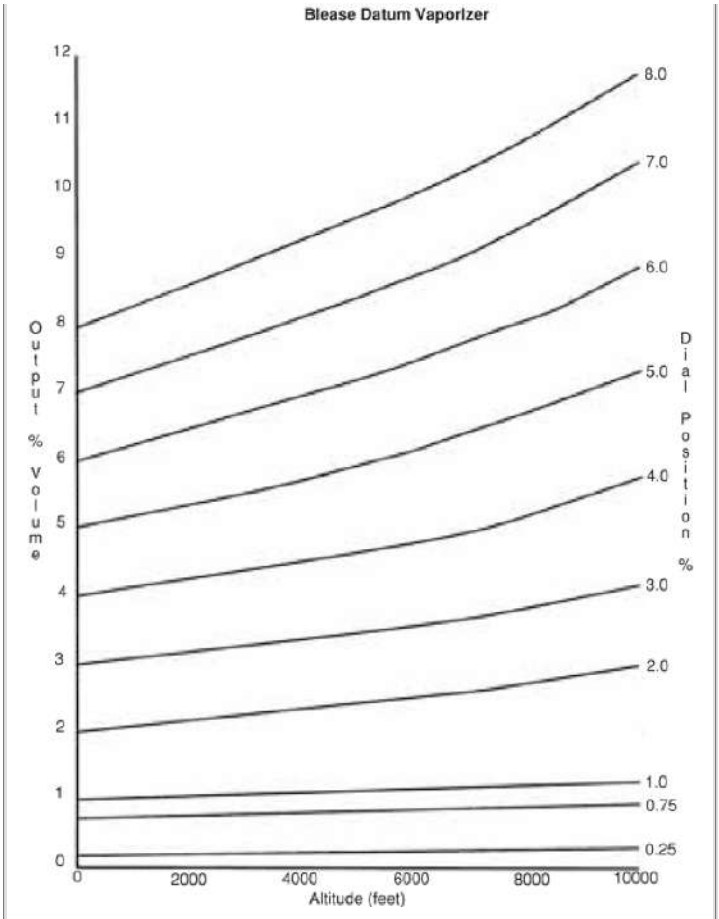

Figure 6.51 Effect of altitude on output of the Blease Datum vaporizer. (Redrawn from information supplied by Blease.)

The sevoflurane vaporizer may not be able to produce a high enough concentration for an inhalation induction (69,70). It may be possible to use two vaporizers in series for inhalation inductions.

Service

Agents such as halothane that leave a residue should periodically be drained and discarded. To clean the vaporizer, it should be emptied and the inlet closed with a stopper and turned on its side with the outlet upper-most. Ether is poured into the outlet, and the control dial is moved repeatedly until the movement is free. After this is accomplished, the control is turned fully counterclockwise, and the vaporizer is agitated gently to wash the wicks. The control is opened fully, and the ether is poured out of the outlet. Ether is then poured through the outlet. The filler cap and drain screw are opened, and ether is allowed to run out through the drain screw. The vaporizer is left with the control lever fully clockwise until all of the ether has evaporated. With the control lever fully open, dry gas is passed through the circuit until no trace of ether vapor can be detected.

Filling Systems

There are a number of different filling systems available at this time (Fig. 6.58). Funnel filling systems are available. Others are designed to allow a vaporizer to

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be filled only with a specific agent. Some systems are specific to one vaporizer manufacturer or anesthetic agent. Some can be used with vaporizers from different manufacturers.

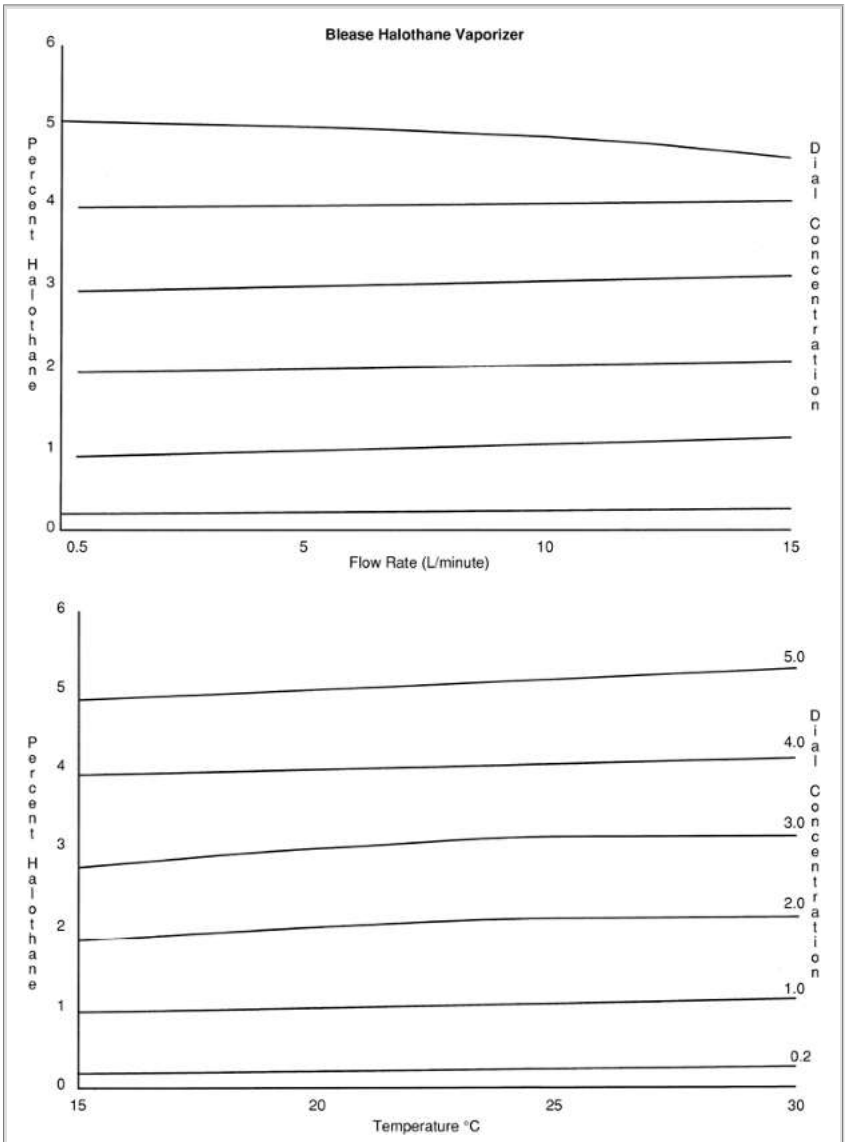


Figure 6.52 Performances of halothane Blease Datum vaporizer. (Redrawn from information supplied by Blease.)

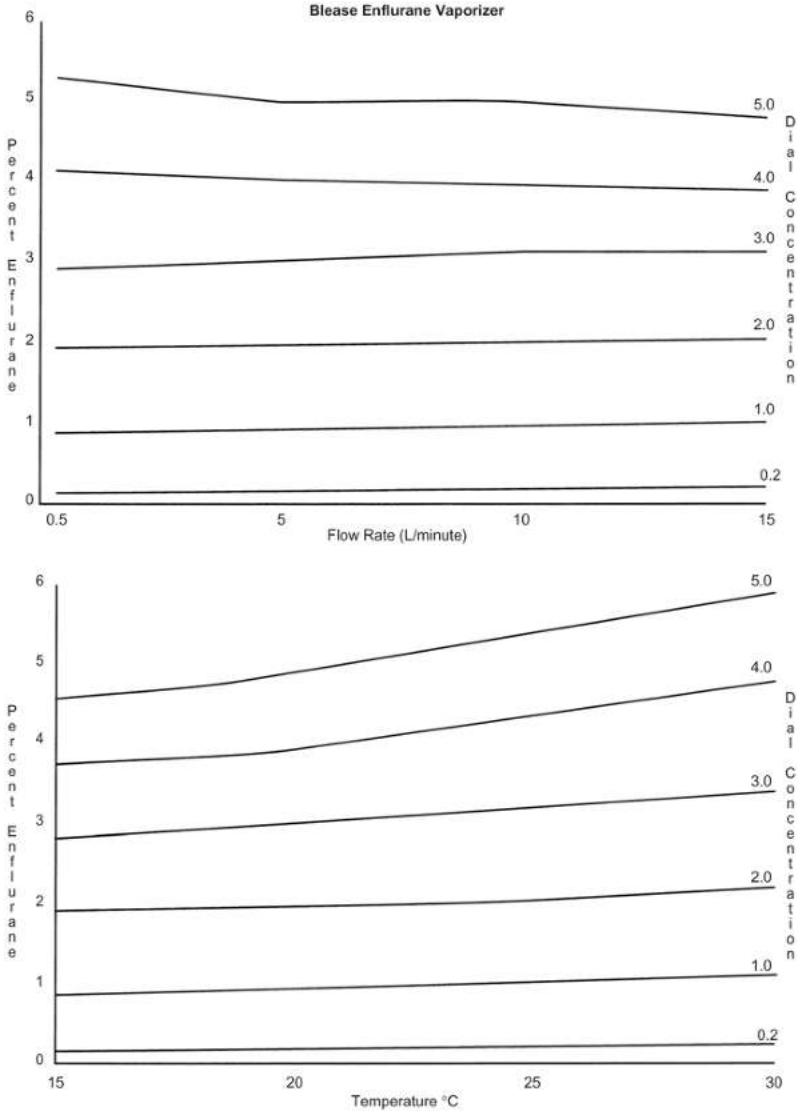


Figure 6.53 Performances of enflurane Blease Datum vaporizer. (Redrawn from information supplied by Blease.)

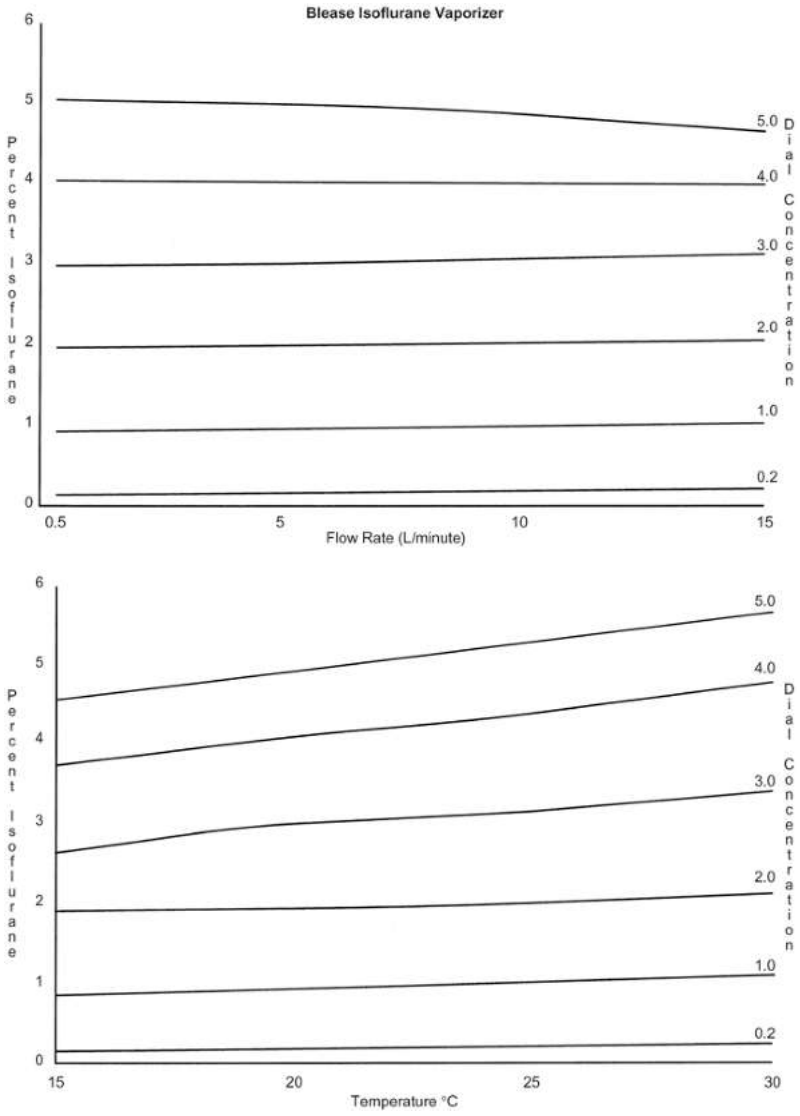


Figure 6.54 Performances of isoflurane Blease Datum vaporizer. (Redrawn from information supplied by Blease.)

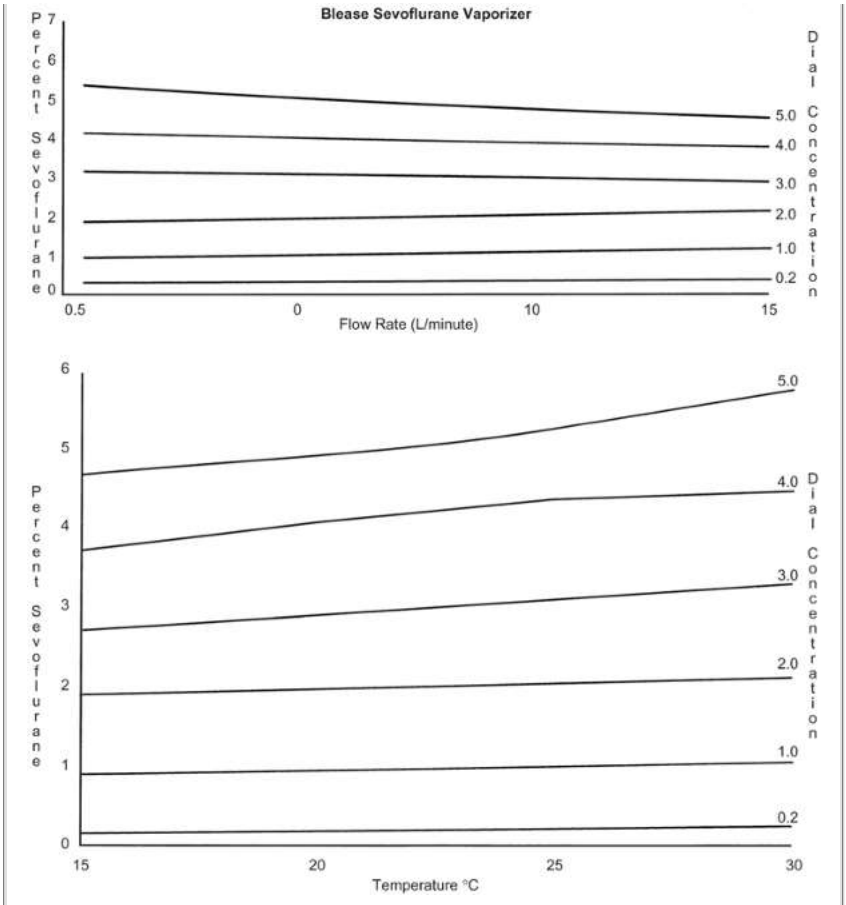


Figure 6.55 Performances of sevoflurane Blease Datum vaporizer. (Redrawn from information supplied by Blease.)

The ASTM machine standard (5) recommends, but does not require, that a vaporizer designed for a single agent be fitted with a permanently attached, agent-specific device to prevent accidental filling with the wrong agent. Some of these devices are covered by international and U.S. standards (71). In addition to preventing a vaporizer from being filled with a wrong agent, these systems may reduce the air pollution associated with filling and draining vaporizers.

Funnel Fill System

Vaporizer Components

The vaporizer filling components include a funnel and cap. When the cap is removed, liquid can be poured into the vaporizing chamber through the funnel. When the full level is reached, liquid will accumulate in the funnel, and no more liquid will enter the vaporizer. A funnel-fill

vaporizer can be converted to an agent-specific keyed filling system by the addition of an adaptor that screws into the

vaporizer filler (Fig. 6.59).

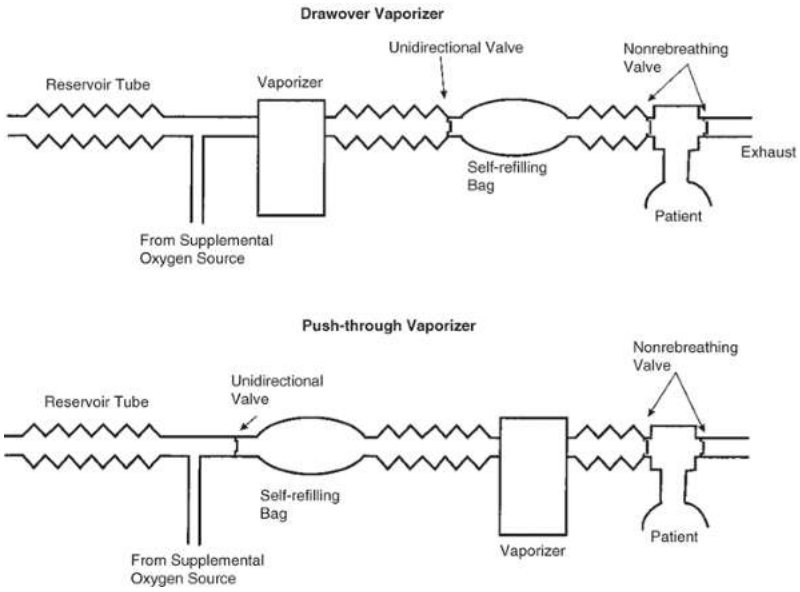


Figure 6.56 Systems for using an in-system vaporizer. The unidirectional valve prevents retrograde flow through the vaporizer.

Figure 6.57 Oxford miniature vaporizer. (Courtesy of Penlon Company UK.)

Bottle Component

A color-coded adaptor is available to aid the filling process (Fig. 6.60). At one end is a connector with a screw thread to match the thread on the bottle (Fig. 6.61) and a skirt that extends beyond the screw threads. It has slots that match the projections on the bottle collar. The adaptor for a different agent than the adaptor is intended for will not screw on either because of

different threads or bottle opening size or because the projections will not line up with the slots on the adaptor.

Filling Procedure

The filler cap is removed by turning it counterclockwise. Agent is poured into the filling port until the level reaches the full mark. The level may fall slightly as the wicks absorb the agent. The filler cap is then securely replaced.

Draining Procedure

To drain the vaporizer, a container is placed under the drain. Removing the filling cap will usually speed drainage. The mechanism for opening the drain varies with the vaporizer. After draining is complete, the drain plug should be replaced and tightened to minimize leaks.

Figure 6.58 Various filling systems for vaporizers. **Left to right:** Keyed fill, Quik-Fil, keyed filled, funnel fill, and keyed filled.

Keyed Filling System

The keyed filling system has been used by many manufacturers for a variety of anesthetic agents (71).

Vaporizer Component

The vaporizer filler receptacle (filler socket or block, vaporizer filler unit, fill and drain system) permits only the intended bottle adaptor to be inserted. A variety of methods are used to fix the adaptor into the vaporizer to prevent leaks while the vaporizer is being filled (Figs. 6.62, 6.63). There must also be a means to seal the receptacle when the bottle adaptor is not inserted. A metal filler block (plug) may be used (Fig. 6.62). There may be a single port for both filling and draining or two ports, the upper one for filling and the lower one for draining (Figs. 6.62, 6.63). An air vent may be located on the vaporizer. This must be

opened prior to filling to prevent an air lock.

Figure 6.59 Adaptor to convert a funnel fill system to an agent-specific keyed filling system. (Picture courtesy of Sharn Inc.)

Bottle Component

Each bottle of liquid anesthetic has a color-coded collar attached securely at the neck (Fig. 6.61). The colors are red for halothane, orange for enflurane, purple for isoflurane, and yellow for sevoflurane. These colors are also used on the bottle labels. Each collar has two projections, one thicker than the other, which are designed to mate with corresponding indentations on the bottle adaptor.

Bottle adaptors (adaptor tubes or assemblies, tube adaptors, filler tubes) are shown in Figures 6.64 and 6.65. They are also color coded. At one end, the adaptor has a connector with a screw thread to match the thread

on the bottle and a skirt that extends beyond the screw threads and has slots that match the projections on the bottle collar. At the other end is the male connector that fits into the vaporizer filler receptacle. A short length of plastic tubing with two inner tubes connects the ends. The tubing allows the bottle to be held higher or lower than the vaporizer.

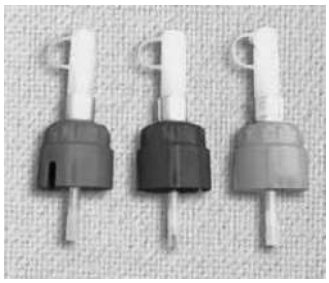


Figure 6.60 Bottle adaptors for vaporizers with funnel filling systems. The skirt fits over the bottle ring. The caps allow the adaptors to remain on the bottles without vapor being lost.

Figure 6.65 shows a male connector on the adaptor (key, probe, tube block, filler plug, male adaptor). It consists of a rectangular piece of plastic with a groove on one side and two holes on another surface. The groove is in different locations, depending on the agent that is to be used. This prevents the probe from being inserted into an incorrect vaporizer. The larger hole is for the agent to enter or leave the vaporizer, and the smaller hole is for air to leave the vaporizing chamber, preventing an air lock from developing. A one-way ball valve in the air line occludes the air port after the vaporizer is filled. This prevents overfilling and flooding the air channel with liquid anesthetic.

Figure 6.61 Bottle collar. The collar is color coded according to the bottle contents. It has two projections, one thicker than the other, which are designed to mate with corresponding grooves on the bottle adaptor.

Figure 6.62 Dual-port vaporizer filler receptacle. Note the plug to prevent leaks, the vent at the top, the drain valve at the bottom, and the two retaining screws at the right. A separate vent is not present on all filling receptacles. It must be loosened to fill the vaporizer. If the plug is not reinserted and the screw tightened, the vaporizer will leak.

Filling

To fill a vaporizer, the cap from the appropriate bottle is removed, and the bottle adaptor is screwed to the bottle until tight. If the connection is not tight, the vaporizer may be overfilled or a leak may occur. The vaporizer should be turned OFF before proceeding further. The plug, if present, is removed. The bottle component is then inserted with the groove matching that on the vaporizer receptacle. During insertion, the bottle should be below the inlet level. After the filler block is inserted, the retaining device is tightened, and the fill valve (vent) is opened. The bottle is then held higher than the filler receptacle so that liquid enters the vaporizer (Fig. 6.63, top). Gentle up-and-down motion may help to clear air bubbles and facilitate filling.

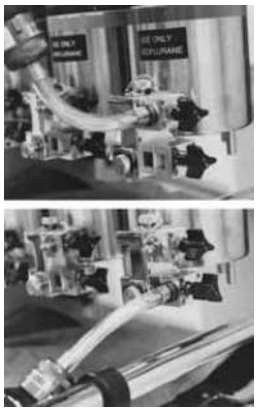


Figure 6.63 Keyed filling device with one front screw and top vent. **Top:** Filling the vaporizer. To fill, the plug is removed, the filler block is inserted, and the retaining screw is tightened. The vent is opened, and the bottle is tipped upward. **Bottom:** Draining the vaporizer. The filler block is inserted into the drain receptacle, the retaining screw is tightened, and the drain is opened. The bottle is held below the vaporizer.

After the desired liquid level has been reached, the fill valve is closed, the bottle lowered, and the retaining device loosened. The bottle adaptor is removed, and the plug is reinserted and tightened in place.

Draining

To drain the vaporizer, the bottle adaptor is attached to an appropriate bottle. In the dual-port filler, the bottom socket is used. The filler plug is removed, the male adaptor inserted, and the retaining device tightened. The bottle is held below the receptacle (Fig. 6.63, bottom), and the drain (spool) valve is opened. Fluid drains through one tube into the bottle, and air moves upward from the bottle through the other tube. After the vaporizer is drained, the drain valve is closed, the retaining device loosened, and the bottle adaptor removed. The filler plug

should be reinserted and the retaining device tightened.

Figure 6.64 Bottle adaptor. The bottle connector is at the left, and the male adaptor is at the right.

Figure 6.65 Male adaptor. The groove corresponds to a projection on the vaporizer filler receptacle. The larger hole is for anesthetic agent, and the smaller hole is for air.

Problems with Keyed Filling Systems

If the bottle collar for enflurane or halothane is upside down on the bottle, the bottle adaptor for the other agent will fit (72).

Liquid can leak if the device that holds the keyed component into the vaporizer is not tight. Failure to tighten the adaptor on the bottle, a blocked fluid path inside the vaporizer, or leakage in a valve or the adapter can result in liquid anesthetic agent leaking during filling (73). Vapor can leak out if the fill or drain valve is not closed (74).

Misalignment of the filling channel and the air channel between the filler and the vaporizer will make it difficult to fill the vaporizer. Other problems that will make it difficult to fill the vaporizer include the adaptor not sealing at the bottle end or a leak in the adaptor (73).

If the bottle does not have a keyed collar or the filler tube is lost, filling is awkward (75). With some filling devices, up to 27 mL of liquid agent may be left in the bottle after the vaporizer is

filled (76,77,78). The residual liquid can be poured into a bottle of the same agent (79).

Some practitioners turn the vaporizer ON and loosen the bottle adaptor to speed filling. One of these maneuvers alone will not cause the vaporizer to overfill, but both together may allow overfilling to occur (52,56,80). Incorrectly manufactured screw threads on the bottle necks may result in leaks with overfilling (81).

If the bottle lacks a keyed collar, it is necessary to develop a special technique to fill the vaporizer (75).

Quik-Fil System

The Quik-Fil system is only used for sevoflurane. It is seen in Figures 6.39, 6.48, 6.58, and 6.66.

Vaporizer Component

The vaporizer filler has a screw-on cap. The filler neck has three grooves that can accept only a special filler device, which comes attached to the bottle (Fig. 6.66).

Bottle Component

The bottle has a permanently attached, agent-specific filling device that has three ridges that fit into slots in the filler. A valve prevents liquid from draining when the bottle is inverted but not inserted into the vaporizer (Fig. 6.67).

Figure 6.66 Vaporizer filler block for Quik-Fil system. Note the three indentations, which allow only a bottle with the correct fitting to the inserted.

Figure 6.67 Bottle inserted into the filler block. Note the projections on the bottle that fit into the indentations on the filler block.

Filling

To fill the vaporizer, the filler cap and the bottle cap are removed. The bottle is inserted so that the projections fit into the corresponding grooves in the filler neck (Fig. 6.67). The bottle is pushed into the vaporizer component as far as it will go and held firmly in place. This will open a valve and allow liquid agent to flow into the vaporizer. After filling, the bottle is removed, and the filler cap and bottle cap are replaced.

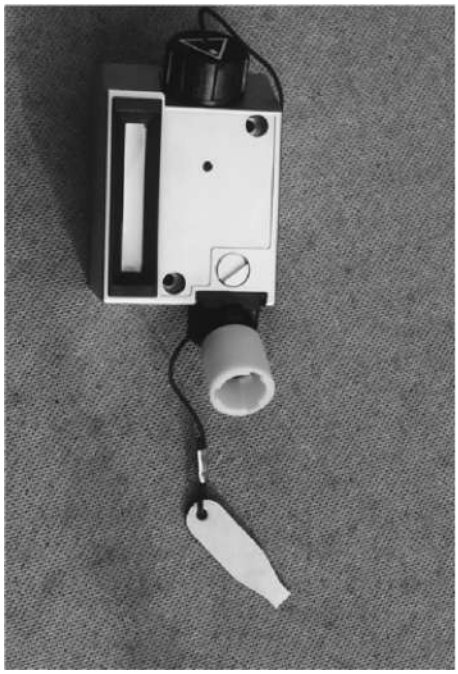


Figure 6.68 Drain attachment fitted to the filler block. The filler cap should be removed. Note the tool for opening and closing the drain plug.

Draining

To empty the vaporizer, the filler cap is removed from the vaporizer. The drain attachment is fitted to the bottom of the block (Fig. 6.68). The bottle is then inserted into the drain attachment (Fig. 6.69). The drain plug is unscrewed by using the tool attached to the filler cap. Fluid will flow from the vaporizer. After draining, the drain plug is tightened, and the filler cap is replaced and tightened.

Easy-Fil System

The Easy-Fil system is used on all four Tec 7 vaporizers.

Vaporizer Component

The vaporizer component (block) (Fig. 6.70) has a cap with a tool that is used to open and close the drain on the end that is inserted into the vaporizer. Inside the filler channel are two keys (ridges) that fit grooves on the bottle adapter.

Bottle Component

The bottle adaptor (Fig. 6.71) attaches to the bottle by aligning the notches with the projections on the bottle collar. The adaptor has grooves that must be aligned with the projections on the vaporizer.

Figure 6.69 Draining the vaporizer.

Filling

To fill the vaporizer, the bottle adaptor is attached securely to the bottle, and the filler cap on the vaporizer is removed. The bottle nozzle is inserted into the filler block, aligning the adaptor grooves with projections in the filler block. When the bottle is fully inserted, liquid will flow into the vaporizer. When the vaporizer is full or the bottle empty, the bottle is released and then removed from the vaporizer filler. The filler cap is replaced, and the cap is replaced on the agent bottle. The filler cap is tightened to minimize leaks.

Draining

To drain, the cap is removed from the vaporizer filler. A suitable container is placed under the drain nozzle. The drain plug is unscrewed by using the tool attached to the filler cap. Liquid should then flow into the container. After draining, the drain plug is tightened, and the filler cap is replaced and tightened.

Figure 6.70 Easy-Fil system on a vaporizer. The inside of the cap fits into the screwlike attachment above the drain port at the bottom. (Courtesy of Datex-Ohmeda.)

Desflurane Filling Systems

Filling systems for vaporizers used with desflurane are different from other filling systems. All use the same bottle to fill the vaporizer. This bottle has a crimped-on adaptor (Fig. 6.72). The bottle adaptor has a spring-loaded valve that opens when the bottle is pushed into the filling port on the vaporizer.

Figure 6.71 Bottle adaptors for the East-Fil system. (Courtesy of Datex-Ohmeda.)

Figure 6.72 Bottle for desflurane. The protection cap has been removed and is at the right. (Courtesy of Ohmeda, a division of BOC Health Care, Inc.)

To fill the Tec 6 vaporizer, the bottle protection cap is removed, and the bottle is fitted to the filler port and pushed up against the spring. After the bottle is fully engaged in the port, it is rotated upward (Fig. 6.73). The bottle is held in this position while filling. When the liquid level gauge indicates that the sump is full or when the

bottle is empty, the bottle is rotated downward and removed from the vaporizer. The valve on the bottle closes automatically to prevent agent spill. The filling port has a spring valve to prevent agent from escaping.

Figure 6.73 Filling Tec 6 vaporizer. The bottle is fitted to the filler port. After it is engaged in the filler port, it is rotated upward. When it reaches the upper stop, agent will enter the vaporizer. (Courtesy of Ohmeda, a division of BOC Health Care, Inc.)

Problems with these filling systems have been reported. Bottles containing desflurane that do not have the cap properly in place can leak agent (82,83). If the ĺ€Oĺ€ ring on the bottle is damaged or missing, agent may leak during filling (84,85,86).

Vaporizer Mounting Systems

Permanent Mounting

Permanent mounting means that tools are required to remove or install a vaporizer on the anesthesia machine. Advantages of this system include less physical damage to vaporizers and fewer leaks. Vaporizers are always filled in the vertical position.

There are problems with permanent mounting. The machine may not have enough mounting locations to accommodate all of the vaporizers that are likely to be needed. A malfunctioning vaporizer cannot easily be exchanged, especially while anesthesia is being administered.

Detachable Mounting

Detachable mounting systems are standard on most new anesthesia machines. They allow the vaporizer to be mounted and removed without the use of tools. The Select-a-tec system and a similar system from Drager Medical are widely used. Vaporizers cannot be exchanged between these two systems. Some other anesthesia machine manufacturers use these mounting systems as well. Some vaporizers from other manufacturers are equipped with mounting systems that are compatible with one of these systems.

The Select-a-tec system is shown in Figures 6.74 and 6.75. It consists of a pair of port valves for each vaporizer position. Each vaporizer has a special mounting bracket containing two plungers (spindles), which fits over the port valves. The weight of the vaporizer and an O-ring around each port valve create a seal

between the mounting system and the vaporizer. On the back of each vaporizer is a locking lever.

Before mounting a vaporizer, the control dial must be in the OFF position, and any adjacent vaporizer must be turned OFF. The locking lever on the vaporizer should be unlocked. The vaporizer is fitted onto the mounting system and locked in position.

To remove a vaporizer, the control dial is turned OFF, and the locking lever moved to the unlock position. The vaporizer can then be lifted off the manifold.

When the vaporizer is turned ON (Fig. 6.75, right), the two plungers move downward, opening the valve ports and connecting the vaporizer into the fresh gas stream. When the vaporizer is turned OFF (Fig. 6.75, left), it is isolated from the fresh gas flow.

The Drager Medical mounting system is shown in Figures 6.24 and 6.76. The Vapor 2000 vaporizer must be in the Î€TÎ€ (travel) position before it can be unlocked from the machine. This position isolates the vaporizing chamber and prevents liquid from passing into the bypass during the time that the vaporizer is not on the machine.

After a vaporizer has been added to a machine, several checks should be made to ensure proper positioning. These include sighting across the tops of the vaporizers to ensure that they are level and at the same height. An attempt should be made to lift each off the manifold without unlocking it. If the vaporizer can be removed, it is improperly positioned. It should be possible to turn ON only one vaporizer at a time. Finally, the anesthesia machine must be checked for leaks with each vaporizer in both the ON and OFF position as described in Chapter 33.

These mounting systems have a number of advantages. The anesthesia machine can have fewer mounting locations, allowing a more compact machine. Vaporizers can be easily removed and replaced, even during a case. If malignant hyperthermia is a potential problem, the vaporizers can be removed. This gives better results than if the vaporizers remain on the machine in the OFF position (87).

There are a number of disadvantages of these mounting systems. Partial or complete obstruction to gas flow

from problems with the mounting system has been reported (88,89,90,91). Leaks may occur (92,93,94,95,96,97,98,99,100,101,102). A common leak source is an absent or damaged O-ring (103,104,105,106,107,108). Another cause is leaving the locking lever in the unlocked position (109). If something is pushed under the vaporizer enough to lift it slightly off of the O-ring, a leak may result when the vaporizer is turned ON. Differences among vaporizers and interlocks from different manufacturers can pose problems of compatibility (98,100).

Figure 6.74 Select-a-tec mounting system. A vaporizer is mounted on the right. In the center position, the nipples and O rings are in place, ready to accept a vaporizer. Caps are over the nipples and O rings on the left, to protect them. The projections between the sets of nipples are to prevent two vaporizers from being turned ON at the same time (vaporizer exclusion or interlock system). The plastic projections are interconnected so that they move from side to side. The rod shown on the vaporizer to the right contacts the right projection. When that vaporizer is turned ON, the rod moves to the left, causing that projection to move to the left. The left projection also moves to the left. If there were vaporizers in those positions, their rods would also be moved in a way that their dials could not be turned ON. The inlet and outlet pipes are below the mounting system. They enter at opposite ends so that they cannot be interchanged.

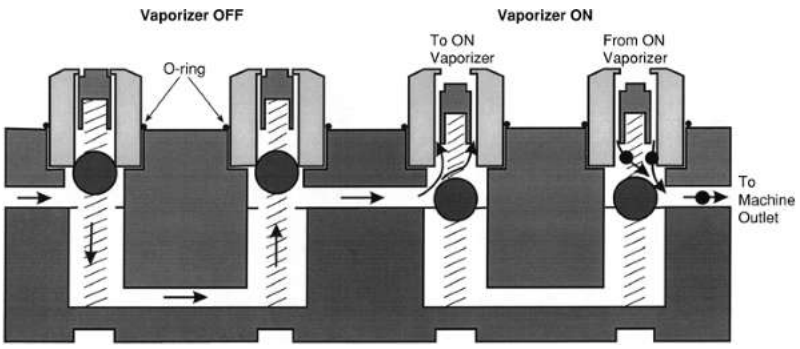


Figure 6.75 Select-a-tec mounting system. The mounting system has channels for the fresh gas flow from the flowmeters toward the machine outlet. When a vaporizer is mounted and turned ON, two plungers push the valves down so that gas passes through the vaporizer. If the mounting position is empty or the vaporizer is turned OFF, the gas passes directly through the mounting system. (Reproduced from a drawing furnished by Datex-Ohmeda.)

Figure 6.76 Drager vaporizer mounting system. Between the two nipples is the receptacle for the locking mechanism.

Several cases have been reported where there was failure to deliver anesthetic agent associated with problems with mounting systems (110,111,112). In another case, a switch malfunction caused the fresh gas flow to be directed to the wrong vaporizer (113). This resulted in delivery of fresh gas with no vapor to the breathing system.

Interlock Devices

Interlock (vaporizer exclusion) systems prevent more than one vaporizer from being turned ON at a time (114). Checking the interlock device should be included with the anesthesia apparatus checkout procedure. Systems are shown in Figures 6.24, 6.74, 6.77, and 6.78. Interlock system failures have been reported (115,116,117,118,119).

For Datex-Ohmeda vaporizers, operating the dial release activates two extension rods that prevent operation of any other vaporizer installed on the manifold. Older versions of the Select-a-tec system that provide mounting positions for three vaporizers require that if only two vaporizers are fitted, then the center position must be occupied. If the center position is not occupied, the interlock that helps to ensure that only one vaporizer at a time can be turned ON is ineffective. Later versions incorporate an additional interlock that helps to ensure that only one vaporizer can be turned ON at a time, even if the center position is not occupied.

Hazards

Incorrect Agent

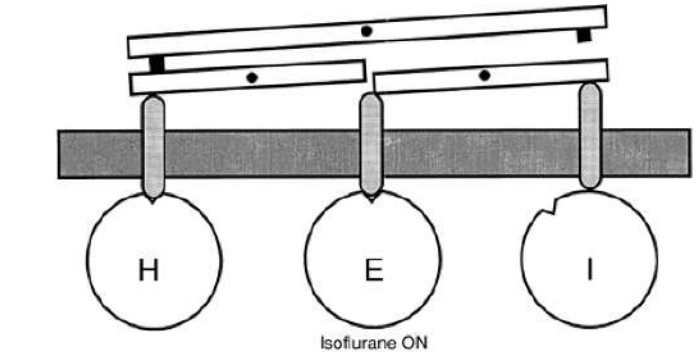
Most contemporary concentration-calibrated vaporizers are agent specific. Filling a vaporizer with an agent other than the one for which it was designed is still a hazard but is less likely if the vaporizer is equipped with an agent-specific filling system (120).

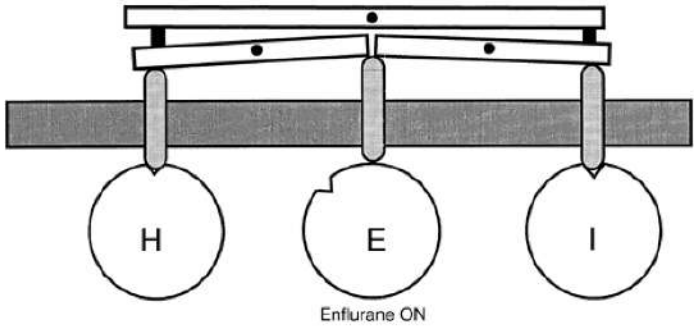
If an agent of low potency or low volatility is placed in a vaporizer designed for an agent of higher potency or volatility, the effect will be an output of low potency (121,122). Conversely, if an agent of high potency or volatility is used in a vaporizer intended for an agent of low potency or volatility, a dangerously high concentration may be delivered.

If an incorrect agent is placed in a vaporizer, there will likely be a mixture of agents in the vaporizer. This will result from the residual amount of the correct agent as well as the amount contained in the wicks. Some anesthetic agent monitors (Chapter 22) will detect agent mixtures. Smelling cannot be relied on to tell which agent is in a vaporizer, because the smell of a small amount of one agent can completely mask the odor of a less-pungent agent, even if the second agent is present in much higher concentration (123). Anesthesia personnel can detect the presence of a volatile agent but are not able to identify an agent by smell (124).

If a vaporizer is filled with the wrong agent, it must be completely drained and all liquid discarded. Gas should

be allowed to flow through it until no agent can be detected in the outflow. Draining cannot be relied on to completely empty a vaporizer.





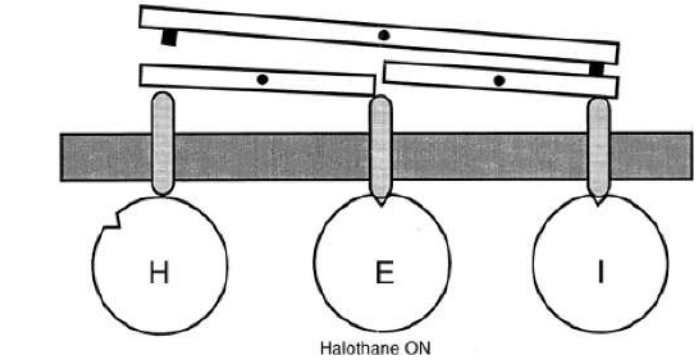


Figure 6.77 North American Drager interlock system. When the vaporizer of choice is turned ON, a pin is forced into a notch on the concentration control knob of each of the other vaporizers. These vaporizers are then locked in the OFF position. (Reproduced from a drawing furnished by North American Drager, Inc, Telford, Pa.)

Tipping

If some vaporizers are tipped sufficiently, liquid from the vaporizing chamber may get into the bypass or outlet. If this occurs, a high concentration will be delivered when the vaporizer is first used.

Tipping can be prevented by mounting vaporizers securely and handling them with care when they are not mounted. Vaporizers should be turned OFF or placed in a travel setting if they are being moved. Should tipping occur, a high flow of gas should be

run through the vaporizer with the concentration dial set at a low concentration until the output shows no excessive agent.

Many new vaporizers have a mechanism that blocks the entrance and exit from the vaporizing chamber. This prevents the problems associated with tipping the vaporizer when it is transported.

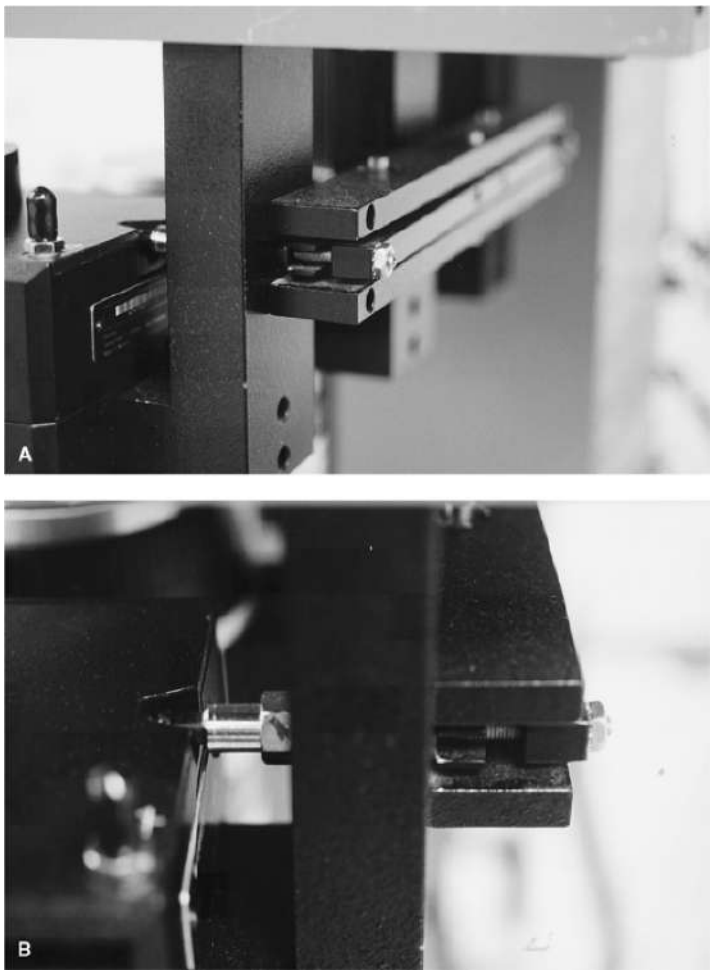


Figure 6.78 North American Drager interlock system. The top picture **(A)** shows the adjustment screw at the back. It is connected to the pin **(B)**, which interlocks with the concentration control dial of the vaporizer.

Overfilling

If a vaporizer is overfilled, liquid agent may enter the fresh gas line, and lethal concentrations may be delivered. Another result of overfilling may be complete vaporizer failure so that it produces no output (19).

On most vaporizers, the filling port is situated so that overfilling cannot occur. Liquid will pour over the edge of the funnel before the level inside the vaporizer rises to a dangerous level.

If a vaporizer is tipped during the filling process, it is possible that it could be overfilled. The vaporizer should be securely attached to the anesthesia machine and in a vertical position.

Agent-specific filling devices prevent overfilling by connecting the air intake in the bottle to the inside of the vaporizer chamber. To facilitate filling when using key filling devices, many users have found that slightly unscrewing the bottle adaptor can speed the filling process. Turning the concentration dial of the vaporizer ON during filling will accomplish the same end. Such practices should be avoided, because they can result in overfilling (16,17,56,125).

Reversed Flow

Although the anesthesia machine standard (5) requires that the vaporizer inlet be male and the outlet female, the direction of gas flow be marked, and the inlet and outlet labeled, it is possible to connect the fresh gas delivery line from the anesthesia machine to the outlet and

the delivery tube to the breathing system to the inlet, especially if the vaporizer is used in a freestanding position (126). Reversed flow through a vaporizer has been reported after improper connection or repairs to the selector valve (127,128).

If the flow through a vaporizer is reversed, in most cases there will be an increased output. The consequences of reversed flow to a particular vaporizer are discussed with individual vaporizers earlier in this chapter.

Control Dial in Wrong Position

After previous vaporizer use or servicing, the vaporizer control dial may be left ON (114,129,130,131). For this reason, the dial should be inspected as part of the preuse checking procedure.

The control dial may be changed during a case without the operator's knowledge. Operating room personnel moving a machine or simply passing by may grab the dial and change the setting.

Leaks

The effects of a leak on a vaporizer will depend on the size and location of the leak and whether or not there is a check valve at the vaporizer outlet. In addition to affecting fresh gas composition and flow, leaks may pollute the operating room air.

A common cause of leaks is failure to replace or adequately tighten the filler cap. If the fill valve or vent on a keyed filling system is not closed or the plug is not replaced and tightened in place, a leak will occur when the vaporizer is turned ON (Fig. 6.79) (74,132). If an incorrect cap is used on the filler device, a leak may result (133).

The fitting between a vaporizer and its inlet or outlet connection may become loose or broken (134,135). A vaporizer may not be mounted properly (37,95,96,97,105,108,109,136,137).

With a leak in a vaporizer or its mount, the machine will often function normally until the vaporizer is turned ON. At that point, fresh gas flow from the machine will be lost through the leak, and the total flow will be reduced. The leak may contain little or no vapor, especially if it is in the mounting mechanism. A leak should be suspected if a vaporizer appears to require filling with unusual frequency, if an odor can be detected, or if there is a loss or reduction in the fresh gas flow into the breathing system after the vaporizer is turned ON. A loose or missing filler cap may be detected by liquid being forced out under pressure when the vaporizer is turned ON (138,139). If the level is low or below the filler, liquid may not be splattered (14). If the device to hold the key filler in place is broken, a leak will occur (54,55). Splattering may not be seen with the key filler system on certain vaporizers.

Figure 6.79 Failure to replace the filler plug will result in a leak when the vaporizer is turned ON.

A leak can be identified by using the sampling tube from an anesthetic agent monitor to ‾€sniff‾€ around the vaporizer (55).

Personnel who fill vaporizers should be instructed to always close filler caps and vents tightly. A leak in a vaporizer can be detected when the anesthesia machine is tested before use if the vaporizer is turned ON (Chapter 33). Even after a proper preuse check, if anything is pushed under the vaporizer and the vaporizer is lifted even slightly from its mount, a leak may occur.

Vapor Leak into the Fresh Gas Line

Some vaporizers leak small amounts of vapor into the bypass when turned OFF (87). Interlock devices or selectors will not prevent this problem if there is still a diffusion pathway via the

selector valve (140). The amount of such a leak depends on the ambient temperature as well as the size and configuration of the internal ports. Although the amounts delivered are usually too small to produce a clinical effect, it might cause a ʃ€sensitizedʃ€ individual to react to a halogenated agent or trigger an episode of malignant hyperthermia. These leaks can be reduced by not turning a vaporizer from the OFF to the ʃ€0ʃ€ setting unless it is to be used.

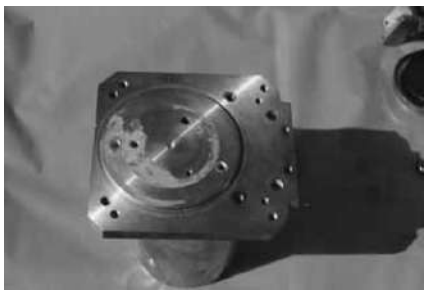


Figure 6.80 Corrosion in vaporizer caused by water and other foreign substances.

Contaminants in the Vaporizing Chamber

It is possible for various substances to be poured into a bottle that should contain anesthetic agent (141). Cleaning agents may collect in the funnel filler and be washed into the vaporizing chamber when it is filled with liquid agent. Water and other foreign substances can cause corrosion (Fig. 6.80). If foreign substances are known to have entered the vaporizer, the manufacturer should be contacted to determine what measures need to be taken.

Physical Damage

Shock, excessive vibration, or mistreatment may lead to malfunction. Damage to vaporizers permanently mounted on a machine is significantly less than with those that can be disconnected and are frequently moved (142). A sufficient number of vaporizers should be purchased so that they do not need to be moved during routine use. If a vaporizer must be removed, care should be taken to protect it from physical damage.

No Vapor Output

The most common cause of no vapor output is an empty vaporizer.

Incorrect vaporizer mounting can result in little or no vapor output (112,143). In most cases, this can be detected by checking for leaks with the vaporizer ON (Chapter 33). An overfilled vaporizer may deliver no vapor (19). Blood entering the vaporizer can cause vaporizer failure (144). If an anesthesia machine is turned OFF and then ON again, the vaporizer settings

may default to zero (145). Failure to deliver adequate vapor can be detected by an anesthetic gas monitor (Chapter 22).

Projectile

A case has been reported in which a portable vaporizer carried into the magnetic resonance imaging (MRI) suite was rapidly attracted to the magnet (146). The vaporizer was considered MRI safe but only when attached to a rack.

Disposing of Liquid Anesthetics

After a vaporizer has been drained, the question of what do with the liquid agent arises. Some of these agents will react with plastic. A simple solution is to place the agent in a bottle or tray and set it outside, where personnel will not be exposed to the vapor. An evaporator has been described (147). It consists of a glass flask with a stopper that has two holes. A glass tubing open to room air is inserted through one hole. The glass tubing that is inserted through the other hole is connected to the vacuum system. The liquid is allowed to evaporate, and the vapor is removed by the vacuum system.

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Questions

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. C if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

1. Which factors will cause a shift from the liquid to the vapor phase?

A. Heating the vaporizer

B. Cooling the room

C. Increasing the flow through the vaporizer

D. Decreasing atmospheric pressure

View Answer

2. Which statements concerning boiling point are true?

A. Boiling point is independent of the atmospheric pressure

B. Boiling points for commonly used volatile anesthetic agents vary between 48ยฐC and 59ยฐC at 760 torr

C. Anesthetic agents with high boiling points are more susceptible to variations in barometric pressure than agents with lower boiling points

D. Atmospheric pressure and the vapor pressure of an agent are equal at the boiling point

View Answer

3. The concentration of a volatile anesthetic may be expressed as

A. Volumes percent

B. The number of units of the vapor in relation to a total of 100 units

C. The partial pressure

D. The pressure of the vapor in relationship to the total pressure exerted by all of the gases in the sample

View Answer

4. Which of the following accurately reflects the heat of vaporization?

A. It is the amount of heat given off in the process of converting a liquid into a vapor

B. The temperature of the liquid increases as vaporization proceeds

C. The greater the flow, the higher the temperature of the liquid will become

D. It is expressed as calories per gram

View Answer

5. Which of the following accurately reflect specific heat?

A. It is the amount of heat needed to raise the temperature of a substance by 1ยฐF

B. The higher the specific heat the more heat that is required to raise the temperature of a quantity of a substance

C. It is the heat required to raise 1 milliliter of a substance by 1ยฐF

D. Substances with high specific heats are preferred when choosing the material from which to construct a vaporizer

View Answer

6. Most concentration-calibrated vaporizers

A. Receive a flow from a dedicated flowmeter

B. Are placed downstream of the fresh gas inlet

C. Have a dial that is turned clockwise to increase the concentration

D. Are calibrated in volumes percent

View Answer

7. Methods used by vaporizers to vaporize agents include

A. Bubble through

B. Flow over

C. Injection into a vaporizing chamber

D. Injection into a known volume of gas

View Answer

8. Thermal compensation in a vaporizer is accomplished by

A. Warming the room

B. Supplying heat to the vaporizer

C. Using glass in the vaporizing chamber to conduct heat

D. Altering the flow through the vaporizing chamber

View Answer

9. How do changes in back pressure affect the output of a vaporizer?

A. The pumping effect will increase vaporizer output

B. A check valve at the machine outlet is not an effective solution to the pumping effect

C. The pressurizing effect will decrease vaporizer output

D. The pumping effect is greater with low fresh gas flows, large pressure fluctuations, and low vaporizer settings

View Answer

10. Acceptable locations for a vaporizer on the anesthesia machine include

A. Between the check valve and the common gas outlet

B. Between the common gas outlet and the breathing system

C. Between the oxygen flush and the breathing system

D. Between the flowmeters and the machine outlet

View Answer

11. Advantages of having detachable vaporizers include

A. A more compact machine is possible

B. Easy removal if vaporizer failure occurs

C. Complete removal during malignant hyperthermia

D. Vaporizers can be used on different brands of anesthesia machine

View Answer

12. If an agent of low potency or volatility were placed in a vaporizer for agents of high volatility and potency,

A. A mixture of agents will likely be delivered

B. The vapor output will be higher than the scale reading

C. The vaporizer output will be lower than the reading on the dial

D. The mixture can be determined by smelling the agents in the fresh gas flow

View Answer

13. Actions that could cause a vaporizer to be overfilled include

A. Loosening the connection between the agent bottle and the filling device

B. Tipping the vaporizer

C. Turning the control dial on the vaporizer ON

D. Filling a vaporizer in the anesthesia work area

View Answer

14. A vaporizer located downstream of the common gas outlet

A. May be installed backward

B. Presents significant resistance to gas flow

C. May deliver a high concentration into the breathing system

D. Can be used if the vaporizer is firmly fixed to a horizontal surface

View Answer

Chapter 7

The Breathing System: General Principles, Common Components, and Classifications

The breathing system (breathing or patient circuit, respiratory circuit or system) is a gas pathway connected to the patient, through which gas flows occur at respiratory pressures, and into which a controlled composition of a gas mixture is dispensed (1). In practice, the breathing system is usually regarded as extending from the point of fresh gas inlet to the point at which gas escapes to atmosphere or a scavenging system. Scavenging equipment is not considered part of the breathing system.

The breathing system receives the gas mixture from the anesthesia machine, delivers gas to the patient, re-moves carbon dioxide, and the conditions temperature and humidity of the inspired mixture (2). It allows the continuous flow from the anesthesia machine to be converted into an intermittent flow; allows spontaneous, controlled, or assisted respiration; and provides for other functions such as gas sampling and airway pressure, flow, and volume monitoring (2).

General Principles

Resistance

Physics

When gas passes through a tube, the pressure at the outlet will be lower than that at the inlet (3). The drop in pressure is a measure of the resistance that must be overcome as the gas moves through the tube. Resistance varies with the volume of gas passing through per unit of time. Therefore, flow rate must be stated when a specific resistance is mentioned.

The nature of the flow is important in determining resistance. There are two types of flow: laminar and turbulent. In clinical

practice, flow is usually a mixture of both.

Laminar Flow

Figure 7.1A illustrates laminar gas flow through a tube. The flow is smooth and orderly, and particles move parallel to the walls of the tube. Flow is fastest in the center of the tube, where there is less friction.

When flow is laminar, the Hagen-Poiseuille law applies. This law states that

ฮ” P = (L ร— v ร— V)/r^4

where r is the radius of the tube, ฮ”P is the pressure gradient across the tube, v is the viscosity of the gas, L is length, and V is the flow rate. Resistance is directly proportional to flow rate during laminar flow.

Turbulent Flow

Figure 7.1B illustrates turbulent gas flow through a tube. The flow lines are no longer parallel. Eddies, composed of particles moving across or opposite the general direction of flow, are present. The flow rate is the same across the diameter of the tube.

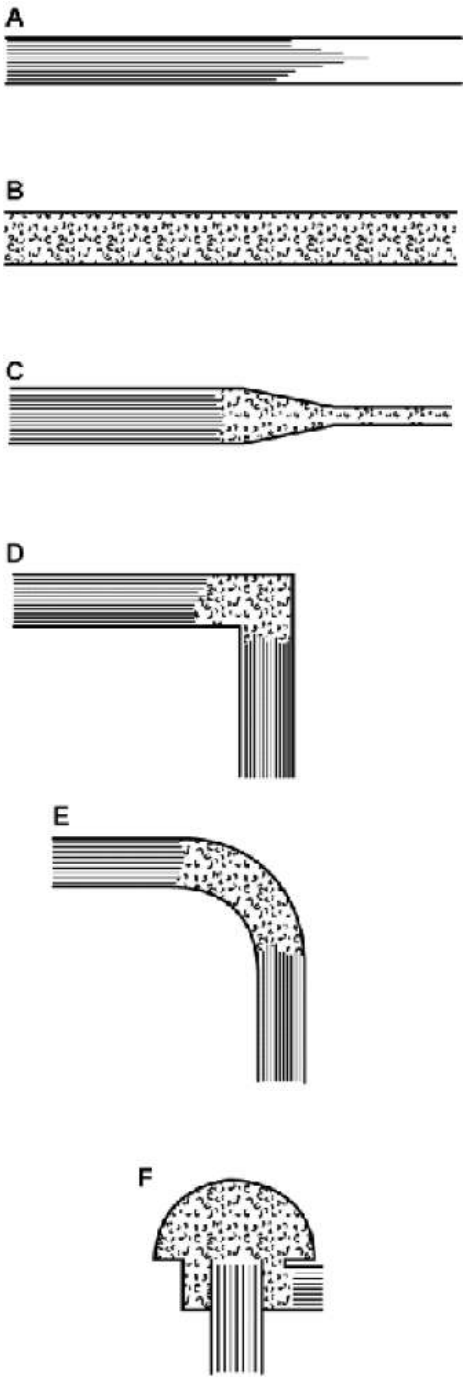

Figure 7.1 Laminar and turbulent flow. **A:** Laminar flow; the lines of flow are parallel and flow is slower near the sides of the tube because of friction. **B:** Generalized turbulent flow, which occurs when the critical flow rate is exceeded. Eddies move across or

opposite the general direction of flow. **CÎ€“F:** Localized turbulence, which occurs when there is change in direction or the gas passes through a constriction.

During turbulent flow, the factors responsible for the pressure drop along the tube include those described for

laminar flow, but in this situation, gas density becomes more important than viscosity.

ƒ” P = (L ร— V^2 ร— K)/r^5

In this equation, K is a constant that includes such factors as gravity, friction, and gas density and viscosity. Resistance is proportional to the *square* of the flow rate with turbulent flow.

Turbulent flow can be generalized or localized.

Generalized Turbulent Flow

When the flow of gas through a tube exceeds a certain value, called the *critical flow rate*, generalized turbulent flow results.

Localized Turbulent Flow

As seen in Figure 7.1CÎ€“F, when gas flow is below the critical flow rate but encounters constrictions, curves, valves, or other irregularities, an area of localized turbulence results. The increase in resistance will depend on the type and number of obstructions encountered.

To minimize resistance, gas-conducting pathways should have minimal length and maximal internal diameter and be without sharp curves or sudden changes in diameter.

Significance of Resistance

Resistance imposes a strain, especially with ventilatory modes where the patient must do part or all of the respiratory work (e.g., spontaneous respiration, intermittent mandatory ventilation, or pressure support ventilation). Changes in resistance tend to parallel changes in the work of breathing. The tracheal tube is usually the source of more resistance and a more important factor when determining the work of breathing than the breathing

system (4).

There is lack of agreement about what level of resistance is excessive. Anesthesia providers should be aware of how much resistance components of breathing systems offer and to employ, wherever possible, those offering the least resistance. For some patients, increased expiratory resistance may be desirable. This should be achieved by using devices designed for that purpose.

Flow-volume loops (Chapter 23) can show changes in resistance to flow in a breathing system.

Compliance

Compliance is the ratio of a change in volume to a change in pressure. It is a measure of distensibility and is usually expressed in milliliters per centimeter of water (mL/cm H_2O).

The most distensible breathing system components are the reservoir bag and the breathing tubes. Compliance will help to determine the tidal volume (5). Compliance can be illustrated graphically with a pressure-volume loop (Chapter 23).

Rebreathing

Rebreathing means to inhale previously respired gases from which carbon dioxide may or may not have been removed. There is a tendency to associate the word *rebreathing* with carbon dioxide accumulation. This is unfortunate because although it is true that rebreathing can result in higher inspired carbon dioxide concentrations than normal, it is possible to have partial or total rebreathing without an increase in carbon dioxide.

Factors Influencing Rebreathing

Fresh Gas Flow

The amount of rebreathing varies inversely with the total fresh gas flow. If the volume of fresh gas supplied per minute is equal to or greater than the patient's minute volume, there will be no rebreathing, as long as provision is made for unimpeded exhaust to atmosphere or to a scavenging system at a point close to the patient's respiratory tract (6). If the total volume of gas supplied per minute is less than the minute volume, some exhaled gases must be rebreathed to make up the required volume (assuming no air dilution).

Mechanical (Apparatus) Dead Space

Mechanical dead space is the volume in a breathing system occupied by gases that are rebreathed without any change in composition. Apparatus dead space can be minimized by separating the inspiratory and expiratory gas streams as close to the patient as possible. If there is a leak around a face mask, dead space decreases (7).

The mechanical dead space should be distinguished from the physiological dead space, which includes (a) anatomical dead space, consisting of the patient's conducting airway down to the alveoli, and (b) alveolar dead space, which is the volume of alveoli ventilated but not perfused.

The gas composition in the mechanical dead space will vary according to whether it is occupied by anatomical dead space gas, alveolar gas, or mixed exhaled gas. Gas exhaled from the anatomical dead space has a composition similar to inspired gas but is saturated with water vapor and is warmer. Alveolar gas is saturated with water vapor at body temperature and has less oxygen and more carbon dioxide than inspired gas. The concentration of anesthetic agent in alveolar gas will differ from that in the inspired gas. Mixed expired gas will have a composition intermediate between that of anatomical dead space and alveolar gas.

Breathing System Design

In addition to the above factors, the various components of a breathing system may be arranged so that there is more or less rebreathing. Chapters 8 and 9 provide more details on breathing systems.

Effects of Rebreathing

With no rebreathing, the composition of inspired gas is identical to that of the fresh gas delivered by the anesthesia machine. With rebreathing, the inspired gas is composed partly of fresh gas and partly of rebreathed gas.

Heat and Moisture Retention

Fresh gas from the anesthesia machine is dry and at room temperature. Exhaled gases are warm and saturated with moisture. Rebreathing reduces heat and moisture loss from the patient. In most breathing systems, heat is rapidly lost to atmosphere, and gas that is reinhaled has a lower temperature and moisture content than exhaled gas.

Altered Inspired Gas Tensions

The effects of rebreathing on inspired gas tensions will depend on what parts of the exhaled gases are rebreathed and whether these pass to the alveoli (and so influence gas exchange) or only to the anatomical dead space.

Oxygen

Rebreathing alveolar gas will cause a reduction in the inspired oxygen tension.

Inhaled Anesthetic Agents

Rebreathing alveolar gas exerts a ‘€cushioning‘€ effect on changes in inspired gas composition with alterations in fresh gas composition. During induction, when alveolar tensions are lower than those in the fresh gas flow, rebreathed alveolar gas will reduce the inspired tension and prolong induction. During recovery, the alveolar tension exceeds that of the inspired gases, and rebreathing slows agent elimination.

Carbon Dioxide

Rebreathing alveolar gas will cause an increased inspired carbon dioxide tension unless the gas passes through an absorbent before being rebreathed. Because carbon dioxide is concentrated in the alveolar portion of expired gases, the efficiency with which it is eliminated from a breathing system varies. If the system is designed so that alveolar gas is preferentially eliminated through the adjustable pressure limiting (APL) valve or the ventilator spill valve, carbon dioxide retention will be minimal, even with a low fresh gas flow. Systems that do not maintain the separation between fresh gas, dead space gas, and alveolar gas require relatively high fresh gas flows to eliminate carbon dioxide.

With spontaneous respiration, carbon dioxide retention is generally considered undesirable. Although the patient can

compensate by increasing minute volume, a price is paid in terms of increased work of breathing. In some cases, compensation by increasing minute volume may not be adequate.

During controlled ventilation, some carbon dioxide in the inhaled gases may be advantageous. Rebreathing will allow normocarbia to be achieved despite hyperventilation. Hypocarbia can be avoided and heat and moisture retained.

Discrepancy between Inspired and Delivered Volumes

The volume of gas discharged by a ventilator or reservoir bag usually differs from that which enters the patient. The volume actually inspired may be less or greater than that delivered.

Causes of Increased Inspired Volume

When a ventilator is in use and the fresh gas flow rate is greater than the rate at which it is absorbed by the patient or lost through leaks in the breathing system, the fresh gas flow delivered during inspiration may be added to the tidal volume delivered by the ventilator (8,9). This augmentation increases with higher fresh gas flows and I:E ratios and lower respiratory rates (10). Modern anesthesia ventilators have been designed to eliminate the additional tidal volume caused by fresh gas flow. For an in-depth discussion of this subject and how modern ventilators deal with it, see Chapter 12.

Causes of Decreased Inspired Volume

A reduction in the tidal volume delivered to the patient will result from gas compression and distention of breathing system components during inspiration (11). This is referred to as *wasted ventilation*. Wasted ventilation increases with increases in airway pressure, tidal volume, increased breathing system volume, and component distensibility (11,12,13,14,15). Proportionally, more of the set tidal volume is lost with small patients (11,16).

Tidal volume is also decreased by leaks in the breathing system. The amount lost will depend on the size and location of the leaks and the pressure in the breathing system.

Tidal volumes are best measured between the patient and the

breathing tubes (Chapter 23). Measuring tidal volume at the end of the expiratory limb will reflect increases caused by fresh gas flow and decreases resulting from leaks in the breathing system but will miss decreases from wasted ventilation. Leaks between the volume sensor located at the patient port and the patient can be detected by comparing the inspired and exhaled tidal volumes. If there is a significant leak, the exhaled volume will be less than the inspired volume.

Discrepancy between Inspired and Delivered Oxygen and Anesthetic Gas Concentrations

The composition of the gas mixture that exits the machine may be modified by the breathing system so that the mixture the patient inspires differs considerably from that delivered to the system. There are several contributing factors.

Rebreathing

The effect of rebreathing will depend on the volume of the rebreathed gas and its composition. This will depend on the factors discussed previously.

Air Dilution

If the fresh gas supplied per respiration is less than the tidal volume, negative pressure in the breathing system may cause air dilution if there is a leak.

Air dilution makes it difficult to maintain a stable anesthetic state. It causes the concentration of anesthetic in the inspired mixture to fall. This results in a lighter level of anesthesia with stimulated ventilation. The increased ventilation causes more air dilution. The opposite is also true. Deepening anesthesia depresses ventilation. Respiratory depression decreases air dilution, which causes an increase in the inspired anesthetic agent concentration. This in turn leads to further depressed respiration.

Leaks

When a leak occurs, positive pressure in the system will force gas out of the system. The composition and amount of the gas

lost will depend on the location and size of the leak, the pressure in the system, and the compliance and resistance of both the system and the patient.

Anesthetic Agent Uptake by the Breathing System Components

Anesthetic agents may be taken up or adhere to rubber, plastics, metal, and carbon dioxide absorbent (17). This will lower the inspired concentration. Uptake will be directly proportional to the concentration gradient between the gas and the components, the partition coefficient, the surface area, the diffusion coefficient, and the square root of time.

Anesthetic Agents Released from the System

Elimination of anesthetic agent from the breathing system will depend on the same factors as uptake. The system may function as a low output vaporizer for many hours after a vaporizer has been turned OFF even if the rubber goods and absorbent are changed. This can result in a patient being inadvertently exposed to the agent.

Common Components

Some components are found in only one type of breathing system. These will be discussed under the individual systems. Others components are found in more than one system, making their inclusion in a general chapter such as this appropriate.

Bushings (Mounts)

A bushing serves to modify the internal diameter of a component. Most often, it has a cylindrical form and is inserted into, and becomes part of, a pliable component such as a reservoir bag or a breathing tube.

Sleeves

A sleeve alters the external diameter of a component.

Connectors and Adaptors

A connector is a fitting intended to join together two or more

similar components. An adaptor is a specialized connector that establishes functional continuity between otherwise disparate or incompatible components.

An adaptor or connector may be distinguished by (a) shape (e.g., straight, right angle or elbow, T, or Y), (b) component(s) to which it is attached, (c) added features (e.g., with nipple or APL valve), and (d) size and type of fitting at either end (e.g., 15-mm male, 22-mm female).

All anesthesia breathing systems terminate at the patient connection port. This is the point where the breathing system connects to a device that establishes continuity with the patient's respiratory system (a tracheal tube, face mask, or supraglottic airway device).

All face masks have a 22-mm female opening while most other devices have a 15-mm male fitting. To facilitate the change from mask to tracheal tube, and the like, a component having a 22-mm male fitting with a concentric 15-mm female fitting is used at the patient connection port. Usually, this component is a right angle connector (Fig. 7.2), also known as an elbow adaptor, elbow joint, elbow connector, mask angle piece, mask adaptor, or mask elbow.

Connectors and adaptors can be used to:

1. Extend the distance between the patient and the breathing system. This is especially important in head and neck surgery when the presence of the breathing system near the head may make it inaccessible to the anesthesia personnel and/or interfere with the surgical field.
2. Change the angle of connection between the patient and the breathing system.
3. Allow a more flexible and/or less kinkable connection between the patient and the breathing system.
4. Increase the dead space.

A variety of connectors are available (Fig. 7.2), and many more have been described in the literature. In selecting a connector, several principles should be kept in mind.

Figure 7.2 Various connectors. **1:** A swivel connector that can be used to insert a flexible fiberscope. It has a flexible accordion-type side arm. **2:** A flexible metal connector that can be used between the tracheal tube and the breathing system. It cannot be used with a mask. **3:** Straight connector with a side gas sampling port. **4:** Right angle connector for insertion of a flexible fiberscope. It can accommodate different sized fiberscopes by changing the diaphragm. The large cap is used if no diaphragm is present. **5:** Right angle connector with gas sampling port.

1. Resistance increases with sharp curves and rough sidewalls.
2. Connectors add dead space if positioned between the breathing system and the patient. In the adult patient, this may not be of much significance. However, in infants, any increase in dead space may be excessive.
3. Connectors increases the number of locations at which disconnections can occur.

Reservoir Bag

Most breathing systems have a reservoir bag, also known as the respiratory, breathing, or sometimes erroneously, rebreathing, bag. Most bags are composed of rubber or plastic and are ellipsoidal in shape so that they can be grasped easily with one

hand. Latex-free reservoir bags are available. The neck is the part of the bag that connects with the breathing system. The neck must have a 22-mm female connector (18,19). The tail is the end opposite from the neck. A loop may be provided near the tail to hold the bag upside down, which facilitates drying if the bag is reusable.

The bag has the following functions:

1. It allows gas to accumulate during exhalation. This provides a reservoir of gas for the next inspiration. This permits rebreathing, allows more economical use of gases, and prevents air dilution.
2. It provides a means whereby ventilation may be assisted or controlled.
3. It can serve through visual and tactile observation as a monitor of a patient's spontaneous respiration (20).
4. Because the bag is the most distensible part of the breathing system, it protects the patient from excessive pressure in the breathing system.

The pressure-volume characteristics of bags become important if there is no way for gases to escape from the system and inflow continues. Adding volume to a bag normally causes a negligible rise in pressure until the nominal capacity is reached. As more volume continues to be added, the pressure rises rapidly to a peak and then reaches a plateau. As the bag distends further, the pressure falls slightly. The peak pressure is of particular interest, because this represents the maximal pressure that can develop in a breathing system. The American Society for Testing and Materials (ASTM) standard for reservoir bags requires that for bags of 1.5 L or smaller, the pressure shall be not less than 30 cm H_2O or over 50 cm H_2O when the bag is expanded to four times its capacity (18). For bags larger than 1.5 L, the pressure shall be not less than 35 cm H_2O or over 60 cm H_2O when the bag is expanded to four times its size. Latex-free reservoir bags may allow higher pressures to develop (21).

New bags develop greater pressures when first overinflated than do bags that have been overinflated several times or have been prestretched (22). It is good practice to overinflate or stretch a

new bag during the preuse checkout. This will not limit the ability to produce high airway pressures when the bag is squeezed.

Bags are available in a variety of sizes. The size that should be used will depend on the patient, the breathing system, and the user's preference. A 3-L bag is traditional for use in adults. A larger bag may be difficult to squeeze and will make monitoring the patient's spontaneous respiration more difficult because the excursions will be smaller. A small bag, on the other hand, provides less safety with respect to pressure fluctuations and may not provide a large enough reservoir or tidal volume.

A spare bag should always be kept immediately available in case the bag develops a leak or becomes lost.

Breathing Tubes

A large-bore, corrugated plastic breathing (conducting) tube (hose) provides a flexible, low-resistance, lightweight connection from one part of the system to another. Corrugations increase flexibility and help to prevent kinking. Breathing tubes have some distensibility but not enough to prevent excessive pressures from developing. Smaller diameter breathing tubings are available for circle systems used for pediatric patients. There

are international and U.S. standards for breathing tubes (23,24).

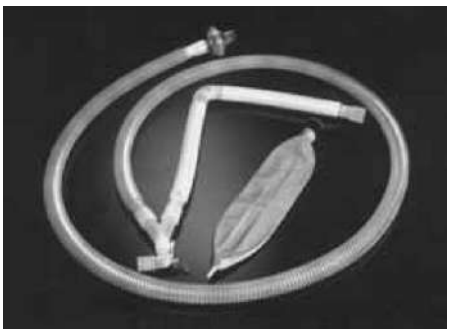

Figure 7.3 Some breathing tubes can be extended or compressed. Note the filter. (Picture courtesy of Kendall Healthcare Products, a division of Becton Dickinson.)

If it is necessary to have the anesthesia machine at some distance from the patient's head, several breathing tubes may be connected in series or extra-long tubings can be used. Special tubings that can be elongated are available (Fig. 7.3).

A tube holder (tree) (Fig. 7.4) can be used to support breathing tubes and prevent them from exerting a pull on the airway device.

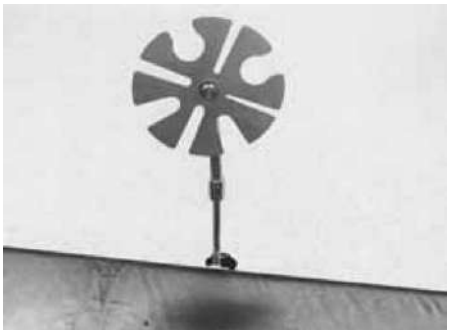

Figure 7.4 Tube holder. The large rounded openings are for adult breathing tubes. The opposite openings are for pediatric tubes. The small grooves can be used for pulse oximeter cables, gas sample lines, pressure monitoring lines, blood pressure tubing, and the like. The device can be rotated.

Adjustable Pressure-Limiting Valve

The APL valve is a user-adjustable valve that releases gases to a scavenging system. It is used to control the pressure in the breathing system. Other commonly used names for this component include pressure relief valve, venting port, relief valve, overspill valve, pop-off valve, overflow valve, dump valve, blow-off valve, safety relief valve, excess valve, Heidbrink valve, adjustable pressure limiter, excess gas venting valve, spill valve, exhaust valve, expiratory valve, excess gas valve, pressure release valve, and release valve.

Construction

Control Part

The control part serves to control the pressure at which the valve opens. Most of these valves are calibrated for the opening pressure (see Figs. 7.8, 7.9). Several types are available.

Spring-loaded Disc

The most commonly used APL valve uses a disc held onto a seat by a spring (Fig. 7.5). A threaded screw cap over the spring allows the pressure exerted by the spring on the disc to be varied. When the cap is fully tightened, the disc will prevent any gas from escaping from the system. As the cap is loosened, the tension on the spring is reduced so that the disc can rise.

When the pressure in the breathing system increases, it exerts an upward force on the disc. When this upward

force exceeds the downward force exerted by the spring, the disc rises and gas flows through the valve. When the pressure in the system falls, the disc returns to its seat. When the cap is at its maximum open position, there will be only minimal pressure exerted by the spring. This allows the patient's exhalation to lift the disc with only minimal pressure. The weight of and pressure on the disc ensures that the reservoir bag fills before the disc rises.

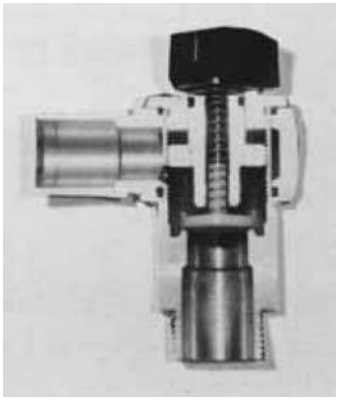

Figure 7.5 APL valve with spring-loaded disc. Gas from the breathing system enters at the base and

passes into the gas collecting assembly at left. Turning the control knob varies the tension in the spring and the pressure necessary to lift the disc off its seat. When the cap is fully tightened, the spring is compressed enough to prevent the valve leaflet from lifting at any airway pressure.

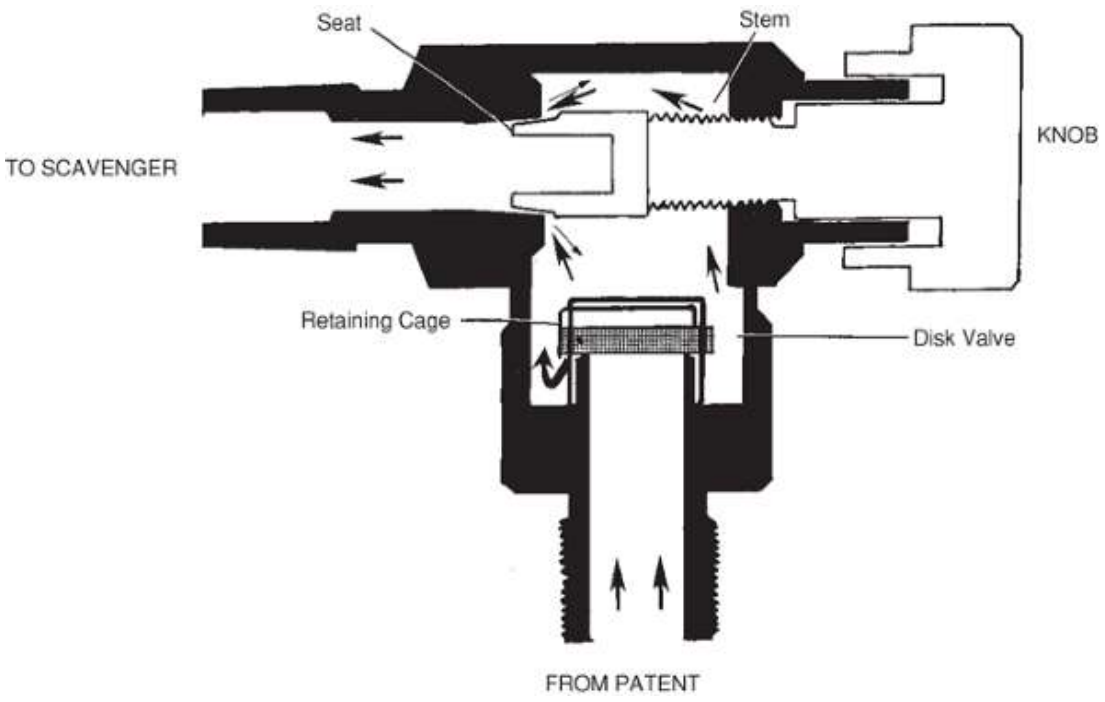

Figure 7.6 APL valve with stem and seat. Rotation of the control knob causes the opening between the stem and seat to change. The disc ensures that the reservoir bag will fill before the valve opens. It also prevents transmission of positive pressure or gas from the scavenging system to the breathing system. (Redrawn courtesy of North American Drager, Inc.)

Increased pressure downstream of the APL valve will increase the pressure needed to open the valve. Positive end-expiratory pressure (PEEP) may then be transmitted to the patient.

Stem and Seat

Another control part employed in APL valves is the stem and

seat (Fig. 7.6). This is similar to a flow control valve in that a threaded stem allows variable contact with a seat. As the valve is opened, the opening at the seat becomes larger and more gas is allowed to escape. Some of these valves have a disc or ball valve in a retaining cage (Fig. 7.6). This served the dual function of preventing gas from the scavenging system from flowing back into the breathing system and supplying a slight pressure to keep the reservoir bag inflated. Sticking of this part has been reported (25).

Control Knob

Most APL valves have a rotary control knob. The ASTM standard requires that valves with rotating controls be designed so that a clockwise motion increases the limiting pressure and ultimately closes the valve (1). It also requires an arrow or other marking to indicate the direction of movement required to close the valve (Fig. 7.8A). The standard recommends that the full range of relief pressure be adjusted by less than one full turn of the control. Some of these valves are marked to show the pressure at which they will open (Figs. 7.7, 7.8).

Collection Device and Exhaust Port

In order to remove excess gases from the breathing system and direct them to a scavenging system, they must be collected by using a collection device at the APL valve. The gases are then directed to the scavenging system through the transfer tubing. The exhaust port is the aperture through which excess gases are discharged to the scavenging system. It must have a 19- or 30-mm male connector (26). Anesthesia gas scavenging is discussed in Chapter 13.

Use

Spontaneous Respiration

With spontaneous respiration, the APL valve remains closed during inspiration and opens during exhalation. Normally, the valve is fully open during spontaneous ventilation. It should be closed slightly only if gas is withdrawn from the breathing system by negative pressure from the scavenging system and the reservoir bag collapses. Partially closing the valve during spontaneous respiration will result in continuous positive airway

pressure (CPAP).

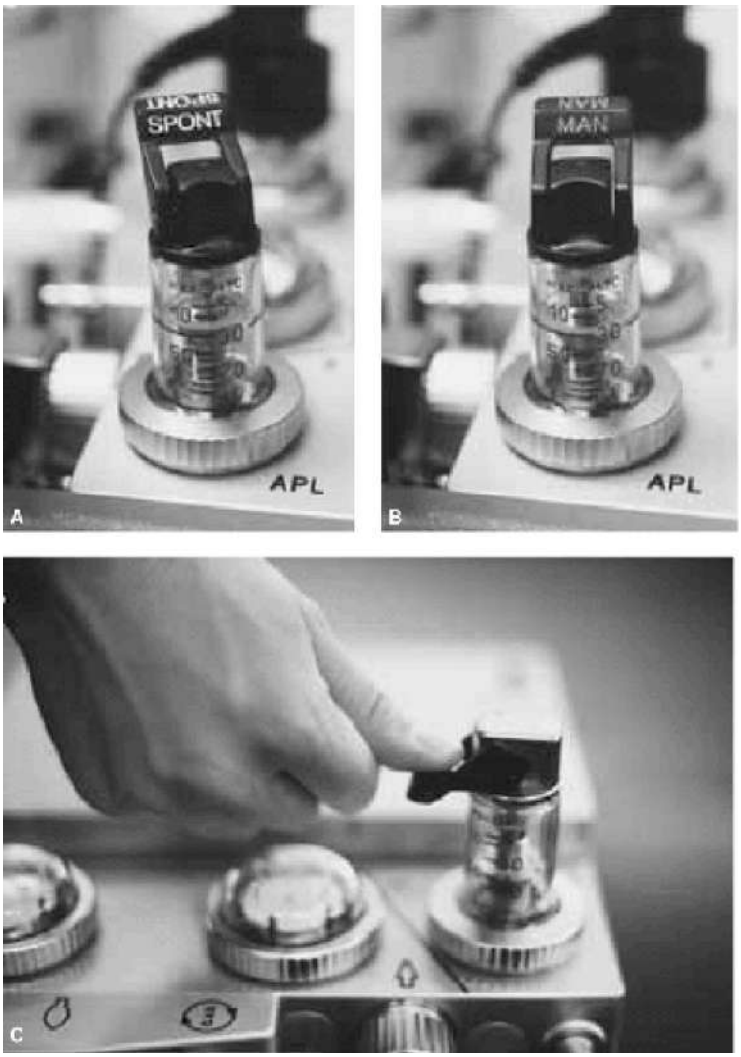

Figure 7.7 APL valve with spontaneous/manual changeover. Note the pressures markings. **A:** When the lever is in the spontaneous position, the valve is fully open, regardless of the set pressure. **B:** When the lever it is placed in the manual position, the knob is rotated to adjust the opening pressure. **C:** In the manual position, the valve can be fully opened by pressing down on the lever.

With spontaneous respiration, the anesthesia provider must be constantly aware of volume of gas in the bag. If attention is diverted, the bag may collapse or become overdistended. Negative pressure transmitted from the scavenging system may cause gases to be evacuated from the breathing system. An obstruction in the scavenging system may result in the bag becoming overdistended and the patient being subjected to CPAP.

Manually Controlled or Assisted Ventilation

During manually controlled or assisted ventilation, the valve is usually left partially open. During inspiration, the bag is squeezed and pressure increases until the relief

pressure is reached. Before this, the patient receives all of the gas displaced from the bag (less a small amount due to gas compression and expansion of the tubes). Once the APL valve opens, the additional volume that the patient receives is determined by the relative resistances to flow exerted by the patient and the APL valve.

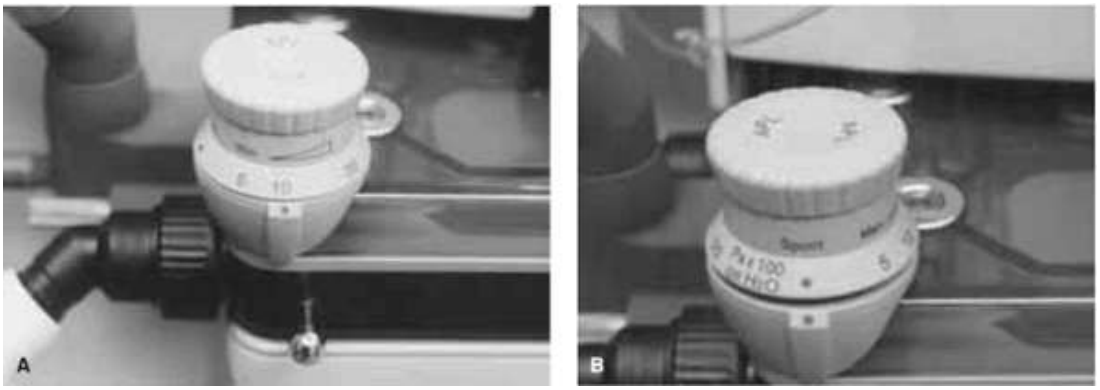

Figure 7.8 Another type of APL valve. The control knob is rotated counterclockwise to increase the opening pressure. **A:** The valve is set for manual ventilation. The valve can be fully opened by pulling up on the control knob. **B:** The valve is set for spontaneous ventilation. Note that the control knob is slightly elevated.

The APL valve must be adjusted on the basis of chest

movements and/or exhaled volume or pressure measurements to achieve the desired level of ventilation and to maintain adequate bag volume. The resistance felt during bag compression (ĩ€the educated handĩ€) cannot be relied on to ensure adequate ventilation (27,28,29). If compliance falls or resistance increases, the valve must be tightened. If the fresh gas flow is increased or decreased, the APL valve must be opened or closed somewhat.

Some APL valves have a lever for changing between spontaneous and manual ventilation (Fig. 7.7).

Mechanical Ventilation

Bag-ventilator selector switches (selector valves) that facilitate the change from manual to automatic ventilation are available and are discussed in Chapter 9. These isolate the APL valve when the selector valve is turned to automatic ventilation. When isolated from the breathing system, the APL valve need not be closed during mechanical ventilation.

Positive End-expiratory Pressure Valves

PEEP and continuous airway pressure (CPAP) are used to improve oxygenation (30). PEEP may be used with spontaneous or controlled ventilation. CPAP is used during spontaneous ventilation and during one-lung ventilation (Chapter 20).

Some older anesthesia machines had manually controlled PEEP valves that were a component of the breathing system. Newer anesthesia machines have electronically controlled PEEP valves (Chapters 9, 12). For a machine not equipped with a PEEP valve, a disposable PEEP valve can be placed in the exhalation limb (Fig. 7.9).

Fixed-pressure PEEP valves are marked to indicate the amount of PEEP that they provide (Fig. 7.9B). More than one can be used to obtain an additive effect. Variable-pressure PEEP valves have a means to adjust the amount of PEEP. Some have a scale that indicates the PEEP at a given setting. If no scale is present, a manometer must be used to measure the pressure.

A PEEP valve can be unidirectional or bidirectional (31). A bidirectional valve has a second flow channel with its own one-way valve. It has been recommended that only bidirectional

PEEP valves be used (32). Only a bidirectional valve should be used between the breathing system and the ventilator.

It is important that a disposable PEEP valve be placed in the correct position and oriented properly. The ASTM standard requires that a PEEP valve be marked with an arrow indicating the proper direction of gas flow or the words *inlet* and *outlet* or both (1). Immediately after a PEEP valve is inserted, the breathing system pressure gauge should be checked to make certain that PEEP is being delivered, and the patient should be checked for effective ventilation. A unidirectional PEEP valve incorrectly oriented against the flow of gas in the inspiratory or expiratory limb will block gas flow (31,32). Incorrectly orienting a bidirectional PEEP valve in either the inspiratory or expiratory limb will not obstruct flow, but no PEEP will be applied.

If a PEEP valve is used with a circle breathing system in which the pressure gauge is on the absorber side of

the expiratory unidirectional valve, PEEP will not be indicated on the gauge (33,34,35). The user must depend on the accuracy of the PEEP valve markings to determine the level of PEEP or use a second pressure gauge upstream of the PEEP valve to determine the actual pressure (31).

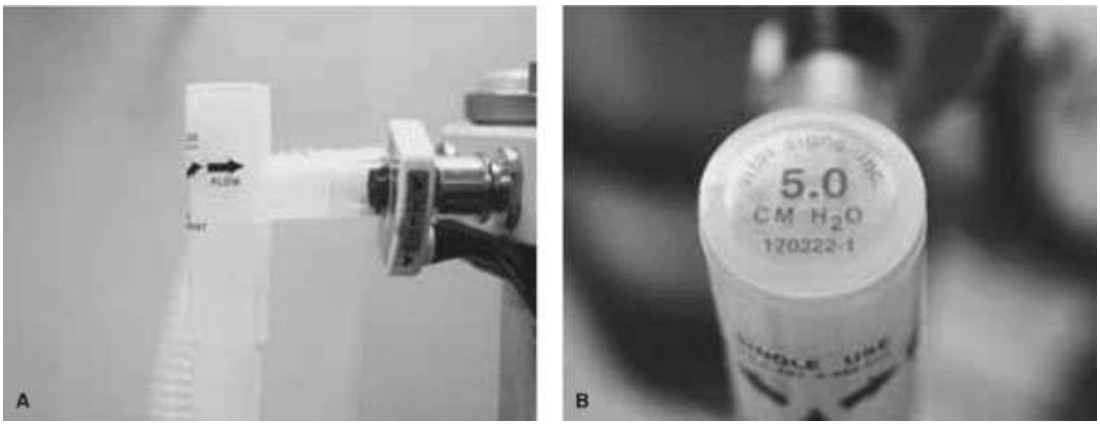

Figure 7.9 Disposable positive end-expiratory valve. **A:** Side view. Note that is shows the direction of flow. **B:** Top of PEEP valve showing the amount of PEEP.

Using PEEP in a spontaneously breathing patient will result in increased work of breathing (36,37). Using PEEP with certain ventilatory modes may result in a substantial decrease in the tidal volume delivered to the patient. The breathing system may become occluded and barotrauma may result if a PEEP valve malfunctions (38).

Filters

Filters are used to protect the patient from microorganisms and airborne particulate matter and to protect anesthesia equipment and the environment from exhaled contaminants. When placed between the patient and the breathing system, a filter may help to increase the inspired humidity (see heat and moisture exchangers in Chapter 11). Another benefit of filters is preventing exposure to latex allergens (39).

The use of filters is controversial (40,41,42,43,44,45,46,47,48). Convincing evidence that their use is of benefit in preventing postoperative infections is lacking. Problems with filters (see below) have resulted in serious complications.

The Centers for Disease Control and Prevention (CDC) and the American Society of Anesthesiologists (ASA) make no recommendation for placing a filter in the breathing system unless there is suspicion that the patient has an infectious pulmonary disease (45,49). The Association of Anaesthetists of Great Britain and Ireland (AAGBI) and others recommend that either a filter be placed between the patient and the breathing system with a new filter being used for each adult patient or that a new breathing system be used for each patient (50). Studies show that filters do become contaminated on the machine side (50A). For pediatric patients, the increased resistance and relative inefficiency of pediatric filters may make other means of humidification and infection control more attractive (51,52,53). The AAGBI recommends that filters not be used for pediatric patients; rather, the breathing system should be replaced between cases.

Two international standards cover filters (54,55). These stipulate that the filter manufacturer must declare the filtration performance, as well as pressure drop and internal volume, but the ranges within which filters must perform are not given.

Types

Mechanical Filters (Pleated Hydrophobic)

Mechanical filters utilize a compact fiber matrix. They are pleated to increase surface area. They have very small pores and act by physically preventing microorganisms and particles from passing.

Electrostatic Filters

Electrostatic filters use a feltlike material that is polarized in an electromagnetic field. They rely on electrostatic forces to hold organisms within a loosely woven charged filter element. The fibers are less dense than those in mechanical filters; hence, the pore size is greater. Most studies show that the filtration performance of these filters is less satisfactory than that of mechanical filters, especially with extreme challenges (50,56,57,58,59,60,61,62,63,64,65,66,67). However, clinical studies show that they are effective in preventing breathing system contamination during clinical use (50A,68,69).

Both types of filters are manufactured with and without additional heat and moisture exchange elements.

Filtration Efficiency

Filter efficiency varies (48). A high-efficiency particulate aerosol (HEPA)-grade device is defined as one capable of trapping at least 99.97% of particles having a diameter of 0.3 ยตm (70). Filter efficiency depends on the experimental test conditions. Therefore, when filter efficiency is stated, the size of the challenge particle or organism should be disclosed. The approximate size of the human immunodeficiency virus (HIV) particle is 0.08 ยต; hepatitis C virus, 0.06 ยตm; *mycobacterium tuberculosis*, 0.3 ยตm; *pseudomonas aeruginosa*, 0.5 ยต; and *staphlococcus aureus*, 1.0 ยต.

Filter Location in the Breathing System

Filters used in anesthesia breathing systems are supplied in three forms: (a) attached to a disposable breathing tube (Fig. 7.3), (b) attached to a ventilator hose, and (c) as a separate component. A filter placed at the patient port may permit disposable breathing systems to be reused. However, the

external surface of these systems will not be protected.

A filter should not be placed downstream of a humidifier or nebulizer, because it may become less efficient when wet. In addition, an increase in resistance, sometimes to a hazardous level, may be seen.

Problems Associated with Filters

Increased Resistance and Dead Space

A filter increases the resistance to gas flow (71,72). Resistance will increase as condensation accumulates (73,74). While increased resistance is usually not a problem during controlled ventilation, it may be problematic with spontaneous respiration.

Adding a filter between the patient and the breathing system increases the dead space. Unless ventilation is increased, significant rebreathing can occur (75). Spontaneously breathing patients who derive a major portion of their minute volume from shallow breaths may find the increase in dead space excessive (70). A large filter should not be used in this location with pediatric patients. Pediatric filters are available.

Obstruction

Filters may be obstructed by exhaled blood, edema or regurgitated fluid, a manufacturing defect, sterilization of a disposable filter, nebulized drugs, or inserting a unidirectional filter backward (76,77,78,79,80,81,82,83,84,85,86). A filter should not be used with a patient who produces copious secretions or downstream of a humidifier or nebulizer. An increase in peak inspiratory pressure may indicate the need to replace a filter.

Leaks

A defect in a filter can cause a leak (79,87).

Liquid Penetration

Since filters located between the breathing system and the patient are sometimes exposed to liquids, the ability to contain that liquid is important. Microbes can transit the filter by way of a liquid that passes through a filter. There is a great variability

among filters in regard to the pressure that will cause liquid to penetrate the filter material (87A). In general, pleated mechanical filters are more resistant to liquid passage than electrostatic filters.

Other

Using a filter between the patient and the breathing system may result in erroneous end-tidal gas concentrations and poor carbon dioxide waveforms (88,89,90,91).

Equipment to Administer Bronchodilators

Intraoperative bronchospasm can be a very serious problem.

Studies show that medications administered by the inhalational route are just as effective as parenteral therapy with fewer side effects (92,93).

Apparatus

Manufacturers have adapted metered-dose inhalers (MDIs) for use with anesthesia breathing circuits. An inhaler may be placed inside the barrel of a large syringe and actuated by pressing the syringe plunger (94,95,96,97). Most adapters are T-shaped with the injection port on the side (Fig. 7.10). Numerous commercial adapters and homemade devices have been described in the literature (98,99,100,101,102,103,104,105,106,107,108). The gas sampling port in the breathing system or the sampling lumen of a specialized tracheal tube (Chapter 19) may be used to deliver medications (96,109). Medication may be delivered by a catheter that extends to the tip of the tracheal tube. This method results in more efficient delivery (94,110,111,112).

The adapter should be placed close to the patient port. There should not be a filter or heat and moisture exchanger (HME) between the adapter and the patient.

A spacer (aerosol holding chamber, reservoir chamber, auxiliary or accessory device, [extension or reservoir]) (Fig. 7.11) may be placed downstream or upstream of the MDI to slow the flow of aerosol and to increase impaction and sedimentation of large particles (113,114). Rigid spacers result in more efficient medication delivery than collapsible ones (115).

Aerosol nebulizers may also be used to deliver bronchodilators

to an anesthesia breathing system. The gas used to aerosolize the agent will affect the composition of the inspired gas (116).

Technique of Use

The inhaler should be shaken well prior to administration (93). Bronchodilator discharge is maximal when the canister is upright. The hole in the adapter should point toward the patient, unless an upstream spacer is used. Actuating the inhaler just after inspiration begins will

maximize delivery to the airways (117). If a spacer is used, the MDI should be actuated 1 to 2 seconds before inspiration or near end-exhalation, depending on the rate (118).

Figure 7.10 Adaptor for administering bronchodilators by using a multidose inhaler. Note the cap that can be fitted over the port when it is not in use. The hole in the inhaler should port toward the patient unless an upstream spacer is used.

A slow, deep inspiration, followed by a pause of 2 to 3 seconds

before exhalation, will enhance the amount of medication deposited into the airway (117,119,120). There should be 30 to 60 seconds between puffs. The inhaler must be shaken prior to each puff (93,118).

Low humidification is desirable when delivering medication (93,115). High humidification causes the aerosol droplets to increase in size, which causes them to rain out. If possible, humidification should be discontinued when an MDI is used.

Using a spacer will increase bronchodilator delivery and reduce the number of puffs (92). However, even with a spacer, as many as 10 to 15 puffs may be required to reach the desired results (92,121). The patient should be monitored for the appearance of beneficial and side effects.

Figure 7.11 Multidose inhaler with downstream spacer in place between the breathing system **(right)** and the patient connection **(left)**.

Advantages

MDIs are easy to use, take little time to set up, and occupy little space on the anesthesia cart (122). They are more efficient at delivering medications and less costly than nebulizers (114,118,123,124).

Disadvantages

A large amount of drug is lost due to rainout in the breathing

system and tracheal tube. Improper technique is one factor (125). The smaller the tracheal tube, the more drug is deposited in the tube (112,115,117).

Another problem is that the carrier gas may cause erroneous readings with an anesthetic agent analyzer (125,126) (Chapter 22).

Size and Type of Fittings

The Compressed Gas Association (CGA) and the ASTM have published standards that specify the size and type of fittings for components in the breathing system (1,18,23). Virtually all breathing system components manufactured in the United States in recent years conform to these standards. The safety provided by standardizing the diameters of various connectors can be jeopardized by the use of adaptors and adhesive tape.

Any component or accessory used in the breathing system that permits only unidirectional flow or any device whose correct function depends on the direction of gas flow through it must be so labeled and marked with an arrow indicating the proper direction of flow or the words *inlet* and *outlet* or both. *Distal* and *proximal* are

used to designate the proximity of a component to the patient.

A fitting that is part of a component such as an absorber, Y-piece, or reservoir bag mount, whose purpose is to permit attaching this component to a reservoir bag, breathing tube, or mask, must be male and rigid. Fittings on the breathing tube, mask, and reservoir bag connectors must be female and nonrigid (resilient).

All connectors in an adult breathing system are 22 mm. The patient port must have a coaxial 15-mm female fitting. The inspiratory and expiratory ports mounted on the absorber and the reservoir bag connector must have male fittings. To avoid problems with connections between the breathing and scavenging systems, the exit port for the APL valve must have either a 19- or 30-mm male fitting. A 30-mm fitting is preferred.

Breathing System Classification

A favorite pastime among anesthesia providers has been the

classification of breathing systems. The result has been a hopelessly confused terminology. There is no agreement about how breathing systems should be classified. In an attempt to provide some relief from this confusion, a description of various authors' classifications will be presented. Subsequently, a nomenclature that the present authors believe is more useful will be described.

Classification by Function

Dripps, Eckenhoff, and Vandam

With this classification, breathing systems are divided into five categories according to the presence or absence of (a) a reservoir bag, (b) rebreathing, (c) an absorber to remove carbon dioxide, and (d) directional valves (127). The five systems are insufflation, open, semiopen, semiclosed, and closed.

The insufflation system is one in which gases are delivered directly into the patient's airway. There are no valves, reservoir bag, or carbon dioxide absorption.

In the open system, the patient inhales only the mixture delivered by the anesthesia machine. Valves direct each exhaled breath into atmosphere. A reservoir bag may or may not be present. Rebreathing is minimal, and there is no carbon dioxide absorption. This includes systems used with intermittent flow anesthesia machines and nonrebreathing valves.

In the semiopen system, exhaled gases flow out of the system and to the inspiratory line of the apparatus to be rebreathed. There is no chemical absorption of carbon dioxide. Rebreathing depends on the fresh gas flow. A reservoir bag and a directional valve are optional.

In the semiclosed system, part of the exhaled gases passes into atmosphere and part mixes with fresh gases and is rebreathed. Chemical absorption of carbon dioxide, directional valves, and a reservoir bag are present.

In the closed system, there is complete rebreathing of expired gas. Carbon dioxide absorption, a reservoir bag, and directional valves are present.

Moyers

This classification is based on the presence or absence of a reservoir bag and rebreathing. An open system has no reservoir or rebreathing (128). The semiopen system has a reservoir but no rebreathing. The semiclosed system has a reservoir and partial rebreathing, and the closed system has a reservoir and complete rebreathing.

Collins

This classification defines an open system as one in which an anesthetic agent is brought to the patient's respiratory tract with atmospheric air as the diluent (129). The respiratory tract has access to the atmosphere during both inspiration and expiration. There is no reservoir or rebreathing.

A semiopen system is one in which the patient's respiratory system is open to atmosphere during both inspiration and expiration. There is a reservoir that is open to atmosphere, rebreathing is absent, and atmospheric air either carries or dilutes the anesthetic agent.

The semiclosed system is one in which the patient's respiratory system is completely closed to atmosphere on inspiration but is open on expiration. A reservoir closed to atmosphere is present.

With a closed system, there is no access to atmosphere either during inspiration or expiration. Rebreathing is complete, and a reservoir is required.

Adriani

This classification divides systems into open vaporization, insufflation, semiclosed, and closed (rebreathing) (130). An open system is one employing an open drop mask. With the insufflation technique, a continuous stream of gas flows to the patient's nasopharynx, oropharynx, or trachea. The semiclosed system is one in which there is complete enclosure of the inspired atmosphere and no air dilution. The closed system permits complete rebreathing.

Conway

With this classification, an open system is one with infinite boundaries and no restriction to fresh gas flow (131). The semiopen system is one partially bounded, with some restriction

to fresh gas flow. The closed system is defined as having no provision for gas overflow. The semiclosed system is one allowing for overflow of excess gas. It is divided into semiclosed rebreathing,

semiclosed absorption, and semiclosed nonrebreathing systems.

Hall

In this classification, an open system has no reservoir bag or rebreathing (132). The semiopen system also has no reservoir bag but has partial rebreathing. Semiclosed systems have a reservoir bag and partial rebreathing. They are divided into those with and without carbon dioxide absorption. The closed system has complete rebreathing and a reservoir.

McMahon

This system uses rebreathing as the basis for classification of breathing systems into open, semiclosed, and closed (133). An open technique is one in which there is no rebreathing. This includes techniques in which gases are administered at a total flow rate equal to or greater than the respiratory minute volume. Techniques with flows less than the respiratory minute volume would also be considered open if there were no increase in dead space. The semiclosed system would employ some rebreathing. The closed system employs total rebreathing.

Baraka

This system classifies systems according to their mechanism of carbon dioxide elimination (134). Open systems are those that eliminate carbon dioxide by washout and have no reservoir bag. Semiopen systems also wash out carbon dioxide but have a reservoir bag. Semiclosed systems use carbon dioxide absorption and have a fresh gas flow that exceeds patient uptake. Closed systems also use carbon dioxide absorption and have a fresh gas flow that equals patient uptake.

The International Standards Organization

The International Standards Organization (ISO) classifies breathing systems as nonrebreathing and partial rebreathing. The terms *semiopen* and *semiclosed* are not used. A

nonrebreathing system is an anaesthesia breathing system from which all of the expired mixture is discharged. A partial rebreathing system is an anaesthesia breathing system in which a portion of the expired mixture is retained within the system (135).

Marini, Culver, and Kirk

This system classifies breathing systems on the basis of carbon dioxide elimination (136). Systems are divided into open, which do not have a reservoir bag, and semiopen, which do have a reservoir bag. Examples of the open variety include the open drop mask, insufflation, and the T-piece (Mapleson E). Semiopen systems include the Magill and Lack (Mapleson A), Bain (Mapleson D), Jackson-Rees (Mapleson F), Mera F, and systems with nonrebreathing valves. The carbon dioxide absorption units include the circle system.

Classification by Equipment

Hamilton (137) recognized the shortcomings of the nomenclatures described previously and proposed that the terms *open*, *semiopen*, and the like be dropped in favor of a description of the equipment and the total fresh gas flow to the system. An example would be a circle system with a 2-L/minute fresh gas flow. The description of the equipment will be familiar to the reader after reading the next two chapters. The fresh gas flow will determine the amount of rebreathing, if any, that takes place.

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Questions

For the following question, select the correct answer.

1. Which of the following offers the most resistance?

A. Nonrebreathing valve

B. CO_2 canister

C. Tracheal tube

D. Y-piece

E. Breathing tubes

View Answer

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

2. The functions of the breathing system include the following:

A. Conveying oxygen and anesthetic gases to the patient

B. Delivering positive pressure

C. Removing waste and anesthetic gases from the patient

D. Conveying excess gases to the scavenging system

View Answer

3. Resistance to breathing through a breathing system is influenced by

A. Laminar flow

B. Gas flow rate

C. Turbulent flow

D. Length of the breathing tubes

View Answer

4. Rebreathing may be influenced by

A. Fresh gas flow

B. Arrangement of components in the breathing system

C. Mechanical dead space

D. The size of the reservoir bag

View Answer

5. Effects of rebreathing include

A. Reduced loss of heat and water from the patient

B. Reduced inspired oxygen

C. Less fluctuation in inspired anesthetic agent concentration

D. Decreased inspired carbon dioxide

View Answer

6. Factors that cause a discrepancy between the composition

of the inspired gas mixture and that of the fresh gas include

A. Rebreathing

B. Leaks in the breathing system

C. Uptake of anesthetic agent by components of the breathing system

D. Increased fresh gas flow

View Answer

7. Factors that can cause a discrepancy between the volume of gas discharged from a ventilator or reservoir bag and that inspired by the patient include

A. Fresh gas flow

B. Compression of gases in the circuit

C. Leaks

D. Distention of breathing system components

View Answer

8. The reservoir bag

A. Allows use of lower fresh gas flows

B. Provides a means for delivering positive pressure

C. Can serve as a monitor of spontaneous respiration

D. Can cause excessive pressure if the APL valve is not open

View Answer

9. Concerning the peak pressure than can be generated in the breathing system if there is a reservoir bag in place,

A. If the reservoir bag is less than 1.5 L in size, the pressure shall not be less than 30 cm H_2O

B. If the reservoir bag is larger than 1.5 L, the pressure shall not be less than 45 cm H_2O

C. If a 1.5-L bag is expanded to four times its normal size, the pressure shall not be greater than 50 cm H_2O

D. If a bag over 1.5 L is expanded to four times its size, the pressure shall not be greater than 65 cm H_2O

View Answer

10. Functions of breathing tubes include

A. Acting as a reservoir in certain systems

B. Protection against excessive pressure

C. Providing a flexible connection between the different parts of the breathing system

D. Expanding during spontaneous breathing to prevent rebreathing

View Answer

11. During spontaneous respiration,

A. The APL valve should be kept partially closed

B. Most APL valves open automatically

C. An obstruction in the scavenging system may result in gas being removed from the breathing system

D. Obstruction of the air intake valve in the scavenging system can result in positive pressure in the breathing system

View Answer

12. With a PEEP valve in the breathing system,

A. An increased exhalation effort is necessary if the patient is breathing spontaneously

B. An increase in tidal volume may be seen with mechanical ventilation

C. The amount of PEEP can be either fixed or adjustable

D. A spring-loaded PEEP valve must be kept in the upright position

View Answer

13. Which of the following connectors are male?

A. Those on the breathing tubes

B. Those on the reservoir bag mount

C. Those on the mask

D. Those on the Y-piece connecting to the breathing tubes

View Answer

14. Deposition of bronchodilators in the patient's tracheobronchial tree is enhanced by

A. Use of a spacer

B. A low inspiratory flow rate

C. Low humidification

D. An expiratory pause

View Answer

15. Causes of localized turbulent flow include

A. Constrictions in the flow channel

B. Valves

C. Curves

D. Gas at a flow rate below the critical number

View Answer

Chapter 8
Mapleson Breathing Systems

The Mapleson systems are characterized by the absence of unidirectional valves to direct gases to or from the patient. Because there is no device for absorbing CO_2, the fresh gas flow must wash CO_2 out of the circuit. For this reason, these systems are sometimes called *carbon dioxide washout circuits* or *flow-controlled breathing systems*.

These systems were first classified into five basic types: A through E (1). A sixth, the Mapleson F system, was added later (2). The classification is shown in Figure 8.1. There are many variations of these systems, but only the ones in common use will be discussed.

Because there is no clear separation of inspired and expired gases, rebreathing will occur when the inspiratory flow exceeds the fresh gas flow. The composition of the inspired mixture will depend on how much rebreathing takes place. A number of studies designed to determine the fresh gas flow needed to prevent rebreathing with these systems have been performed, with often widely differing results. This is partly because different criteria have been used to define the onset of rebreathing and because variables such as minute ventilation, respiratory waveform, CO_2 production, patient responsiveness, and stimulation and physiological dead space may be unpredictable in anesthetized patients (3,4,5). Monitoring end-tidal CO_2 is the best method to determine the optimal fresh gas flow. It should be noted that with rebreathing, the arterial CO_2 to end-tidal CO_2 gradient decreases (6).

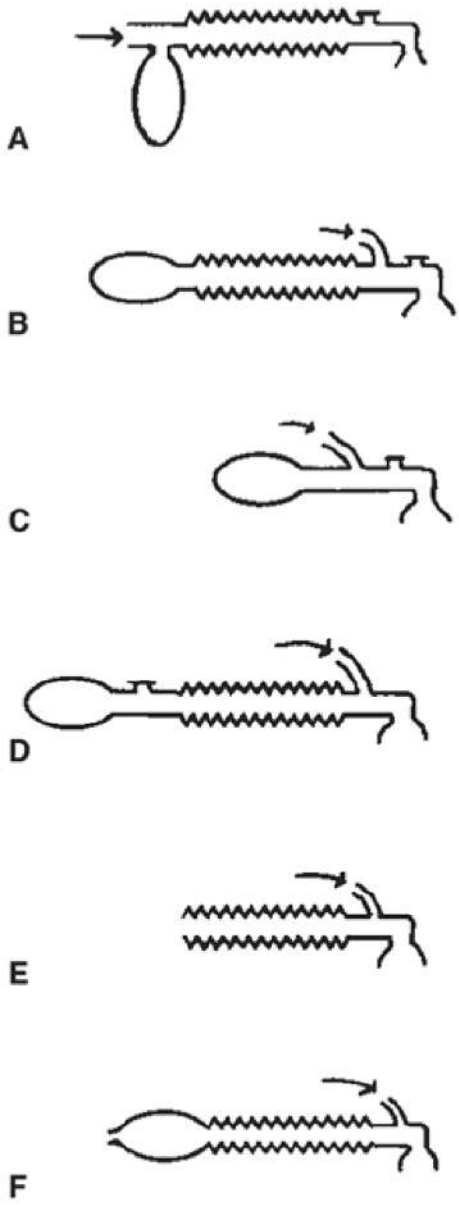

Figure 8.1 The Mapleson systems. Components include a reservoir bag, corrugated tubing, APL valve, fresh gas inlet, and patient connection. They lack CO_2 absorbers, unidirectional valves, and separate inspiratory and expiratory limbs. (Redrawn from Mapleson WW. The elimination of rebreathing in various semiclosed anesthetic systems. Br J Anaesth 1954;26:323Ì€“332.)

Mapleson A System

Configurations

Classic Form

The Mapleson A system (Magill attachment or system) is shown in Figure 8.1A. It differs from the other Mapleson systems in that fresh gas does not enter the system near the patient connection but enters at the other end of the system near the reservoir bag. A corrugated tubing connects the bag to the adjustable pressure limiting (APL) valve at the patient end of the system.

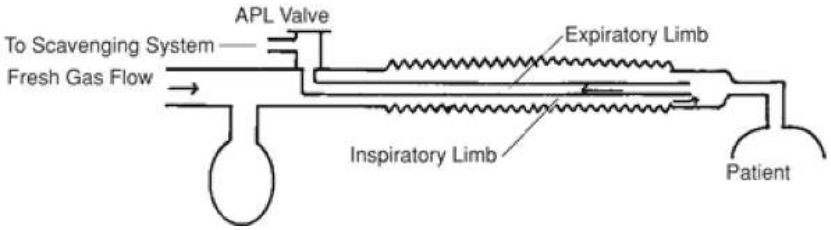

Figure 8.2 Lack modification of the Mapleson A system. The coaxial version is shown. APL, adjustable pressure limiting.

A sensor for a nondiverting respiratory gas monitor or the sampling site for a diverting monitor (Chapter 22) may be placed between the APL valve and the corrugated tubing. In adults, it may be placed between the APL valve and the patient. In small patients, this location could result in excessive dead space. It could also be placed between the neck of the bag and its mount, between the bag and the corrugated tubing, or in the fresh gas supply tube. However, in these locations, the concentration shown on the monitor may differ substantially from the inspired concentration, especially during controlled ventilation.

Lack Modification

The Lack modification of the Mapleson A system (Fig. 8.2) has an added ‘€expiratory‘€ limb, which runs from the patient connection to the APL valve at the machine end of the system (7,8). This makes it easier to adjust the valve and facilitates scavenging excess gases, but it increases the work of breathing slightly (3).

The Lack system is available in both a dual (parallel) tube arrangement and a tube-within-a-tube (coaxial) configuration in which the expiratory limb runs concentrically inside the outer inspiratory limb (9).

Techniques of Use

For spontaneous ventilation, the APL valve is kept in the fully open position. Excess gas exits through it during the latter part of exhalation.

For controlled or assisted ventilation, intermittent positive pressure is applied to the bag. The APL valve is partially closed so that when the bag is squeezed, sufficient pressure to inflate the lungs is achieved. The APL valve opens during inspiration.

Functional Analysis

Spontaneous Respiration

The sequence of events during the respiratory cycle using the Magill system with spontaneous ventilation is shown in Figure 8.3 (10,11). As the patient exhales (Fig. 8.3C), first dead space and then alveolar gases flow into the corrugated tubing toward the bag. At the same time,

fresh gas flows into the bag. When the bag is full, the pressure in the system rises until the APL valve opens. The first gas vented will be alveolar gas. The remainder of exhalation, which contains only alveolar gas, exhausts through the open APL valve. The continuing inflow of fresh gas reverses the flow of exhaled gases in the corrugated tubing. Some alveolar gas that bypassed the APL valve now returns and exits through it. If the fresh gas flow is high (Fig. 8.3A), it will also force the dead space gas out. If the fresh flow gas is intermediate (Fig. 8.3D), some dead space gas will be retained in the system. If the fresh

gas flow is low (Fig. 8.3E), more alveolar gas will be retained.

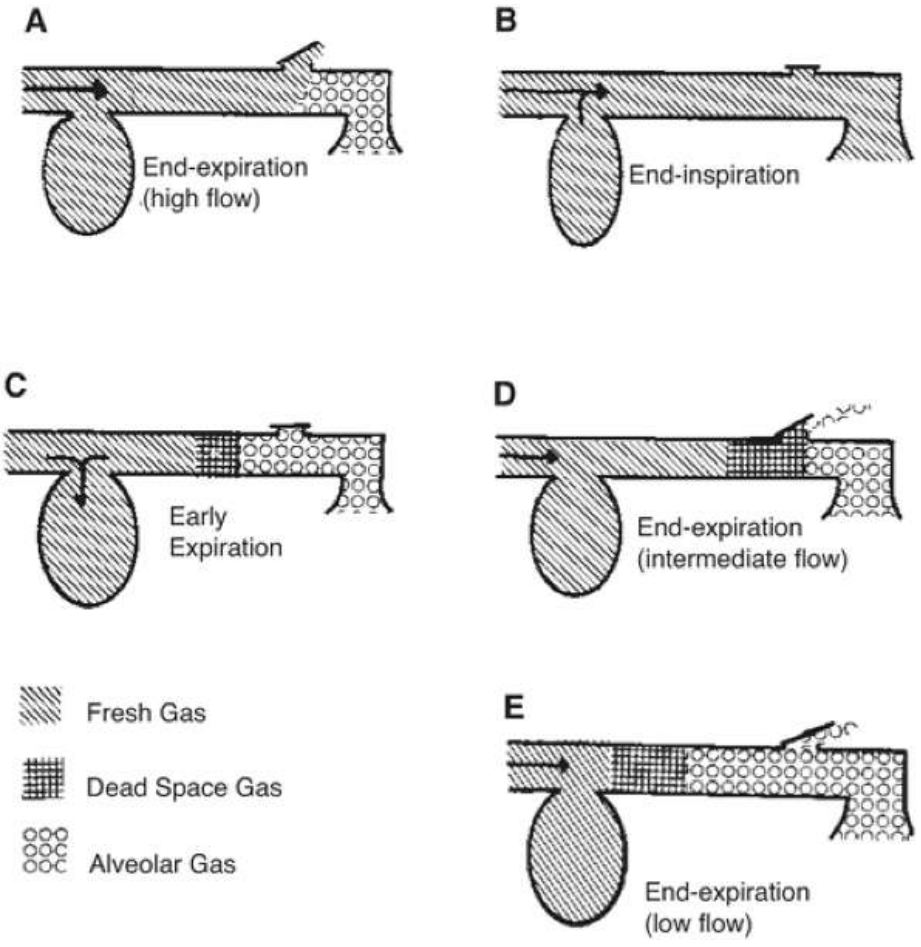

Figure 8.3 Magill system with spontaneous ventilation. (See text for details.) (Redrawn from Kain ML, Nunn JF. Fresh gas economies of the Magill circuit. Anesthesiology 1968;29:964–974.)

At the start of inspiration, the first gas inhaled will be from dead space between the patient and the APL valve. The next gas will be either alveolar gas (if the fresh gas flow is low), dead space gas (if the fresh gas flow is intermediate), or fresh gas (if the fresh gas flow is high) (Fig. 8.3B). Changes in respiratory pattern have little effect on rebreathing (11,12,13).

With the classic Magill system, investigators have found that

rebreathing begins when the fresh gas flow is reduced to 56 to 82 mL/kg/minute (3,14,15,16,17), or 58% to 83% of minute volume (3,10,18,19,20,21). Fresh gas flows of 51 to 85 mL/kg/minute (3,14,22,23,24) and 42% to 88% of minute volume (3,19,23) have been recommended to avoid rebreathing.

Controlled or Assisted Ventilation

During controlled or assisted ventilation (Fig. 8.4), the pattern of gas flow changes. During exhalation (Fig. 8.4A), the pressure in the system will remain low and no gas will escape through the APL valve, unless the bag becomes distended. All exhaled gases, both dead space and alveolar, remain in the corrugated tubing, with alveolar gas nearest the patient. If the tidal volume is large, some alveolar gas may enter the bag (25).

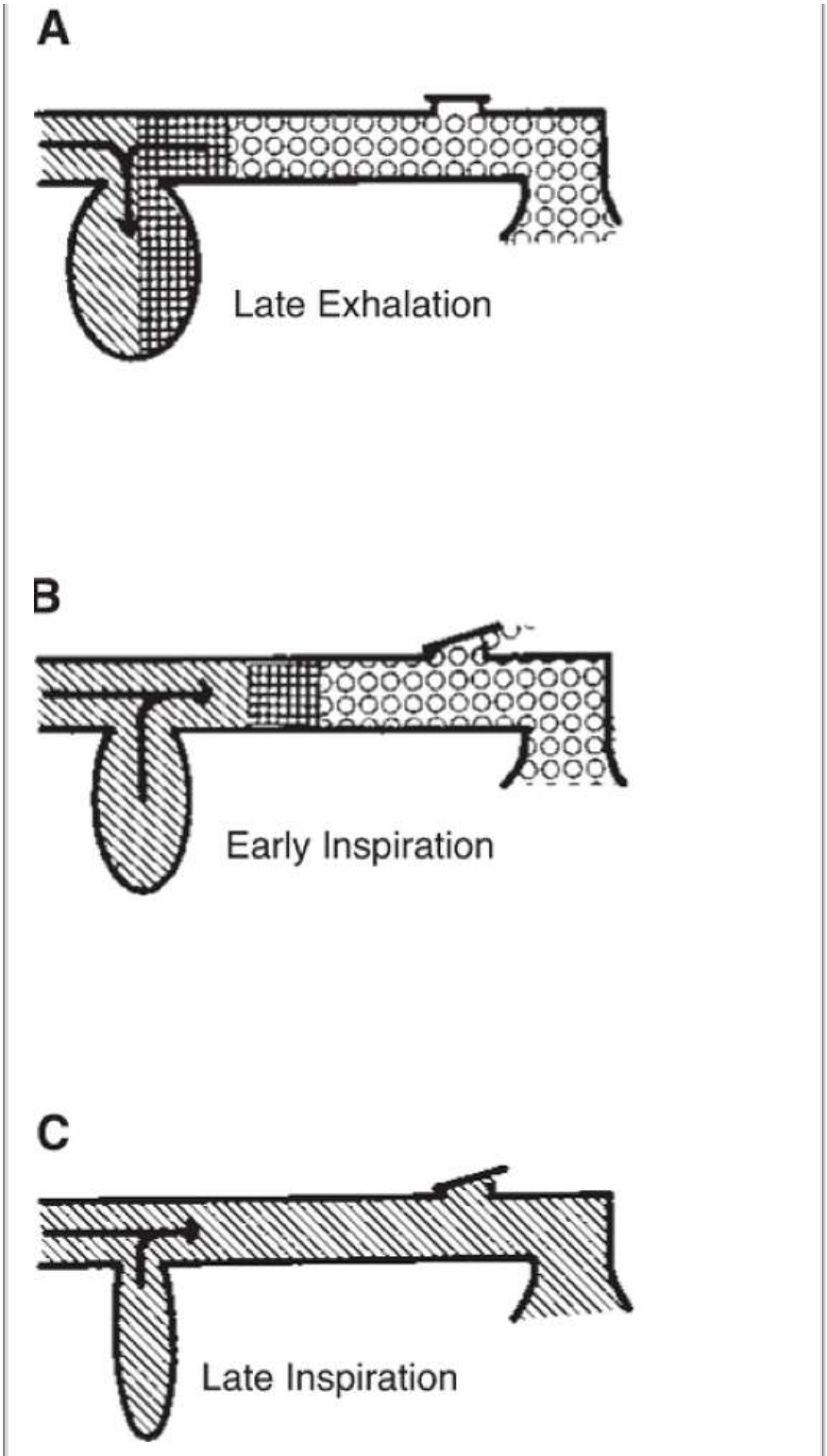

Figure 8.4 Magill system with controlled ventilation.

(See text for details.)

At the start of inspiration (Fig. 8.4B), gases in the tubing flow to the patient. Because alveolar gas occupies the space nearest the patient, it will be inhaled first. As the pressure in the system rises, the APL valve opens so that gas both exits through the APL valve and flows to the patient. When all the exhaled gas has been driven from the tube, fresh gas fills the tubing (Fig. 8.4C). Some fresh gas enters the patient, and some is vented through the valve. Thus, during controlled ventilation, there is considerable rebreathing of alveolar gases and venting of fresh gas. The composition of the inspired gas mixture depends on the respiratory pattern (25,26). The system becomes more efficient as the expiratory phase is prolonged. Most investigators believe that it is illogical to use the Mapleson A system for controlled ventilation. However, if the APL valve in the Mapleson A system does not vent gas during inspiration, the Mapleson A system can be as efficient as the Mapleson D during controlled ventilation (27).

During assisted ventilation, the Mapleson A system is somewhat less efficient than with spontaneous ventilation but is more efficient than with controlled ventilation (28).

Hazards

A mechanical ventilator that vents excess gases should not be used with this system, because the entire system then becomes dead space. The ventilators found on most anesthesia machines in the United States are unsuitable for use with the Mapleson A system.

Cases have been reported where a Lack circuit was incorrectly manufactured or assembled so that the fresh gas inlet was mounted adjacent to the APL valve rather than the reservoir bag (29,30,31). This would result in a substantial increase in dead space.

Preuse Checks

The Mapleson A system is tested for leaks by occluding the patient end of the system, closing the APL valve, and

pressurizing the system. Opening the APL valve will confirm proper functioning of that component. In addition, the user or a patient should breathe through the system.

The coaxial Lack system requires additional testing to confirm the integrity of the inner tube. One method is to attach a tracheal tube to the inner tubing at the patient end of the system (32). Blowing down the tube with the APL valve closed will produce movement of the bag if there is a leak between the two limbs. Another method is to occlude both limbs at the patient connection with the APL valve open and then squeeze the bag (33). If there is a leak in the inner limb, gas will escape through the APL valve, and the bag will collapse.

Mapleson B System

The Mapleson B system is shown in Figure 8.1B. The fresh gas inlet and APL valve are both located near the patient port. The reservoir bag is at the patient end of the system, separated from the fresh gas inlet by corrugated tubing.

Techniques of Use

To use the Mapleson B system with spontaneous respiration, the APL valve is opened completely. Excess gas is vented through the valve during exhalation. Assisted or controlled ventilation is accomplished by closing the APL valve sufficiently to allow the lungs to be inflated. Excess gases are vented during inspiration.

Functional Analysis

Spontaneous Respiration

As the patient exhales, dead space gas will pass down the corrugated tubing, along with fresh gas. At the end of exhalation, the tubing near the patient will be filled with fresh gas and some alveolar gas. When the bag reaches full capacity, the APL valve opens, and both fresh gas and alveolar gas will exit from the system. When the patient begins to inspire, the APL valve closes, and the patient inhales fresh gas and gas from the tubing. No gas will be inhaled from the bag if the volume of the tubing exceeds the tidal volume.

To avoid rebreathing, the fresh gas flow must be equal to peak inspiratory flow rate (normally 20 to 25 L/minute) (34). A fresh

gas flow more than double minute volume has been recommended (34,35), but flows as low as 0.8 to 1.2 times minute volume may be sufficient (25).

Controlled or Assisted Ventilation

The behavior of the Mapleson B system during controlled or assisted ventilation is similar to that of the Mapleson A, but it is slightly more efficient because fresh gas accumulates at the patient end of the tubing during the expiratory pause (25,34). Because the composition of inspired gas is greatly influenced by the ventilatory pattern, this system has variable performance during controlled ventilation (25). A fresh gas flow of 2 to 2.5 times minute volume has been recommended (25,34,36).

Mapleson C System

The Mapleson C system is identical to the Mapleson B system except that the corrugated tubing is omitted (Fig. 8.1C).

Techniques of Use

Use of this system is similar to that described for the Mapleson B system.

Functional Analysis

The Mapleson C system behaves similarly to the Mapleson B system. With spontaneous ventilation, the Mapleson C system is almost as efficient as the Mapleson A when the expiratory pause is minimal, but it becomes less efficient as the expiratory pause increases (11,13,37). A fresh gas flow of 2 times minute volume has been recommended for spontaneous breathing. During controlled ventilation, a fresh gas flow of 2 to 2.5 times minute volume is recommended (25,38).

Mapleson D System

The Mapleson D, E, and F systems all have a T-piece near the patient and function similarly. The T-piece is a three-way tubular connector with a patient connection port, a fresh gas port, and a port for connection to a corrugated tubing. The Mapleson D system is popular because excess gas scavenging is relatively easy, and it is the most efficient of the Mapleson systems during

controlled ventilation.

Configuration

Classic Form

The Mapleson D system is shown in Figures 8.1D and 8.5. A length of tubing connects the T-piece at the patient end to the APL valve and the reservoir bag adjacent to it. The length of the tubing determines the distance the user can be from the patient but has minimal effects on ventilation (39).

The sensor or sampling site for a respiratory gas monitor may be placed between the bag and its mount, between the corrugated tubing and the T-piece, or between the corrugated tubing and the APL valve. In adults, it may be placed between the T-piece and the patient.

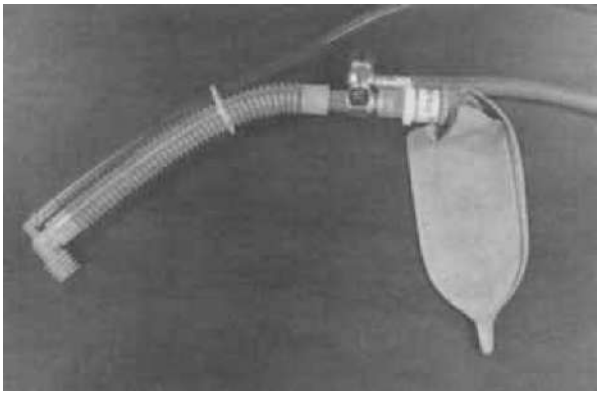

Figure 8.5 Mapleson D system. A tube leading to the scavenging system is attached to the APL valve.

A bidirectional positive end-expiratory pressure (PEEP) valve may be placed between the corrugated tubing and the APL valve of the Mapleson D system (40). This permits PEEP to be administered during manual or mechanical ventilation. However, some PEEP valves will close when a negative pressure is applied, so spontaneous breathing is impossible with that type of PEEP valve in the system. The PEEP valve may be placed in the hose leading to the anesthesia ventilator. In this location, it will

be effective only during mechanical ventilation. A unidirectional PEEP valve can be used at the bag attachment site by using special connectors and unidirectional valves (41). Such an arrangement allows PEEP to be applied during spontaneous or mechanical but not manual ventilation (40).

Bain Modification

In the Bain modification (Fig. 8.6), the fresh gas supply tube runs coaxially inside the corrugated tubing and ends at the point where the fresh gas would enter if the classic Mapleson D form were used (42). The outer tube is clear so that the inner tube can be inspected (43). The outer tubing of most commercially available versions of the Bain system is narrower than conventional corrugated tubing (25). The Bain system is available with a metal head with channels drilled into it. This provides a fixed position for the reservoir bag and APL valve and attachment of corrugated tubing. Some heads also have a pressure manometer.

A long version of the Bain system may be used for remote anesthesia in locations such as the magnetic resonance imaging (MRI) unit (44). Compared with the usual Bain system, static compliance is increased with a

reduction in peak inspiratory pressure and tidal volume with the same ventilator settings. Also, PEEP is increased. A longer Bain system also presents increased resistance to spontaneous breathing (45).

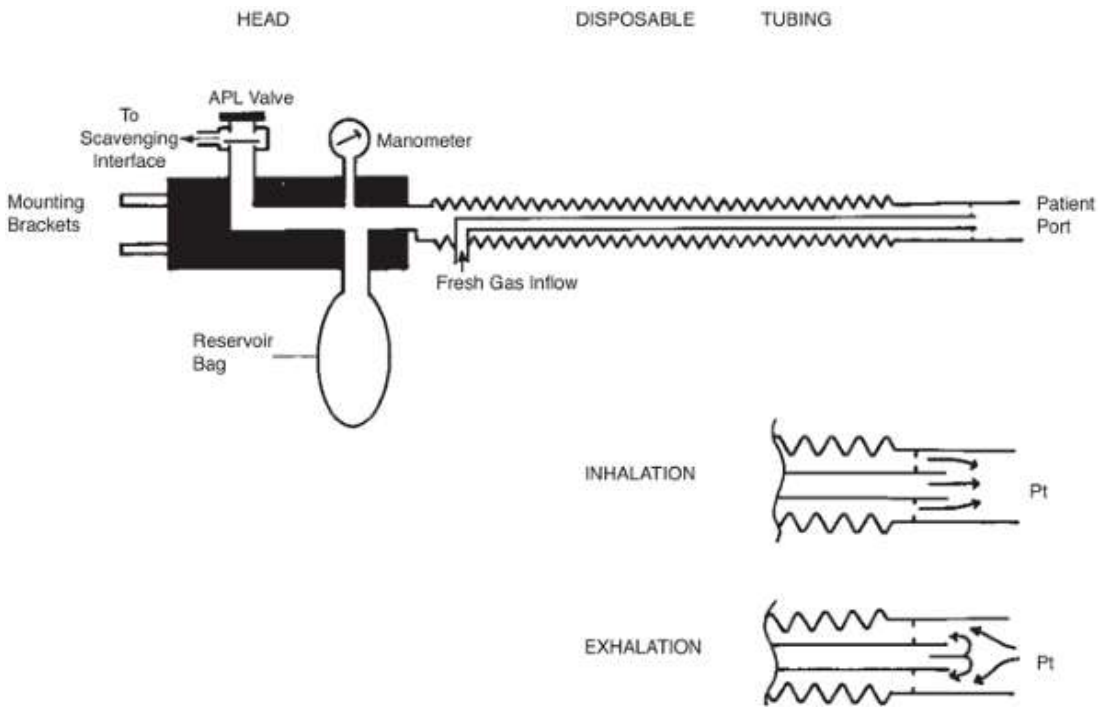

Figure 8.6 Bain modification of the Mapleson D system. The fresh gas supply tube is inside the corrugated tubing. APL, adjustable pressure limiting; Pt, patient.

Techniques of Use

For spontaneous respiration, the APL valve is left open, and excess gases are vented during expiration. Manually controlled or assisted ventilation is performed by partially closing the APL valve and squeezing the bag. Excess gases are vented during inspiration. Mechanically controlled ventilation is achieved by connecting the hose from a ventilator in place of the reservoir bag and closing the APL valve. Excess gases are vented through the ventilator spill valve.

Functional Analysis

Spontaneous Breathing

During exhalation (Fig. 8.7), exhaled gases mix with fresh gases and move through the corrugated tube toward the bag. After the bag has filled, gas exits via the APL valve. During the expiratory

pause, fresh gas pushes exhaled gases down the corrugated tubing.

During inspiration, the patient will inhale gas from the fresh gas inlet and the corrugated tubing. If the fresh gas flow is high, all the gas drawn from the corrugated tube will be fresh gas. If the fresh gas flow is low, some exhaled gas containing CO_2 will be inhaled. The ventilatory pattern will help to determine the amount of rebreathing. Factors that tend to decrease rebreathing include a high inspiratory:expiratory (I:E) time ratio, a slow rise in inspiratory flow rate, a low flow rate during the last part of exhalation, and a long expiratory pause, with the long expiratory pause having the greatest effect (11,12,13,37,46,47,48).

As gas containing CO_2 is inhaled, the end-tidal CO_2 will rise. If the patient's spontaneous respiration then increases, the end-tidal CO_2 will fall while inspired CO_2 will increase (49). Provided rebreathing is not extreme, a normal end-tidal CO_2 can be achieved but only at the cost of increased work on the part of the patient. The end-tidal CO_2 tends to reach a plateau. At that point, no matter how hard the patient works, the end-tidal CO_2 cannot be lowered further. If the patient's respiration is depressed, end-tidal CO_2 will rise further (49).

End-tidal CO_2 depends on both the ratio of minute volume and fresh gas flow and their absolute values (49). If expired volume is greater than fresh gas flow, end-tidal CO_2 will be determined mainly by fresh gas flow. If fresh gas flow is greater than minute volume, end-tidal CO_2 will be determined mainly by minute volume. Recommendations for fresh gas flows based on body weight vary from 100 to 300 mL/kg/minute (14,17,23,24,29,50,51). Most studies have recommended that the fresh gas flow be 1.5 to 3.0 times the minute volume (20,23,50,52,53,54,55,56) while others have held that a fresh gas flow approximately equal to total ventilation is adequate (57). In terms of body surface area, fresh gas

flows of 4000 to 4700 mL/m^2/minute have been recom-mended (58).

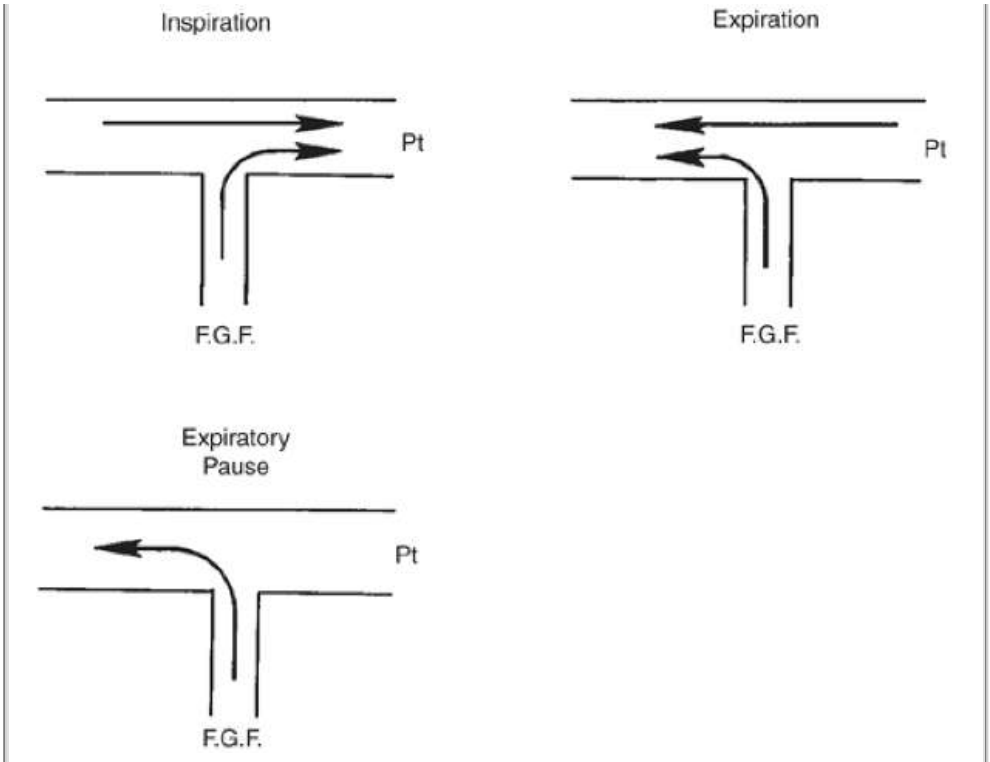

Figure 8.7 Functioning of the Mapleson D system. (See text for details.) Pt, patient; F.G.F., fresh gas flow.

Controlled Ventilation

During exhalation (Fig. 8.7), gases flow from the patient down the corrugated tubing. At the same time, fresh gas enters the tubing. During the expiratory pause, the fresh gas flow continues and pushes exhaled gases down the tubing.

During inspiration, fresh gas and gas from the corrugated tubing enter the patient. If the fresh gas flow is low, some exhaled gases may be inhaled. Prolonging the inspiratory time, increasing the respiratory rate, or adding an inspiratory plateau will increase rebreathing (47,59). Rebreathing can be decreased by allowing a long expiratory pause so that fresh gas can flush exhaled gases from the tubing.

When the fresh gas flow is high, there is little rebreathing, and the end-tidal CO_2 is determined mainly by minute ventilation. Tidal volume, the volume of the expiratory limb, and expiratory

resistance also affect it (60). When minute volume substantially exceeds the fresh gas flow, the fresh gas flow is the main factor controlling CO_2 elimination. The higher the fresh gas flow, the lower the end-tidal CO_2.

Combining fresh gas flow, minute volume, and arterial CO_2 levels, a series of curves can be constructed (Fig. 8.8). An infinite number of combinations of fresh gas flow and minute volume can be used to produce a given $PaCO_2$. High fresh gas flows and low minute volumes or high minute volumes and low fresh gas flows or combinations in between can be used. In Figure 8.8, at the left, with a high fresh gas flow, the circuit is a nonrebreathing one and end-tidal CO_2 depends only on ventilation. Such high flows are uneconomical and are associated with lost heat and humidity. End-tidal CO_2 depends on minute volume, which is difficult to adjust accurately, especially in small patients. On the right is the region of hyperventilation and partial rebreathing. End-tidal CO_2 is regulated by adjusting the fresh gas flow. Lower fresh gas flows (and increased rebreathing) are associated with higher humidity, less heat loss, and greater fresh gas economy. Hyperventilation can be used without inducing hypocarbia. Individual differences in dead space:tidal volume are minimized at high levels of minute volume. For these reasons, in most cases, it is advantageous to aim for the right side of the graph. In patients with stiff lungs, poor cardiac performance, or hypovolemia, using the left side of the graph and a relatively small total ventilation with a high fresh gas flow may be better (61).

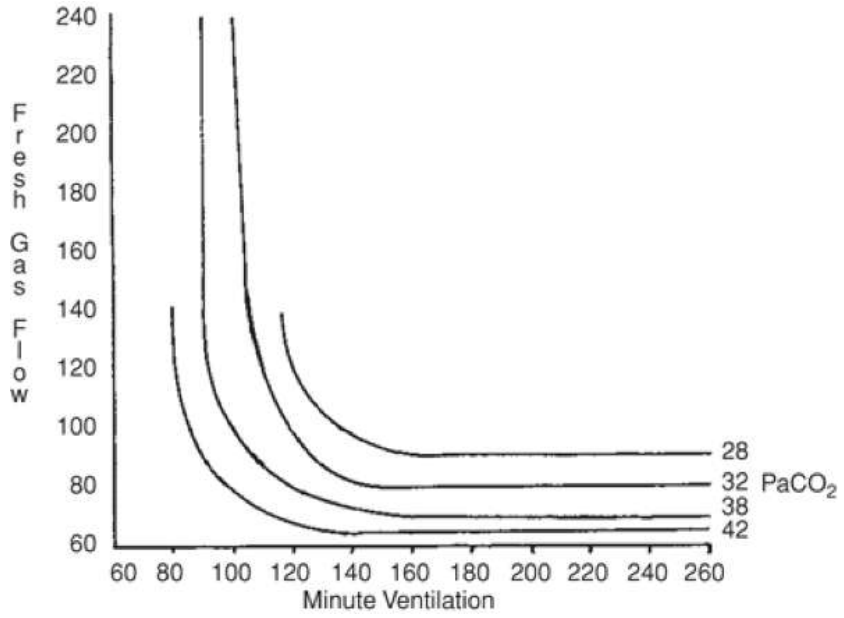

Figure 8.8 Mapleson D system used with controlled ventilation. Each isopleth represents a constant level of $PaCO_2$. Note that essentially the same $PaCO_2$ can be achieved for fresh gas flows from 100 to 240 mL/kg/minute. (Redrawn from Froese AB. Anesthesia circuits for children [ASA Refresher Course]. Park Ridge, IL: ASA, 1978.)

Formulas to predict fresh gas flow requirements have been based on body weight (62,63,64), minute volume (65), and body surface area (66). If the system is used for patients undergoing laparoscopy, the fresh gas flow needs to be increased to overcome the CO_2 that is absorbed from the abdomen (67).

With assisted ventilation, the efficiency of the Mapleson D system is intermediate between that for spontaneous and controlled ventilation (28). Slightly higher fresh gas flows should be used.

Bain System Hazards

If the inner tube of the Bain system becomes detached from its connections at either end or develops a leak at the machine end, if the fresh gas supply tube becomes kinked or twisted, if the system is incorrectly assembled (such as using standard

corrugated tubing), or if there is a defect in the metal head so that fresh gas and exhaled gas mix, the entire limb becomes dead space (43,68,69,70,71,72,73). In one case, it was reported that a manufacturing defect caused the inner tube to be blocked (74).

Preuse Checks

The Mapleson D System is tested for leaks by occluding the patient end, closing the APL valve, and pressurizing the system. The APL valve is then opened. The bag should deflate easily if the valve and scavenging system are working properly. Either the user or a patient should breathe through the system to detect obstructions.

The Bain modification of the Mapleson D requires special testing to confirm the integrity of the inner tubing. This can be performed by setting a low flow on the oxygen flowmeter and occluding the inner tube (with a finger or the barrel of a small syringe) at the patient end while observing the flowmeter indicator. If the inner tube is intact and correctly connected, the indicator will fall (70,75). The integrity of the inner tube can also be confirmed by activating the oxygen flush and observing the bag (76). A Venturi effect caused by the high flow at the patient end will create a negative pressure in the outer exhalation tubing, and this will cause the bag to deflate. If the inner tube is not intact, this maneuver will cause the bag to inflate slightly. However, this test will not detect a system in which the inner tube is omitted or does not extend to the patient port or one that has holes at the patient end of the inner tube (77,78).

Continuous Positive Airway Pressure

During one-lung ventilation using a double-lumen tube (Chapter 20), a modified Mapleson D system attached to the lumen leading to the nondependent lung is often used to apply continuous positive airway pressure (CPAP) to that lung.

A number of configurations have been described (79,80,81,82,83,84,85,86,87,88,89,90,91,92,93). One is shown in Figure 8.9. A source of oxygen is connected to the system. The APL valve is set to maintain the desired pressure. A PEEP valve may be added to function as a high-pressure relief device (94).

Mapleson E System

The Mapleson E (T-piece) system is shown in Figure 8.1E. A length of tubing may be attached to the T-piece to form a reservoir. It does not have a bag. The expiratory port may be enclosed in a chamber from which excess gases are evacuated.

The sensor or sampling site for the respiratory gas monitor may be placed between the expiratory port and the expiratory tubing. In larger patients, it may be placed between the T-piece and the patient, but this location

should be avoided in small patients because it increases dead space.

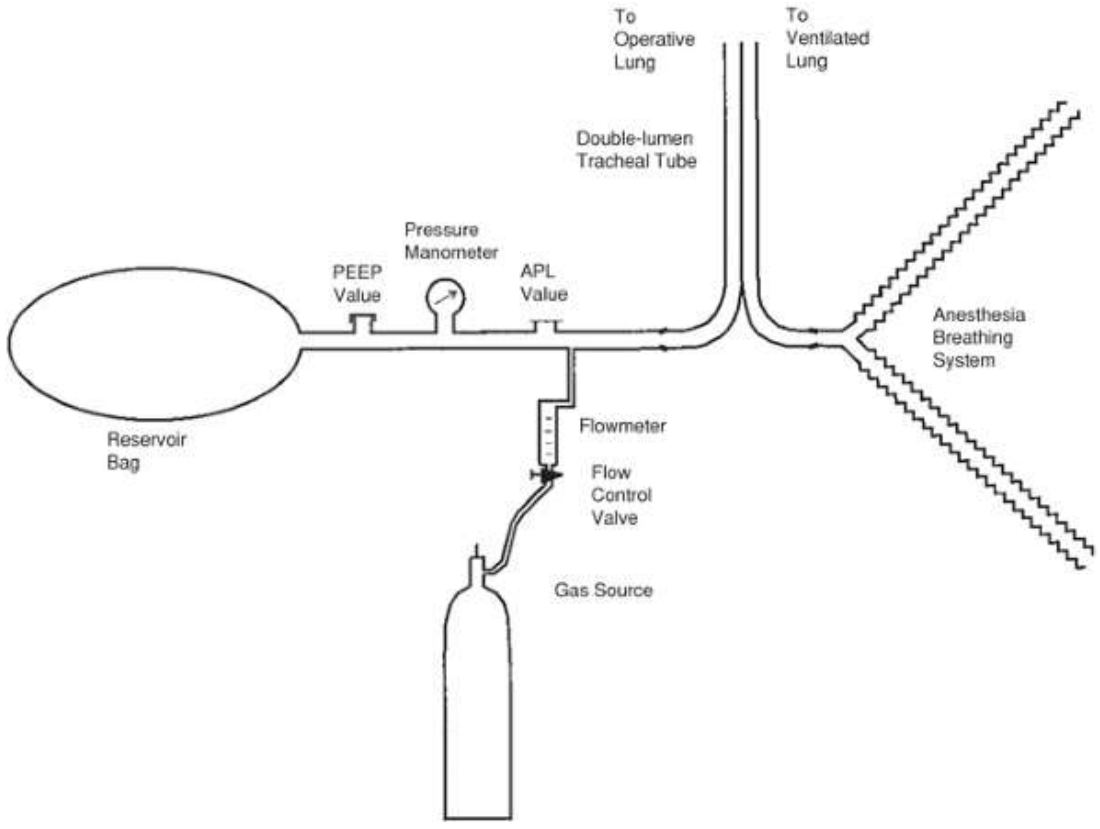

Figure 8.9 System for continuous positive airway pressure. (See text for details.) PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

Numerous modifications of the original T-piece have been made. Many have the fresh gas inlet extending inside the body of the T-piece toward the patient connection to minimize dead space. A pressure-limiting device may be added to the system.

Use of the Mapleson E system for anesthesia has decreased because of the difficulty in scavenging excess gases. It is commonly used to administer oxygen or humidified gas to patients breathing spontaneously.

Techniques of Use

For spontaneous ventilation, the expiratory limb is open to atmosphere. Controlled ventilation can be performed by intermittently occluding the expiratory limb and allowing the fresh gas flow to inflate the lungs. Assisted respiration is difficult to perform.

Functional Analysis

The sequence of events during the respiratory cycle is similar to that of the Mapleson D system shown in Figure 8.7. The presence or absence and the amount of rebreathing or air dilution will depend on the fresh gas flow, the patient's minute volume, the volume of the exhalation limb, the type of ventilation (spontaneous or controlled), and the respiratory pattern.

Rebreathing

With spontaneous ventilation, no rebreathing can occur if there is no exhalation limb. If there is an expiratory limb, the fresh gas flow needed to prevent rebreathing will be the same as for the Mapleson D system. During controlled ventilation, there can be no rebreathing, because only fresh gas will inflate the lungs.

Air Dilution

No air dilution can occur during controlled ventilation. During spontaneous ventilation, air dilution cannot occur if the volume of the tubing is greater than the patient's tidal volume. If there is no expiratory limb or if the volume of the limb is less than the patient's tidal volume, air dilution can be prevented by providing a fresh gas flow that exceeds the peak inspiratory flow rate, normally three to five times the minute volume. A fresh gas flow

of two times minute volume and a reservoir volume one third of the tidal volume will prevent air dilution (95).

Hazards

Controlling ventilation by intermittently occluding the expiratory limb may lead to overinflation and

barotrauma. This is a danger with this system in particular because the anesthesia provider does not have the ‾€feel‾€ of the bag during inflation that she or he has with other systems. The pressure-buffering effect of the bag is absent, and there is no APL valve to moderate the pressure in the lungs. To overcome this potential hazard, it has been recommended that a pressure-limiting device be placed in the system (96).

Mapleson F System

The Mapleson F (Jackson-Rees, Rees, Jackson-Rees modification of the T-piece) system has a bag with a mechanism for venting excess gases (97) (Fig. 8.1F). The mechanism can be a hole in the tail or side of the bag that is occluded by using a finger to provide pressure. It may be fitted with a device to prevent the bag from collapsing while at the same time allowing excess gases to escape. An anesthesia ventilator may be used in place of the bag (98). An APL valve may be placed near the patient connection to provide protection from high pressure (99).

Scavenging can be performed by enclosing the bag in a chamber from which waste gases are suctioned (100) or by attaching various devices to the relief mechanism in the bag (101).

Techniques of Use

For spontaneous respiration, the relief mechanism is left fully open. For assisted or controlled respiration, the relief mechanism is occluded sufficiently to distend the bag. Respiration can then be controlled or assisted by squeezing the bag. Alternately, the hole in the bag can be occluded by the user's finger during inspiration. For mechanical ventilation, the bag is replaced by the hose from a ventilator.

A heat and moisture exchanger (HME) can be used with a Mapleson F system either by inserting it between the patient and the T-piece or by using the gas sampling port on the HME as the

fresh gas inlet (102). However, this will result in most of the fresh gas being vented from the distal end of the expiratory limb during spontaneous respiration (103,104,105). To overcome this problem, the expiratory limb can be partially or totally occluded, the fresh gas flow increased, or the HME not used with spontaneous respiration.

Functional Analysis

The Mapleson F system functions much like the Mapleson D system. The flows required to prevent rebreathing during spontaneous and controlled respiration are the same as those required with the Mapleson D system. This system offers less work of breathing than a pediatric circle system (106). While one study did find that there was less work of breathing with the Jackson-Rees system, it was considered by other investigators to be a negligible difference and of importance in only the sickest patients breathing spontaneously (107).

PEEP does not affect end-tidal CO_2 during controlled ventilation but causes an increase during spontaneous breathing when fresh gas flows are less than three times minute volume (108). PEEP should not be applied by using an underwater seal (109).

If a heat and moisture exchanger (Chapter 11) is added to the Mapleson F system during an inhalation induction, the increased resistance will result in more of the fresh gas flow entering the expiratory limb, delaying induction (104).

Hazards

The hazards of the Mapleson F system are the same as those described for the Mapleson E system. Excessive pressure is less likely to develop, because there is a bag in the system.

If a ventilator that uses a ram of oxygen to produce inspiration is used with a T-piece system, a disconnection at the common gas outlet may not be detected by an airway pressure monitor due to the high resistance of the fresh gas tubing (110).

Respiratory Gas Monitoring with the Mapleson Systems

All of the Mapleson systems except the A system have the fresh gas inlet near the patient connection port. This may make it

difficult to get a reliable sample of exhaled gases. One study examined four sampling sites (Fig. 8.10): at the junction of the breathing system and elbow connector, at the corner of the elbow connector, 2 cm distal in the elbow connector, and in the tracheal tube connector (111). It was found that if sampling were carried out at the two sites closest to the patient, values were accurate. Significant errors were noted when samples were taken from the corner of the elbow connector but only if a high fresh gas flow was used. Significant errors were noted when sampling was performed at the junction of the breathing system and elbow connector even if low fresh gas flows were used. A cannula that projects into the airway can be used to improve sampling (112).

In another study involving infants and children, sampling at the junction of the tracheal tube and breathing system resulted in falsely low end-tidal CO_2 values in patients weighing less than 8 kg (59). The accuracy of measurements can be improved by inserting a small heat and moisture exchanger between the breathing system and the tracheal tube connector (113). However, using a device at this site will increase dead space and may result

in excessive resistance so that spontaneous respiration cannot be used (103,114).

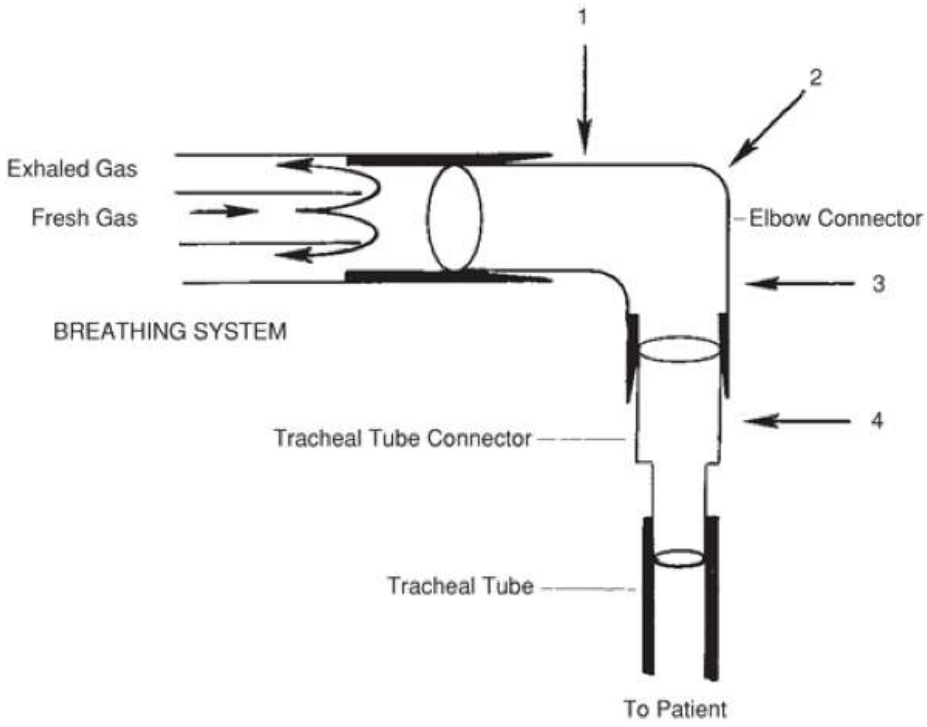

Figure 8.10 Respiratory gas sampling with a Mapleson system. Accurate values for expiratory concentrations can be obtained by sampling at sites 3 and 4. Sampling at site 2 will yield accurate values only if the fresh gas flow is not high. Sampling at site 1 will yield inaccurate values even at low fresh gas flows. (Redrawn from Gravenstein N, Lampotang S, Beneken JEW. Factors influencing capnography in the Bain circuit. J Clin Monit 1985; 1:6Ì€“10.)

Advantages of the Mapleson Systems

1. The equipment is simple, inexpensive, and rugged. With the exception of the APL valve, there are no moving parts. The components are easy to disassemble and can be disinfected or sterilized in a variety of ways. For these reasons, they continue to be a popular choice to provide positive pressure ventilation in emergencies (115).
2. Variations in minute volume affect end-tidal CO_2 less than in a circle system.
3. In coaxial systems (Lack, Bain), the inspiratory limb is

heated by the warm exhaled gas in the coaxial expiratory tubing.

4. Resistance is usually low at flows likely to be experienced in practice (116,117,118,119). A commonly held view is that the work of breathing during spontaneous ventilation is significantly less with these systems than with the circle system. However, studies indicate that this is not always the case (120,121,122). The work of breathing may be increased if the APL valve is not oriented properly.
5. These systems are lightweight and not bulky. They are not likely to cause drag on the mask or tracheal tube or accidental extubation.
6. They are easy to position conveniently. A long Mapleson D system with an aluminum APL valve may be used to ventilate a patient in the MRI unit (123).
7. Compression and compliance volume losses are less with the Mapleson systems than with the circle system.
8. Changes in fresh gas concentrations result in rapid changes in inspiratory gas composition.
9. Since there is no CO_2 absorbent, there will be no production of possibly toxic products such as carbon monoxide and compound A (Chapter 9).

Disadvantages of the Mapleson Systems

1. These systems require high gas flows. This results in higher costs, increased atmospheric pollution, and difficulty assessing spontaneous ventilation.

2. Because of the high fresh gas flow, inspired heat and humidity tend to be low, unless a humidification device is used (124).
3. The optimum fresh gas flow may be difficult to determine. It is necessary to change the flow when changing from spontaneous to controlled ventilation or vice versa. Anything that causes the fresh gas flow to be lowered presents a hazard, because rebreathing may occur.

4. In the Mapleson A, B, and C systems the APL valve is located close to the patient, where it may be inaccessible to the user. In addition, scavenging is awkward. This disadvantage can be overcome by using the Lack modification of the Mapleson A.
5. The Mapleson E and F systems are difficult to scavenge, and air dilution can occur with the Mapleson E system.
6. Mapleson systems are not suitable for patients with malignant hyperthermia, because it may not be possible to increase the fresh gas flow enough to remove the increased CO_2 load (125).

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Questions

For the following questions, select the correct answer.

1. In which of the following is the fresh gas inlet most distant from the patient connection port?

A. Mapleson A

B. Mapleson B

C. Mapleson C

D. Mapleson D

E. Mapleson E

View Answer

2. Which of the following is most efficient during spontaneous ventilation?

A. Mapleson A

B. Mapleson B

C. Mapleson C

D. Mapleson D

E. Mapleson E

View Answer

3. Which of the following systems lacks a reservoir bag?

A. Mapleson A

B. Mapleson B

C. Mapleson C

D. Mapleson D

E. Mapleson E

View Answer

4. Which of the following is the most efficient during controlled ventilation?

A. Mapleson A

B. Mapleson B

C. Mapleson C

D. Mapleson D

E. Mapleson E

View Answer

5. Advantages of the Mapleson systems include all of the following except

A. Buffering effect on end-tidal CO_2

B. Simple, inexpensive equipment

C. Useful in treating malignant hyperthermia

D. Lightweight

E. Ease of disassembly

View Answer

Chapter 9
The Circle System

The circle system is so named because gases flow in a circular pathway through separate inspiratory and expiratory channels. Carbon dioxide exhaled by the patient is removed by an absorbent. International and U.S. standards for breathing systems with particular emphasis on circle systems have been published (1,2).

Components

Absorber

The absorber is usually attached to the anesthesia machine but may be separate. An absorber assembly consists of an absorber, two ports for connection to breathing tubes and a fresh gas inlet. Other components that may be mounted on the absorber assembly include inspiratory and expiratory unidirectional valves, an adjustable pressure limiting (APL) valve, and a bag mount. Modern anesthesia machines often incorporate components of the anesthesia ventilator into the absorber assembly. Disposable absorbers and absorber assemblies are available.

Canisters

Construction

The absorbent is held in canisters (carbon dioxide‍€“absorbent containers, chambers, units, or cartridges). The side walls are transparent so that the absorbent color can be monitored. A canister with tinted side walls may make it difficult to detect color changes

in the absorbent (3). A screen at the bottom of each canister holds the absorbent in place.

Figure 9.1 Absorber with two canisters in series, a dust/moisture trap at the bottom and a drain at the side. The lever at the right is used to tighten and loosen the canisters. Note that the date the absorbent was last changed is marked on the lower canister.

Many absorbers use two canisters in series (Fig. 9.1). A single canister may also be used (Fig. 9.2). Some newer machines use a single, small disposable canister that can be quickly changed during an anesthetic without interrupting breathing system continuity (Figs. 9.3, 9.4).

Figure 9.2 Absorber with a single canister. It is loosened and tightened by twisting.

Prepackaged absorbent containers are available and are placed inside the canisters that are a part of an absorber. These eliminate the need to pour absorbent into the canister. These containers can cause an obstruction if the label or wrap covering them is not removed or an excessive number of holes are occluded (4,5,6).

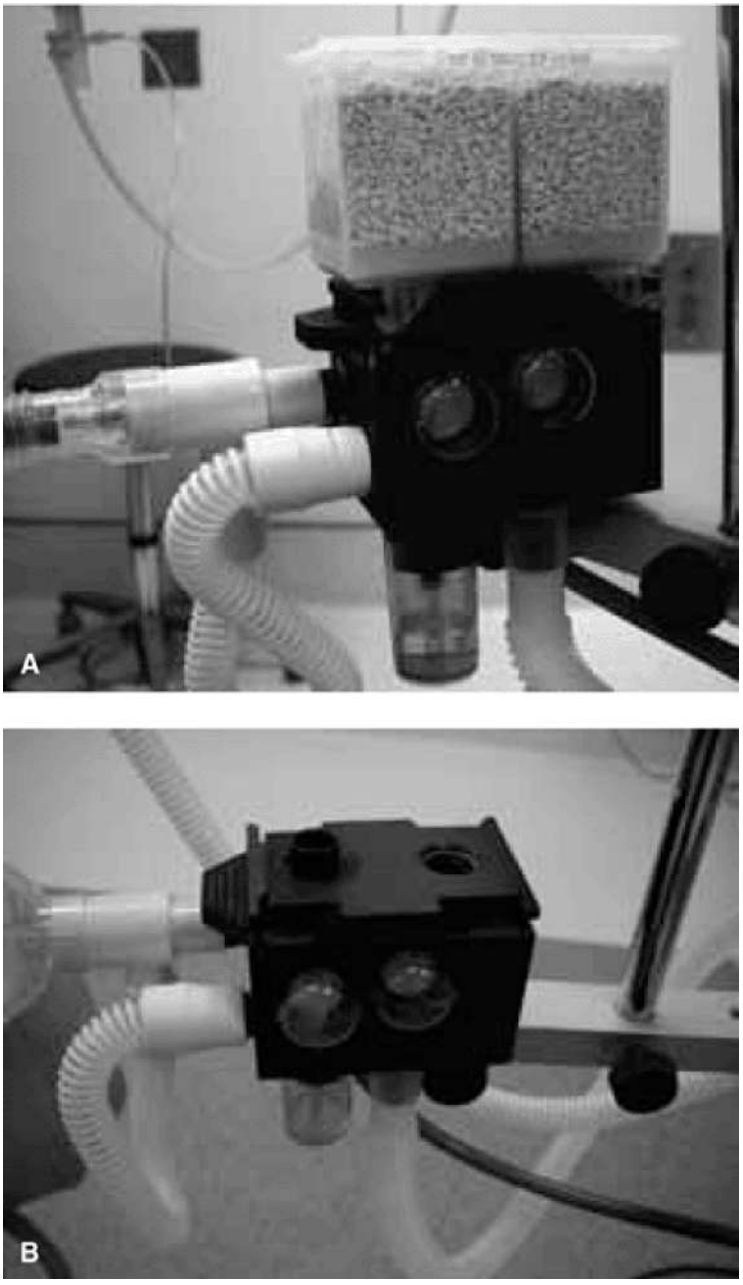

Figure 9.3 Absorber with single disposable canister. **A:** With the canister in place. **B:** With canister removed. The two valves at the top prevent loss of gas when the canister is removed.

Size

Canisters of varying capacity have been used. An advantage of large canisters is longer intervals between absorbent changes (7). This advantage may be offset by the possibility that absorbent may become desiccated when it resides in the absorber for a long time.

Newer use anesthesia machines use small canisters that must be changed more frequently. Frequent changes help to provide fresh absorbent with proper water content. This will lessen the likelihood that carbon monoxide or Compound A will be produced (8,9,10). Some manufacturers recommend that a new canister be used for each anesthetic.

Another advantage of small absorbers is that the internal volume of the breathing system is reduced. This will allow changes in the fresh gas flow concentration to be reflected more quickly in the inspired concentration and improve ventilator performance.

Absorption Pattern

The pattern of absorption within a properly packed canister is shown in Figure 9.5. It makes no difference whether the gases enter at the top or bottom. The first absorption occurs at the inlet and along the canister sides. As this absorbent becomes exhausted, carbon dioxide will be absorbed farther downstream in the canister.

Housing

The head and base of the absorber (Fig. 9.1) are constructed of metal or plastic. There are spaces at the top and bottom of the absorber for incoming gases to disperse before passing through the absorbent or for outgoing gases to collect before passing on through the circle. This promotes even distribution of flow through the absorber. In the base, this space allows dust and condensed water to accumulate (Fig. 9.1). Some bases have a means of draining water from the bottom (Fig. 9.1). Because this water will be highly alkaline, care should be taken that it does not contact skin.

On many modern machines, the canister is attached to a housing that incorporates valves that will close the entrance and exit from the canister when the canister is removed (Figs. 9.3, 9.4). This allows breathing system continuity to be maintained when the canister is changed.

Baffles

Baffles, which are annular rings that serve to direct gas flow toward the central part of the canister, are frequently used to increase the travel path for gases that pass along the sides of the canister and compensate for the reduced flow resistance along the walls of the canister.

Side or Center Tube

There must be a way to conduct gases to or from the bottom of the canister and return them to the patient. Some absorbers have a side tube external to the canister(s). The tube may also be in the center of the absorber (Fig. 9.6).

Bypass

On older absorbers, there was a bypass valve that allowed exhaled gases to completely or partially bypass the absorber. As has been discussed earlier in this chapter, most modern absorbers with small canisters allow the canister to be changed during a case without disrupting the breathing system integrity. If the canister is intentionally removed and not replaced, this becomes a bypass. Care must be taken to replace the canister

so that another anesthetic will not begin without it in place. Low-flow anesthesia is dangerous in the absence of the carbon dioxide absorbent. The bypass can be used to allow carbon dioxide to accumulate in the breathing system.

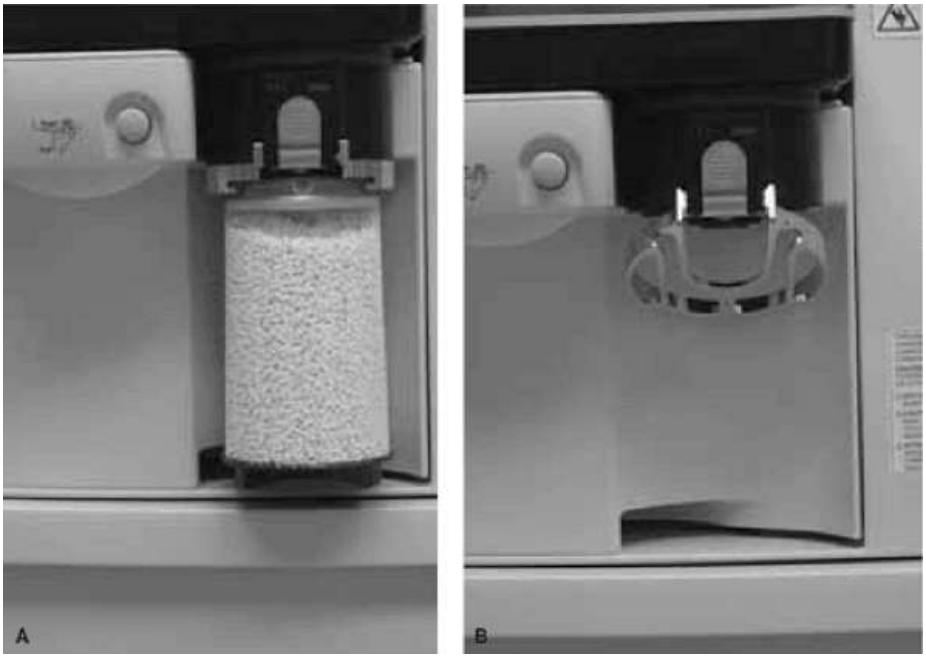

Figure 9.4 Absorber with a single disposable canister. **A:** With canister in place. **B:** With canister removed. The canister fits into grooves in the bracket and is pushed up to lock it in place. Note the release button.

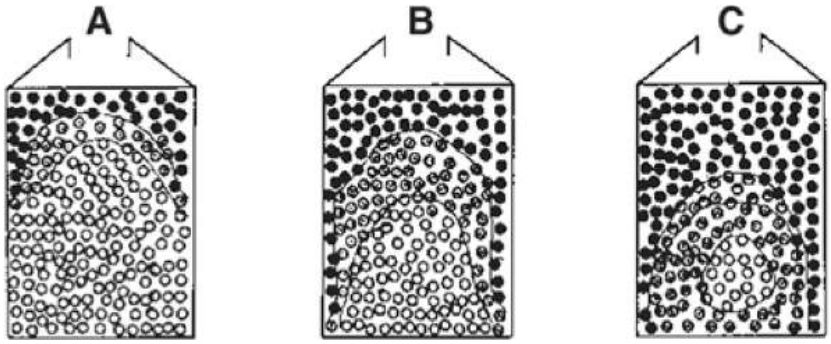

Figure 9.5 Pattern of carbon dioxide absorption in a canister. *Darkened circles* represent exhausted absorbent. **A:** After limited use; absorption has occurred primarily at the inlet and to a lesser extent along the sides. **B:** After extensive use; the granules at

the inlet and along the sides are exhausted. **C:** Carbon dioxide is filtering through the canister; in the distal third of the canister, a spot remains where the granules are still capable of absorbing carbon dioxide. (Redrawn from Adriani J, Rovenstein EA. Experimental studies on carbon dioxide absorbers for anesthesia. Anesthesiology 1941;2:10.)

Absorbents

Composition

Carbon dioxide absorption employs the general principle of a base neutralizing an acid. The acid is carbonic acid formed by the reaction of carbon dioxide with

water. The end products of the reaction are water and a carbonate. Heat is liberated by the reaction.

Figure 9.6 Center tube in canister. Note the grooves around the edge that allow the canister to be screwed tightly in place.

High-alkali Absorbents

Some absorbents, including such traditional ones as some formulations of soda lime, contain relatively high amounts of potassium and/or sodium hydroxide. When these absorbents

become desiccated, they react with volatile anesthetics to form carbon monoxide. Compound A can be formed with sevoflurane. These absorbents often do not change color when dry. The capacity to absorb carbon dioxide is decreased by decreased moisture (11).

Low-alkali Absorbents

Some carbon dioxide absorbents contain reduced amounts of sodium or potassium hydroxide. Studies differ on whether these produce smaller amounts of Compound A and carbon monoxide than absorbents with more strong alkalis (12,13,14,15,16,17).

Alkali-free Absorbents

Alkali-free absorbents consist mainly of calcium hydroxide with small amounts of other agents added to accelerate carbon dioxide absorption and bind water. There is no evidence of carbon monoxide formation with any anesthetic agent, even if the absorbent becomes desiccated (14,18,19,20,21,22,23,24,25). There is little or no Compound A formation with sevoflurane even with a closed circuit and desiccated absorbent (12,17,18,22,26,27,28,29,30,31,32,33).

The indicator in these absorbents changes color on drying (34,35,36,37). This property can be used to indicate dehydration in absorbents with strong bases by placing the absorbent with no strong base at the site where fresh gas enters the canister (34). Once exhausted, these absorbents do not revert to their original color.

The carbon dioxide absorption capacity of these absorbents is less than absorbents containing strong alkali (11,22,25,31,38,39,40,41,42) but does not deteriorate when moisture is lost (11).

Lithium Hydroxide

Lithium hydroxide reacts with carbon dioxide to form carbonate. It does not react with anesthetic agents, even if desiccated (17,43,44,45,46). However, it is expensive and requires careful handling because it may cause burns to the eyes, skin, and respiratory tract (47).

Indicators

An indicator is an acid or base whose color depends on pH. It is added to the absorbent to signify when the absorbent's ability to absorb carbon dioxide is exhausted. The indicator does not affect absorption. Some of the commonly used indicators and their colors are shown in Table 9.1. Ethyl violet is most commonly employed, because the color change is vivid with a high contrast (48). Confusion may result because one indicator is white when fresh whereas another is white when exhausted. The user should always know which indicator is being used and what color change is seen when the absorption capacity is exhausted.

TABLE 9.1 Indicators for Absorbents

Indicator	*Color When Fresh*	*Color When Exhausted*
Phenolphthalein	White	Pink
Ethyl violet	White	Purple
Clayton yellow	Red	Yellow
Ethyl orange	Orange	Yellow
Mimosa Z	Red	White

Shape and Size

Absorbents are supplied in pellets or granules. Pellets or small granules provide greater surface area and decrease gas channeling along low-resistance pathways. However, they may cause more resistance and caking.

Granule size is measured by mesh number. A 4-mesh strainer has four openings per square inch whereas one of 8 mesh has eight openings per square inch. Granules graded 4 mesh will pass through the 4-mesh strainer but not through a strainer with smaller holes. In other words, the higher the mesh number, the smaller the particles. Most absorbents used in anesthesia today

consist of granules in the range of 4 to 8 mesh.

Hardness

Some absorbent granules fragment easily, producing dust (fines). There may be variations in the dust content of different absorbents (49). Excessive powder produces channeling, resistance to flow, and caking. Dust may be blown through the system to the patient or may cause system components to malfunction (50,51). To prevent this, small amounts of a hardening agent are added. Some manufacturers coat the outside of the granules with a film to which dust particles adhere. If a filter is used on the inspiratory side of the breathing system, dust should not reach the patient.

Reactions between Absorbents and Anesthetic Agents

Haloalkene Formation

Halothane degradation most often occurs during closed-circuit anesthesia and produces the haloalkene 2-bromo-2-chloro-1, 1-difluoroethene (BCDFE). Although BCDFE is nephrotoxic in rats, halothane has not been found to be nephrotoxic in humans after over four decades of use (52).

Compound A Formation

Sevoflurane decomposes in the presence of some carbon dioxide absorbents to form

several degradation compounds. Only one, Compound A, a vinyl ether that has a dose-dependent nephrotoxic effect in rats, reaches significant concentrations (53,54,55,56,57,58). It has been the subject of intense debate regarding possible nephrotoxicity in humans (59,60,61,62,63,64,65,66). A large number of scientific reports on this topic have been published, sometimes with contradictory results and conclusions (59,62,65,67,68,69,70,71,72,73,74,75,76,77,78,79,80,81,82,83,84,85,86,87,88,89).

Several factors influence the amount of Compound A in the breathing system.

Fresh Gas Flow

More Compound A is produced with lower fresh gas flows (90,91). However, a number of studies have been carried out in closed system without significant Compound A formation (17,26,32).

Absorbent Composition

Compound A production is greatest with absorbents containing potassium or sodium hydroxide. Absorbents with decreased potassium hydroxide/sodium hydroxide produce lower concentrations of Compound A (92). Absorbents that are free of strong alkali produce little or no Compound A, even during closed system anesthesia (12,18,26,92,93).

Absorbent Temperature

Temperature in the absorber correlates with the amount of Compound A that is generated (94,95,96). Lowering the absorber temperature decreases the amount of Compound A produced (94,97). Increased absorber temperature associated with an increase in carbon dioxide eliminated by the patient may result in modest increases in Compound A production (98,99).

The reaction between desiccated absorbent and sevoflurane produces heat, which increases the reaction speed, so the rate of sevoflurane breakdown can accelerate rapidly (100,101,102). Sevoflurane may be so extensively consumed that maintaining anesthesia is difficult.

The size and shape of the canister may be important in determining the temperature of the absorbent. Small chambers may result in lower temperatures.

One study found that if dead space were added between the circle system and the Y-piece and the volume of ventilation increased to compensate for the increased dead space without changing alveolar ventilation, the temperature of the absorbent would be reduced (103). However, another study found that sevoflurane breakdown increased with higher minute volumes (100).

Concentration of Sevoflurane

Higher concentrations of Compound A occur when higher concentrations of sevoflurane are used (95,101).

Anesthetic Length

Compound A concentration increases with longer anesthetics.

Water Content

The effect of absorbent dryness is complex (101,104,105,106,107). Dehydrated absorbents increase both the degradation of sevoflurane to Compound A and the degradation of Compound A (104,108). The absorbent in small canisters is less likely to become desiccated probably because it is changed more frequently. Absorbent dryness can be predicted by measuring the percent of water in the outflow gas (109). Smaller patients are less likely to rehydrate the absorbent through exhaled water vapor and carbon dioxide neutralization.

Absorbent can be rehydrated to some extent by using humidified gases (110). Absorbent manufacturers have cautioned against adding moisture directly to absorbent (111). Poured water will not uniformly hydrate all of the absorbent. This will leave desiccated granules that can react with anesthetic agents. Alkaline water could potentially be carried to the patient (112). Adding water could lead to agglomeration of the absorbent granules, which could increase the resistance to gas flow and cause a significant loss in absorption capacity (111).

Carbon Monoxide Formation

Carbon monoxide is produced when desflurane, enflurane, or isoflurane is passed through dry absorbent containing a strong alkali (potassium or sodium hydroxide) (9,10,22,113,114,115,116,117,118,119,120,121,122). When sevoflurane is degraded by absorbent, carbon monoxide is formed if the temperature exceeds 80ยฐC (100). The incidence of carbon monixide formation is not known but is probably greater than thought (117,123,124). Cases of severe carbon monoxide poisoning have been reported (117,118,120,125).

Most reported cases have occurred during the first general anesthetic of the day and on Monday morning, presumably because fresh dry gas was flowing into the circle system over the weekend, causing the absorbent to become dehydrated (126). Carbon monoxide formation has also been reported when anesthesia was administered from a little-used machine in a

remote location (124).

The carbon monoxide concentration in the breathing system varies with time, tending to peak in the first 60 minutes (10,114,121).

Carbon monoxide can present a serious hazard to the patient. Signs and symptoms of moderate carbon monoxide toxicity such as confusion, headache, and nausea are masked during and after anesthesia and may resemble common sequelae (127). The consequences are more severe in patients with low hemoglobin levels and in small patients (100,128).

Carbon Monoxide Detection

Some desiccated absorbents will continue to absorb carbon dioxide; therefore, the presence of an acceptable capnographic waveform should not be taken as evidence that the inspired gas is free from carbon monoxide (129).

Most pulse oximeters (Chapter 24) cannot detect carbon monoxide and read carboxyhemoglobin as oxyhemoglobin. However, a very high carboxyhemoglobin concentration may cause a slight decrease in SpO_2 (117).

Respiratory gas monitors in current use cannot directly detect carbon monoxide. Multiwavelength infrared analyzers may provide warning of isoflurane or

desflurane (but not sevoflurane) breakdown by displaying the wrong agent or mixed agents (100,117,118,130,131,132).

An unusually delayed rise or unexpected decrease in the inspired concentration of a volatile anesthetic in the breathing system compared with the vaporizer setting, a failed inhalation induction, inadequate anesthesia, or an unexpected decrease in inspired concentration may indicate that chemical breakdown (with possible production of carbon monoxide) is occurring (120,133,134,135).

Carbon monoxide monitors that work in the presence of clinical concentrations of volatile anesthetics are commercially available (124,136,137,138). Carboxyhemoglobin monitoring is available through co-oximetry but is not routinely assessed. A combination pulse oximeter and carbon monoxide detector is commercially

available (Chapter 24).

Since the reaction of anesthetics with desiccated absorbent is exothermic, an unusually high temperature in the canister may be a sign of carbon monoxide formation (139,140). However, this is not a reliable method of detecting carbon monoxide formation (141). With gas channeling inside the absorber, the outside of the canister may feel only warm despite high internal temperatures.

Factors Associated with Carbon Monoxide Formation

Absorbent Composition

Only absorbents that contain sodium and/or potassium hydroxide are associated with the formation of carbon monoxide.

Absorbent Desiccation

No significant carbon monoxide production occurs with normally hydrated absorbents (100,142). Fresh gas flowing through the absorbent during an extended period of nonuse is thought to be the main factor that causes desiccation. The impact of fresh gas flow in various circle system configurations that can lead to absorbent desiccation is discussed more fully later in this chapter. Use of a heat and moisture exchanger (HME) will result in decreased humidity in the circle system.

Detecting absorbent desiccation is difficult. The lack of significant color change with many of the absorbents does not ensure adequate absorbent hydration (134). An absorbent with no strong bases can be used to detect dehydration before carbon monoxide is formed from anesthetic degradation by layering it at the site of fresh gas inflow (34). These absorbents will change color when dry. Another way to detect desiccation is to fill the breathing system with gas containing sevoflurane and circulate it through the absorbent while monitoring the sevoflurane concentration (143). A rapid decline in sevoflurane concentration may indicate desiccated absorbent.

Anesthetic Agent

The highest carbon monoxide levels have been seen with desflurane followed by enflurane then isoflurane (9,144). The

amount of carbon monoxide produced with halothane is small. Significant amounts of carbon monoxide have been reported with sevoflurane only when the absorbent temperature was greater than 80ยฐC (10,100,120,145,146).

Temperature Inside the Absorber

High temperatures in the absorbent facilitate carbon monoxide production from sevoflurane (102,145). However, if an exothermic reaction is occurring deep in the absorber, it may not be detected by feeling the outside of the canister.

Fresh Gas Flow

Higher fresh gas flows remove more carbon monoxide, producing lower carbon monoxide concentrations, although more carbon monoxide is produced at higher fresh gas flows because of the greater quantity of anesthetic reacting with desiccated absorbent (9,100,137,147). High fresh gas flows are more likely to promote absorbent desiccation.

Carbon Dioxide Absorption

Carbon monoxide formation is reduced by carbon dioxide absorption (141,148). This could be significant with smaller patients who produce less carbon dioxide. Carbon monoxide levels are increased with reduced patient size (147).

Preventing Carbon Monoxide Formation

The Anesthesia Patient Safety Foundation (APSF) has recommended that carbon dioxide absorbents that do not degrade when they are desiccated and exposed to volatile agents should be used (129). These include absorbents without KOH and little or no NaOH. Since the composition and names of these absorbents change frequently, clinicians must look at the composition of a particular absorbent to see if it fits the above recommendation.

The APSF has provided a number of recommendations that an anesthesia department should take to prevent absorbent desiccation if the department continues to use strong alkali absorbents with volatile anesthetic agents (129). These, including a few more discussed in the literature, are presented below.

1. All gas flows should be turned OFF after each case. This is probably the most important measure. When the daily schedule is finished, the anesthesia machine should be disconnected from the medical gas pipeline system at the pipeline outlet.
2. Vaporizers should be turned OFF when not in use. At the end of each case, the breathing system should be flushed with gas that is free of volatile anes-thetic.
3. The absorbent should be changed routinely, at least once a week, preferably on a Monday morning, and whenever fresh gas has been flowing for an extensive or indeterminate period of time. The canister should be labeled with the filling date (Fig. 9.1). Checking

this date should be part of the daily machine checklist (112). If a double-chamber absorber is used, the absorbent in both canisters should be changed at the same time.

4. Canisters on an anesthesia machine that is commonly not used for a long period of time should not be filled with absorbent that contains strong alkali or should be filled with fresh absorbent before each use.
5. The integrity of the absorbent packaging should be verified prior to use. Opened containers that contain absorbent should be carefully closed after use, and the rest of the absorbent should be used as soon as possible.
6. The practice of supplying oxygen for administration to a patient who is not receiving general anesthesia through the circle system should be strongly discouraged (124). This is associated with other hazards, including accidental administration of nitrous oxide and volatile anesthetics (149). Supplemental oxygen should be obtained from a flowmeter that is connected directly to the oxygen pipeline system or an auxiliary oxygen flowmeter on the anesthesia machine (Chapter 5).
7. Using fresh gas to dry breathing system components should be discouraged (124).
8. The negative pressure relief valve on a closed scavenging

system (Chapter 13) should be checked regularly. Failure of this valve to pull in room air may result in fresh gas from the machine being drawn through the absorbent if the APL valve is open (124).

9. The temperature in the canister should be monitored and the absorbent changed if excessive heat is detected. A simple patient temperature monitor may be used for this purpose. If the temperature approaches 50ยฐC, excessive heating from anesthetic breakdown should be suspected (127). However, if the probe is not in the area where the temperature increase occurs, the rise in temperature may be missed.
10. Consideration should be given to removing absorbent from canisters in induction rooms and to using high fresh gas flows to eliminate rebreathing (146).

It is important to involve anesthesia technicians, cleaning staff, nursing personnel, and anyone else who might come into contact with an anesthesia machine in the program to prevent absorbent drying. These personnel need to be trained to look out for flowmeters that are left ON. They should be instructed to turn OFF any flows at the end of the day and to reduce the flow to a minimum between cases. The absorbent should be changed if it is likely that prolonged exposure to dry gases has occurred. One study found that these measures reduced, but did not eliminate, absorbent desiccation (150).

Absorbent can be rehydrated to some extent by using humidified gases (110). Absorbent manufacturers have cautioned against adding moisture directly to absorbent (111). Poured water will not uniformly hydrate all of the absorbent. This will leave desiccated granules that can react with anesthetic agents. Alkaline water could potentially be carried to the patient (112). Adding water could lead to agglomeration of the absorbent granules in addition to increased resistance to flow and a significant loss in absorption capacity if moisture content standards are exceeded (111).

Flushing the breathing system with fresh gas before use will not prevent carbon monoxide exposure.

Excessive Heat and Fires

The interaction of desiccated barium hydroxide absorbent and sevoflurane can produce temperatures of several hundred degrees centigrade (100,104,120). Cases of fires and/or melted components in the absorber have been reported (100,112,120,134,135,139,146,151). Because of these problems, barium hydroxide has been removed from the market (152). Using soda lime results in less elevated temperatures (153), although fires involving desiccated soda lime have also been reported (135,154).

It is possible that damage from excessive heat is not reported more often because patient absorption of the toxic products reduced their concentrations below the lower limit of flammability. Cases of melted or burned absorber parts should be reported to the Food and Drug Administration (FDA), suppliers, and the Emergency Care Research Institute (ECRI) (112).

Absorbent Storage and Handling

Absorbents are supplied in several types of containers: resealable packages, pails, cans, cartons, and disposable prefilled containers. Once opened, containers should be resealed as soon as possible to prevent absorbent reaction with carbon dioxide in the air, indicator deactivation, and moisture loss. High temperatures will have no effect on absorbents if the containers are sealed, but temperatures below freezing are harmful because the moisture will expand and cause the granules to fragment.

Absorbents should always be handled gently to avoid fragmentation and dust formation. All personnel involved in handling absorbents should be periodically warned that absorbent dust is irritating to the eyes and respiratory tract and that absorbents are caustic to the skin, particularly when damp. When a canister is emptied, care should be taken to remove dust particles, because they will cause the seals to warp, making it difficult to achieve a tight fit. Screens should be cleared to reduce resistance to gas flow.

The canister should always be filled with care. It should be held over a suitable container to avoid getting particles on the floor. The absorbent should be

poured slowly into the canister while the canister is rotated,

stopping occasionally to tap the sides. The canister should be filled completely but not overfilled. A small space should be left at the top to promote even gas flow through the canister. The upper layer of absorbent should be level.

When using disposable, prefilled containers, it is important to remove the top and bottom labels or plastic wrap, if present, before insertion. If these are not removed, gas cannot flow through the container, and complete breathing system obstruction will occur (4).

When and How to Change the Absorbent

There are a variety of opinions about when the absorbent should be changed. Changing it too often is uneconomical. However, absorbent that has become desiccated or exhausted must be changed.

Inspired Carbon Dioxide

The appearance of carbon dioxide in the inspired gas is the most reliable method to detect absorbent exhaustion (155). This allows the absorbent to be used most efficiently.

Indicator Color Change

Indicator color change can be used but does not demonstrate carbon dioxide breakthrough as reliably as inspired carbon dioxide when absorbents containing strong bases are in use (3).

The following considerations should be kept in mind when using an indicator:

1. A phenomenon known as *peaking* or *regeneration* is seen with absorbents that contain strong bases. The absorbent appears to be reactivated with rest. The amount of regeneration depends on how long the absorbent is rested. After a number of such periods of efficient absorption with intervening periods of rest, terminal exhaustion occurs. Regeneration has some importance when indicators are used. An absorbent that shows an exhausted color, if allowed to rest, will often show color reversal. The absorption capacity will be low, and the exhausted color will reappear after only a brief exposure to carbon dioxide. The rested canister, therefore, can give a false impression

of its usefulness.

2. When the exhausted color shows strongly, the absorbent is at or near the point of exhaustion. When little or no color change shows, active absorbent may be present, but the amount is indeterminate and may be quite small.
3. Absorbents without a strong base change color when dried (34).
4. If channeling occurs, the absorbent along the channels will become exhausted, and carbon dioxide will pass through the canister. If the channeling occurs at sites other than the sides of the canister, the color change may not be visible.
5. The absorbent may not contain an indicator (156,157,158). Some companies make an industrial absorbent that does not contain an indicator, and this product may be supplied as the result of an administrative error.
6. Ethyl violet undergoes deactivation even if it is stored in the dark (159). Deactivation is accelerated in the presence of light, especially high-intensity or ultraviolet light.
7. Coloration in the outer wall of the canister may obscure the color change (3).

Heat in the Canister

The reaction of carbon dioxide with absorbent produces heat. Changes in absorbent temperature occur earlier than changes in the color of the indicator. Periodically checking the canister temperature is useful (160). Some heat production should be apparent, unless high fresh gas flows are being used. Studies suggest that when the temperature of the downstream canister exceeds that of the upstream chamber, the absorbent in the upstream canister should be changed (161). Recent recommendations are that both canisters be changed even if only one shows color change (129).

To change the absorbent, the absorber is opened and the canister removed. The absorbent is discarded and the canister filled with fresh absorbent. Care should be taken when placing the last of the absorbent into the canister. If excessive dust is present, the remaining absorbent should be discarded and filling

completed from a new container (162).

Absorption of Other Agents

Carbon dioxide absorbents remove nitric oxide and/or nitrogen dioxide from the inspiratory limb of a ventilator circuit (163). Absorbents vary widely in their ability to absorb these entities. If nitric oxide is being used, nitric oxide monitoring should be performed downstream from the absorber.

Unidirectional Valves

Two unidirectional (flutter, one-way, check, directional, dome, flap, nonreturn, inspiratory, and expiratory) valves are used in each circle system to ensure that gases flow toward the patient in one breathing tube and away in the other. They are usually part of the absorber assembly. The American Society for Testing and Materials (ASTM) standard requires that the direction of intended gas flow be permanently marked on the valve housing or near its associated port with either a directional arrow or with the marking *inspiration* or *expiration* so that it is visible to the user (1).

A typical horizontal unidirectional valve is shown diagrammatically in Figure 9.7. A light, thin disc (leaflet or poppet) seats horizontally on an annular seat. The disc has a slightly larger diameter than the circular knife

edge on which it sits. A cage or guide mechanism (retainer) (such as projections from the seat and dome) may be present to prevent the disc from becoming dislodged laterally or vertically (Fig. 9.8). The disc should be hydrophobic so that condensate does not cause it to stick and increase the resistance to opening. The top of the valve is covered by a clear plastic dome so that the disc can be observed. Gas enters at the bottom and flows through the center of the valve, raising the disc from its seat. The gas then passes under the dome and on through the breathing system. Reversing the gas flow will cause the disc to contact the seat, preventing retrograde flow.

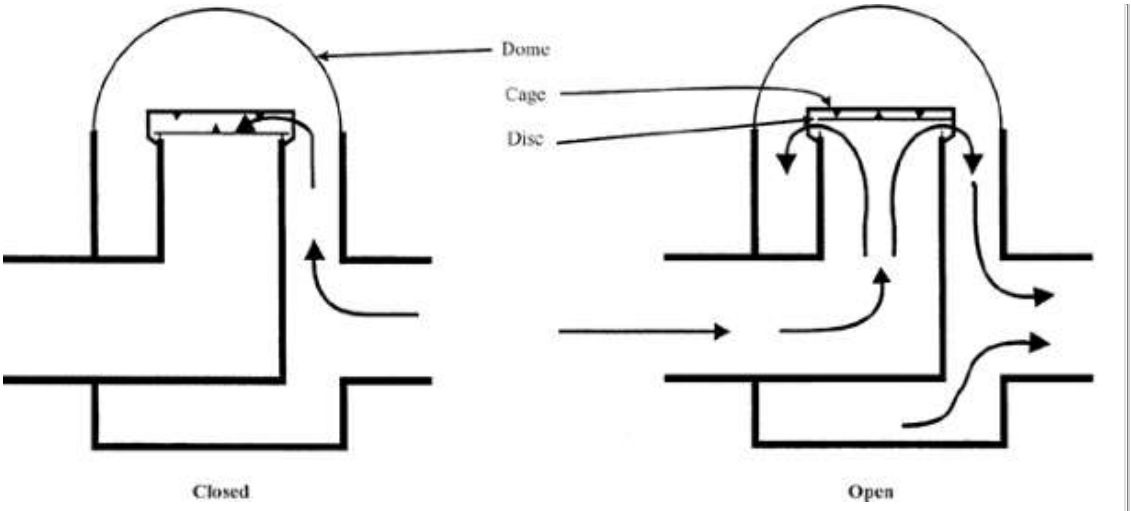

Figure 9.7 Unidirectional valve. **Left:** Reversing the gas flow causes the disc to contact its seat, stopping further retrograde flow. **Right:** Gas flowing into the valve raises the disc from its seat and then passes through the valve. The guide (cage) prevents lateral or vertical displacement of the disc. The transparent dome allows observation of disc movement.

Unidirectional valves may be vertical rather than horizontal (Fig. 9.9). They have the disc hinged at the top. Vertical unidirectional valves reduce the resistance to gas flow (164).

Figure 9.8 Horizontal unidirectional valves. Note the cages that prevent the discs from being displaced.

One or both unidirectional valves may become incompetent (165,166,167,168,169,170). Movement of the disc does not guarantee valve competence. Because an incompetent valve offers less resistance to flow than one that must open, the flow of gas will be primarily through the incompetent valve, resulting in rebreathing. The valve on the exhalation side is most prone to this problem because it is subjected to more moisture, but incompetence has also been described with the inspiratory valve (171,172). A unidirectional valve leak produces a characteristic waveform on the capnograph (Chapter 22).

A unidirectional valve may jam, obstructing gas flow (173,174). In one reported case, the disc was lost during cleaning and not recovered (175). It was later found out of sight below the seat, where it had moved into such a position that it covered the opening to the bag mount and functioned as a one-way valve. Gas from the bag could flow into the system, but not back into the bag again.

Inspiratory and Expiratory Ports

The inspiratory port has a 22-mm male connector downstream of the inspiratory unidirectional valve through which gases pass toward the patient during inspiration. The expiratory port has a 22-mm male connector upstream of the unidirectional valve through which gases pass during exhalation. These ports are usually mounted on the absorber (Figs. 9.3B, 9.10).

Figure 9.9 Vertical unidirectional valves.

Y-piece

The Y-piece (Y-piece connector, Y-connector, Y-yoke, Y-adaptor, three-way breathing system connector) is a three-way tubular connector with two 22-mm male ports for connection to the breathing tubes and a 15-mm female patient connector for a tracheal tube or supraglottic airway device. The patient connection port usually has a coaxial 22-mm male fitting to allow direct connection between the Y-piece and a face mask. In most disposable systems, the Y-piece and breathing tubes are permanently attached. The Y-piece may be designed so that the patient port swivels. A septum may be placed in the Y-piece to decrease the dead space.

Figure 9.10 The breathing tubes attach to the inspiratory and expiratory ports.

Coaxial breathing systems (Fig. 9.11) have a component that replaces but serves the same function as the Y-piece. The inner (inspiratory) tube ends just before the connection to the patient. The exhalation channel though the outer tube begins just downstream of the end of the inspiratory tubing.

Fresh Gas Inlet

The fresh gas inlet may be connected to the common gas outlet on the anesthesia machine by flexible tubing. The ASTM standard requires that the fresh gas inlet port, or nipple, has an inside diameter of at least 4.0 mm and

that the fresh gas delivery tube has an inside diameter of at least 6.4 mm (1). The fresh gas may enter the breathing system downstream of the inspiratory unidirectional valve. This location and its consequences are discussed later in this chapter. On most newer anesthesia machines, there is a direct connection between the machine outlet and the breathing system, so the user does not see a fresh gas hose.

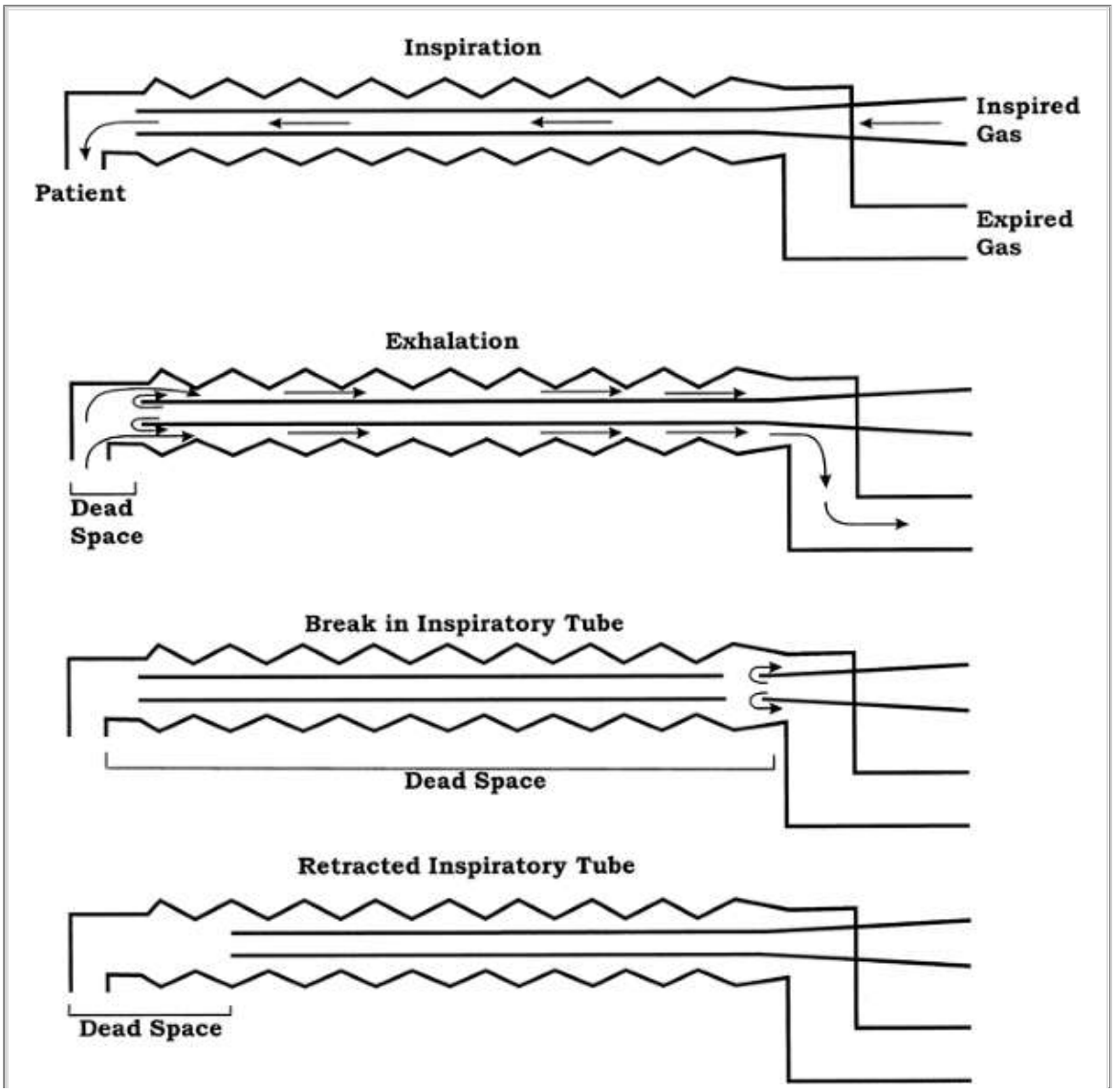

Figure 9.11 Coaxial circle system. If there is a break in the inspiratory tube or the inspiratory tube becomes retracted, there will be an increase in dead space.

Adjustable Pressure-limiting Valve

The APL valve is discussed in Chapter 7. During spontaneous breathing, the valve is left fully open and gas flows through the valve during exhalation. When manually assisted or controlled ventilation is used, the APL valve should be closed enough that the desired inspiratory pressure can be achieved. When this pressure is reached, the valve opens and excess gas is vented to the scavenging system during inspiration. There is a case report where this valve jammed in the closed position (176). During mechanical ventilation the APL valve is isolated from the breathing system.

Pressure Gauge

Many circle systems have an analog pressure gauge (manometer) attached to the exhalation pathway. The gauge is usually the diaphragm type that is shown in Figure 9.12. Changes in pressure in the breathing system are transmitted to the space between two diaphragms, causing them to move inward or outward. Movements of one diaphragm are transmitted to the pointer, which moves over a calibrated scale. The ASTM standard

requires that the gauge be marked in units of kPa and/or cm H_2O (1).

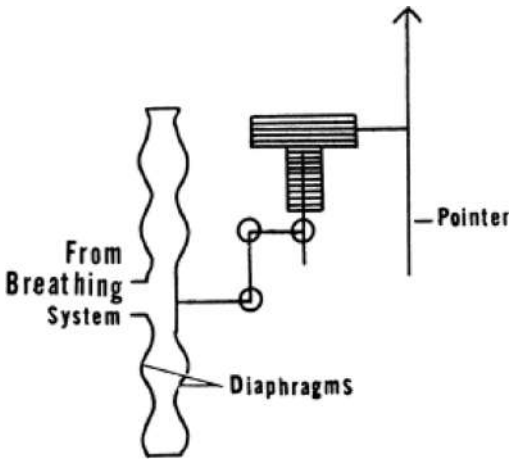

Figure 9.12 Diaphragm-activated pressure gauge. Two thin metal diaphragms are sealed together, with a space between them. This space is connected to the breathing system. Variations in pressure in the breathing system are transmitted to the diaphragms, which bulge outward or inward. A series of levers is activated, moving the pointer, which records the pressure.

On newer machines, breathing system pressure is often monitored electronically and displayed on a screen. The analogue pressure gauge may not be present. A virtual pressure gauge may be displayed on the screen (Figure 23.19).

Breathing Tubes

Two breathing tubes carry gases to and from the patient. Each tube connects to a port on the absorber at one end and the Y-piece at the other. The dead space in the system extends from the Y-piece to the patient. The length of the tubes does not affect the amount of dead space or rebreathing because of the unidirectional gas flow. Longer tubes allow the anesthesia machine and other equipment to be located farther from the patient's head (177). Expandable tubes are available (see Fig. 7.3).

The majority of breathing tubes used in the United States are plastic, disposable, and nonconductive. Reusable breathing tubes are available. A useful device to keep the tubings in place and separate from other tubings is shown in Figure 9.13 (also

see Fig. 7.4).

Coaxial circle systems are available. The breathing tubes may be concentric or side by side (Fig. 9.14). As shown in Figures 9.15 and 9.16, the tubings attach to a conventional absorber assembly. Gases flow through the inner tube to the patient, and exhaled gases flow to the absorber assembly via the outer corrugated tube (Fig. 9.11). The inspired gas is somewhat warmed in the process. Advantages of this system include compactness and moderately increased inspired heat and humidity

(178,179,180). A disadvantage is the increased resistance. If the inner tube has a leak or becomes retracted at the patient end (Fig. 9.11), the dead space will be increased. This problem may not be easily detected and may result in hypercapnea (181). If the flow of gases is reversed, entering the patient through the outer tube and returning through the smaller inner tubing, the resistance during exhalation will be increased.

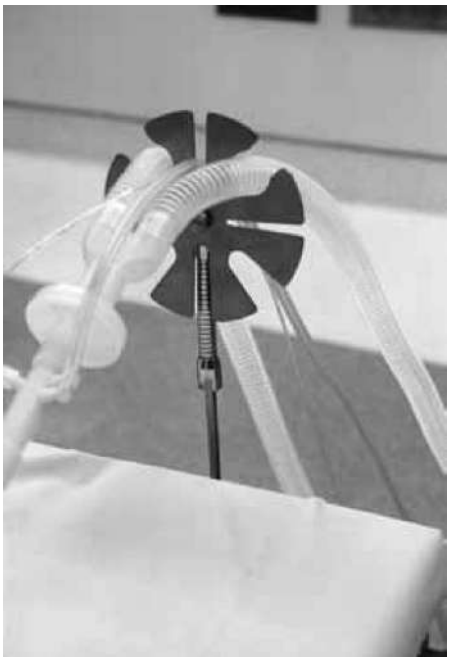

Figure 9.13 A tube retainer (tube tree) is useful to hold the breathing tubes and other tubes in place.

Figure 9.14 The inspiratory and expiratory pathways are side by side in one tubing.

Figure 9.15 Coaxial system attached to the absorber.

Figure 9.16 Having the reservoir bag on an extended arm may make it easier for the anesthesia provider to move around. Note the coaxial system attached to the absorber assembly.

Reservoir Bag

Bags were discussed in Chapter 7. The bag is usually attached to a 22-mm male bag port (bag mount or extension). It may also be placed at the end of a length of corrugated tubing or a metal tube leading from the bag mount (Fig. 9.16), providing some freedom of movement for the anesthesia provider.

Ventilator

In the past, the ventilator was considered a replacement for the reservoir bag and was attached at the bag mount. As machines and ventilators have evolved, the ventilator has become an integral part of the circle system. The ventilator's place in the breathing system is discussed later in this chapter. Individual ventilators are discussed in Chapter 12.

Bag/Ventilator Selector Switch

A bag/ventilator selector switch (switch valve, mode selector valve, selector valve, bag-ventilator switch valve, switching valve, switchover valve, manual/automatic selector valve, ventilator valve assembly) (Fig. 9.17)

provides a convenient method to shift rapidly between manual or

spontaneous respiration and automatic ventilation without removing the bag or the ventilator hose from its mount. As shown in Figure 9.18, the selector switch is essentially a three-way stopcock. One port connects to the breathing system. The second is attached to the bag mount. The third attaches to the ventilator hose. The handle or knob that is used to select the position indicates the position in which the switch is set.

Figure 9.17 This bag/ventilator selector switch and APL valve are on the front of the ventilator.

A selector switch with APL valve isolation is the only type allowed by the ASTM standard (1). When the selector switch is in the ventilator position, the APL valve is isolated from the circuit, so it does not need to be closed. Switching to the bag mode causes the APL valve to be connected into the breathing system.

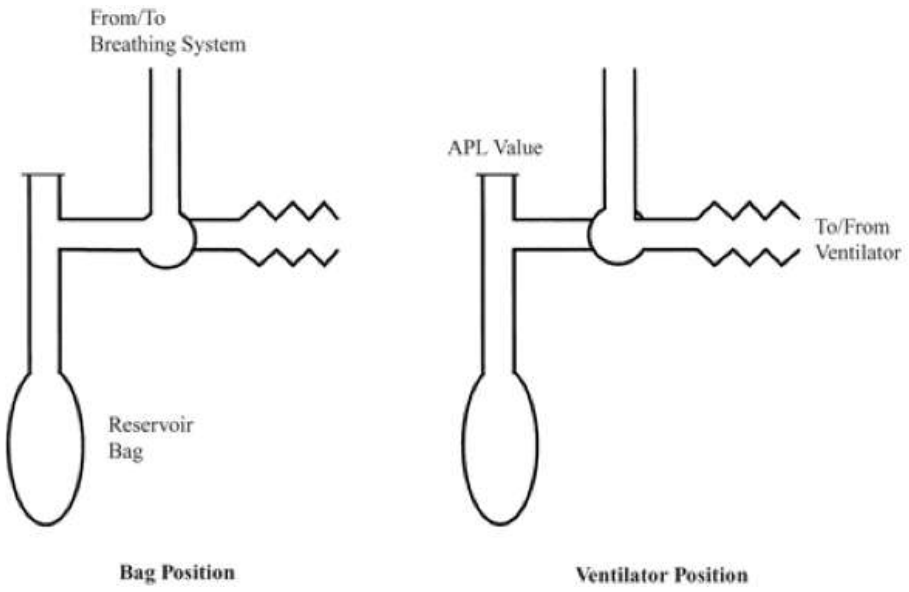

Figure 9.18 Bag/ventilator selector switch. In the Bag position, the reservoir bag and APL valve are connected to the breathing system. In the Ventilator position, the APL valve and bag are excluded from the breathing system. On most new machines, putting this in the ventilator position turns ON the ventilator.

On newer anesthesia machines, turning the bag/ ventilator selector switch to the ventilator position causes the ventilator to be turned ON. Some modern anesthesia machines do not have a bag/ventilator selector switch. Turning the ventilator ON causes electronically controlled valves to direct gases into the proper channels.

Respiratory Gas Monitor Sensor or Connector

Respiratory gas monitors are discussed in Chapter 22. Both mainstream and sidestream devices can be used with the circle system.

Airway Pressure Monitor Sensor

Airway pressure monitors are discussed in Chapter 23. The sensor can be inserted into the circle system by using an

adaptor, or it may be incorporated into the absorber assembly.

Respirometer

A respirometer is commonly used in the circle system to measure ventilatory volumes. These are discussed in Chapter 23.

Optional Equipment

Positive End-expiratory Pressure Valve

On most modern machines, the positive end-expiratory pressure (PEEP) valve is an integral part of the breathing system or ventilator. On other machines, it can be added when needed. It is critical that the valve be placed in the expiratory limb and oriented correctly. Placing a unidirectional PEEP valve backward will block gas flow. If a bidirectional PEEP valve is placed backward, gas flow will not be occluded, but no PEEP will be produced.

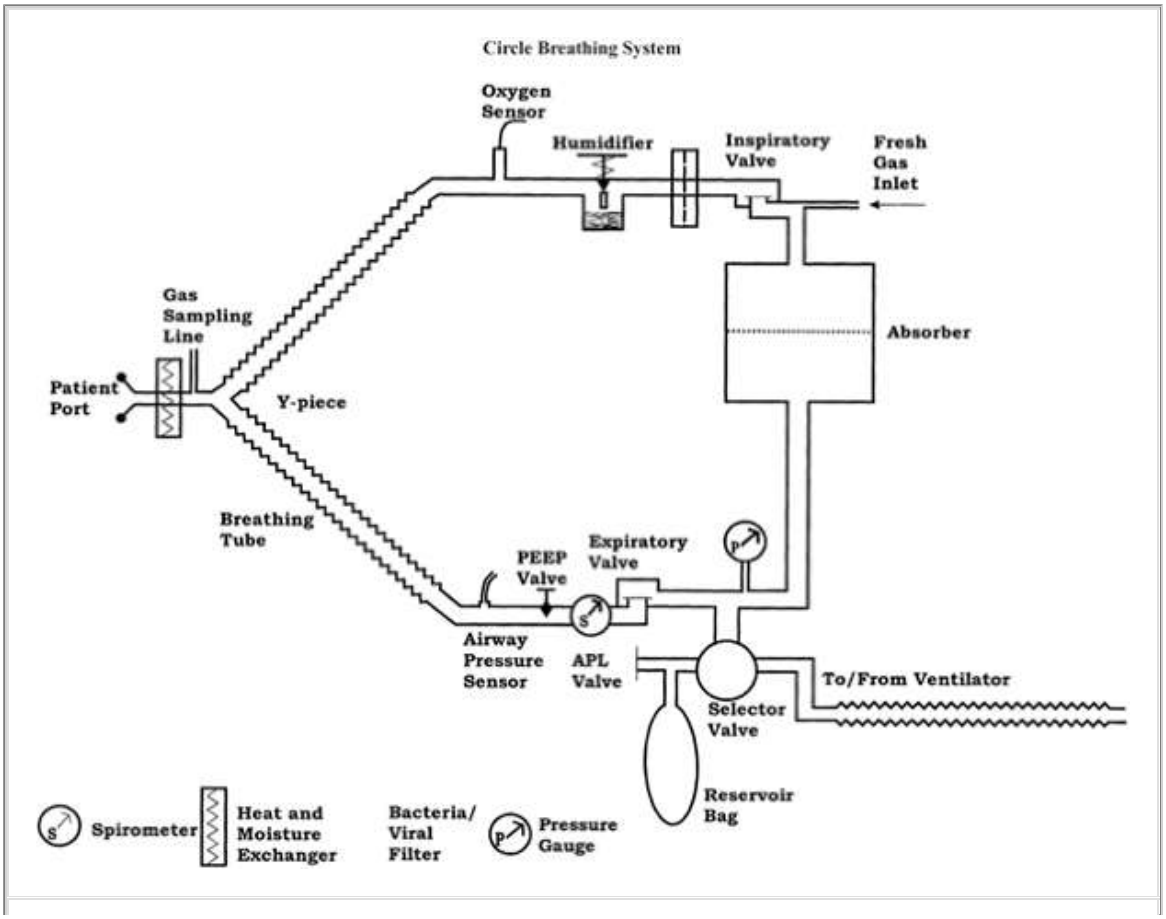

Figure 9.19 Classic circle system. Not all these components may be present in a given system. For example, a heat and moisture exchanger and a humidifier would not be used at the same time. PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

Filters

One of the disadvantages of the circle system is that it is difficult to clean and/or sterilize certain components. Filters are discussed in Chapter 7. They are used to protect the equipment from the patient and/or to protect the patient from the equipment.

Heated Humidifier

A heated humidifier can be placed in the inspiratory limb of the circle system. These are discussed in Chapter 11.

Arrangement of Components

Figure 9.19 shows an arrangement of components that has been used commonly in the past and is still used in many systems. Because it has been around so long and has been used so frequently, it is often referred to as the

classic circle system. This is the basic system that will be discussed in relation to the sequence of components.

With the integration of the ventilator into the circle system, many new configurations have been introduced. These will be discussed in greater detail later in this chapter and in Chapter 12. They differ primarily in where the ventilator is located and in the components necessary for ventilator function.

Objectives

There are a number of objectives in determining the best arrangement of components in the classic circle system. Unfortunately, not all can be met.

1. *Minimizing absorbent desiccation*. Desiccated absorbent has been identified as a significant cause of degradation of anesthetic agents and carbon monoxide formation. This was discussed earlier in this chapter.

2. *Maximum inclusion of fresh gas in the inspired mixture and maximum venting of alveolar gas* (182). Preferentially including fresh gas in the inspired mixture will result in faster inductions and emergences. The lower the fresh gas flow, the more important this objective becomes, because one of the effects of using lower fresh gas flows is that changes in concentration in the fresh gas flow are reflected more slowly in inspired concentrations.

3. *Minimal consumption of absorbent*. For efficient absorbent use, the gas vented through the APL valve should have the highest possible concentration of carbon dioxide. This will occur when (a) exhaled gas does not pass through the absorber before being vented, (b) exhaled gas is diluted as little as possible before venting, and (c) the vented gas is that exhaled late in exhalation, because the first gas exhaled is that from the dead space and has a low carbon dioxide concentration.

   As fresh gas flow is reduced, more exhaled gas must pass through the absorbent, so this objective becomes less important. When using a closed system, the arrangement of components should have no effect on absorbent utilization, because all exhaled gases will pass through the absorber.

4. *Accurate readings from a respirometer placed in the system*. If the fresh gas inlet is positioned so that the fresh gas continuously flows through the respirometer, the measured volumes may not be accurate.

5. *Maximal humidification of inspired gases*.

6. *Minimal dead space*.

7. *Low resistance*.

8. *Minimal pull on the tracheal tube, mask, or supraglottic device*.

9. *Convenience*. Components should be arranged so that they do not create difficulties during use. Tubings and wires should not become tangled.

There is no single arrangement of components that will meet all of the mentioned objectives, and objectives may conflict in some cases. For example, venting carbon dioxide upstream of the

absorber will conserve absorbent but may reduce inspired humidity. In certain clinical situations, particular objectives need to be given priority. In pediatric patients, dead space and humidification are usually more significant than in adults.

Consideration of Individual Components

Fresh Gas Inlet

Figure 9.20 shows possible locations of the fresh gas inlet in the classic circle system. It is most commonly placed upstream of the inspiratory unidirectional valve and downstream of the absorber (position A). In this position, during exhalation and the expiratory pause, fresh gas will flow in a retrograde direction into the absorber and then, depending on the fresh gas flow, into components between the expiratory unidirectional valve and the absorber. This flow can cause absorbent desiccation at the absorber outlet. At low fresh gas flows, no gas vented through the APL valve will have passed through the absorber. With higher fresh flows, some gas that has been in the absorber may be vented. At very high flows, some fresh gas may be vented.

Placing the fresh gas inlet just upstream of the absorber (position B) will result in less inclusion of fresh gas in the inspired mixture. Because of the proximity to the APL valve, fresh gas will be vented. Placing the fresh gas inlet in this position will improve humidification of inspired gases but will result in more absorbent desiccation. Another problem is that absorbent dust may be blown into the inspiratory limb when the oxygen flush is activated.

Placing the fresh gas inlet upstream of the bag and the APL valve (position E) has all of the disadvantages of position B and will result in more venting of fresh gas and dilution of exhaled gas before it is vented.

Placing the fresh gas inlet upstream of the expiratory unidirectional valve (position D) has all of the disadvantages of position E. In addition, during inspiration, the fresh gas flow will force exhaled gases that contain carbon dioxide back toward the patient.

Position C, downstream of the inspiratory unidirectional valve, is used on at least one modern anesthesia machine. An advantage is that changes in the fresh gas composition will be reflected

more rapidly in the inspired gases. Another advantage is that there will be no retrograde flow of fresh gas through the absorbent with a continuous flow of fresh gas when the machine is not

in use. During exhalation, fresh gases join exhaled gases and escape though the APL valve without reaching the patient. This results in poor economy of fresh gas and absorbent, because fresh gas will be lost during exhalation and will dilute the concentration of carbon dioxide in the gas vented through the APL valve. Another disadvantage of position C is that a respirometer placed on the exhalation side of the circuit will not record volumes accurately unless the fresh gas flow is turned OFF. This is not a problem if the respired volumes are measured between the Y-piece and the patient. Finally, end-tidal values may be affected by fresh gas flow (183).

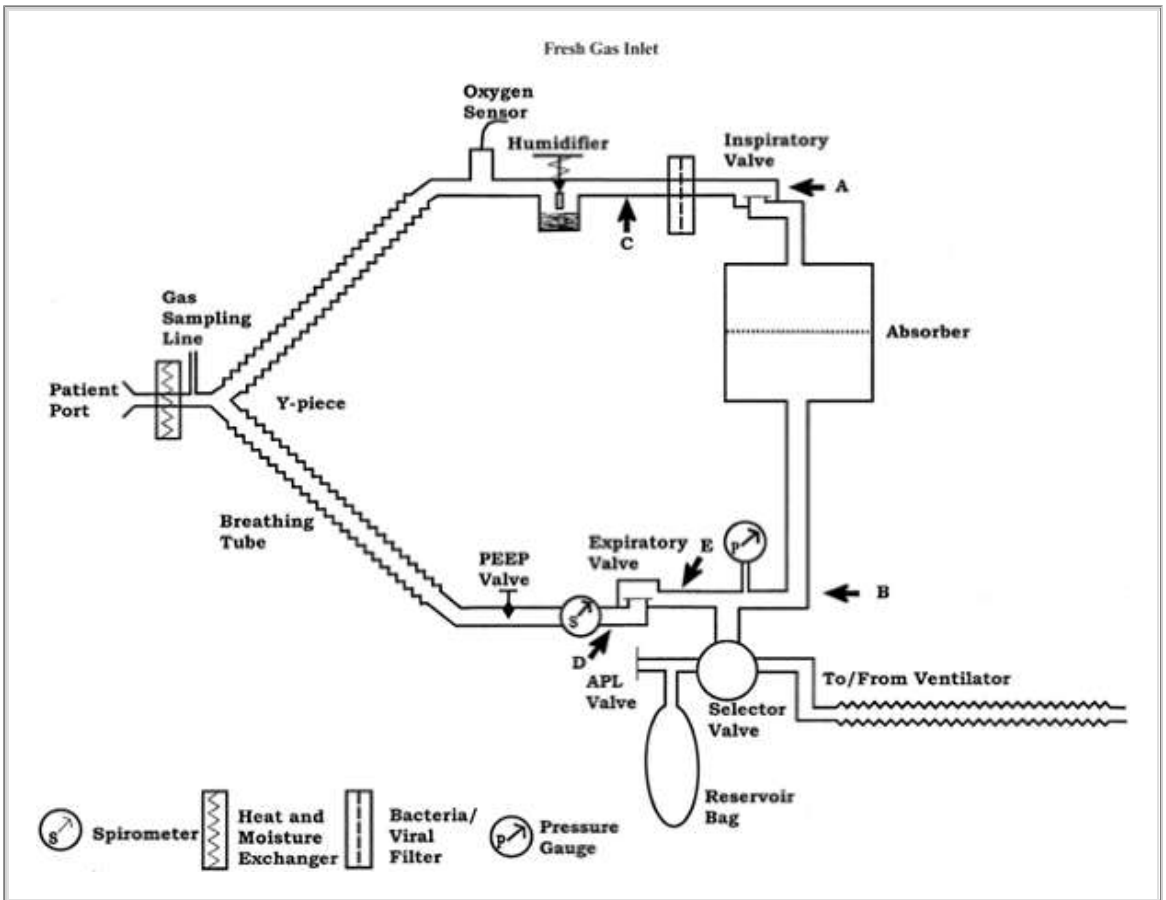

Figure 9.20 Possible locations for the fresh gas inlet. (See text for

details.) PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

Reservoir Bag

Figure 9.21 shows possible locations for the reservoir bag in the classic circle system. It is most commonly placed between the expiratory unidirectional valve and the absorber (position A). A disadvantage of placing the bag upstream of the absorber is that a sudden increase in pressure from squeezing the bag may force dust from the absorber into the inspiratory tubing (184).

During spontaneous respiration, absorbent use is equally efficient if the bag is downstream (position A) or upstream (position D or E) of the absorber. With manually controlled or assisted ventilation, more efficient use occurs with the bag upstream of the absorber. If the bag were in position D, exhaled gases would pass through the absorber to the bag during exhalation. Squeezing the bag during inhalation would cause the gases to reverse flow and pass retrograde through the absorber, to be vented through the APL valve. This would result in inefficient absorbent use, because gases cleared of carbon dioxide would be vented. This would also lead to absorbent desiccation, as dry fresh gas would be part of the retrograde flow through the absorber.

On some modern machines, the bag is connected to the circle system just downstream of the fresh gas inlet (position E). This will be discussed in detail later in this chapter.

If the bag is placed between the patient and either of the unidirectional valves (position B or C), it will form a reservoir for exhaled gases that will then be rebreathed.

Unidirectional Valves

Two locations have been used for the unidirectional valves: in the Y-piece and attached to the absorber. Valved Y-pieces are no longer available commercially and are not permitted by the ASTM standard (1). Valves in this position are bulky, and serious accidents have

occurred when a valved Y-piece was placed in a circle system

that contained absorber-mounted valves (185).

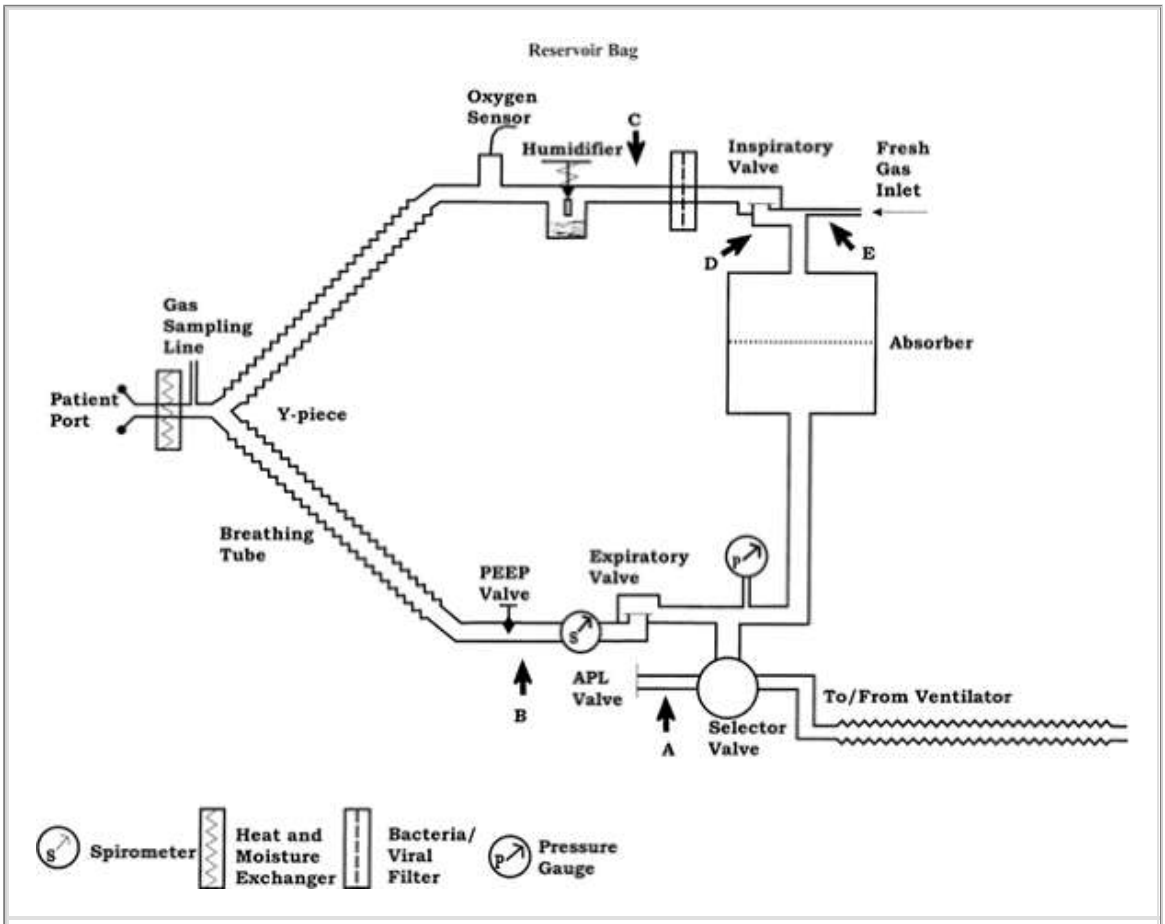

Figure 9.21 Possible locations for the reservoir bag. (See text for details.)

Adjustable Pressure-Limiting Valve

Figure 9.22 shows possible locations for the APL valve in the classic circle system. It is most commonly located near the reservoir bag downstream of the expiratory unidirectional valve and upstream of the absorber (position A). In this position, fresh gas will be vented only if the fresh gas flow is high (186).

During manually controlled or assisted ventilation, excess gas overflow occurs during inspiration. Fresh gas and gas that has passed through the absorber will be vented if the APL valve is placed between the fresh gas inlet and the patient (position B, C,

or D). If the valve is located at position E, upstream of the expiratory unidirectional valve, absorbent use will be inefficient, because all gas in the reservoir bag will have to pass through the absorber before being vented.

Locating the APL valve at the reservoir bag with an extender hose between the bag and the bag mount has been suggested (187). This will allow fresh gas that travels retrograde through the absorber during exhalation more space in which to collect.

During spontaneous respiration, the most efficient use of absorbent will occur with the APL valve on the Y-piece (position B). This is because during spontaneous respiration, overflow occurs in the latter part of exhalation. Gas exhaled during the first part of expiration is dead space gas with a low concentration of carbon dioxide. Because the APL valve is not open, this gas bypasses it. When the bag is filled, the pressure in the system rises and the APL valve opens. Since this opening occurs during the latter part of exhalation, the gas vented through the APL valve is mainly alveolar gas (with a high carbon dioxide content). No such discrimination is possible when the APL valve is distant from the patient. However, if the APL valve is at the Y-piece, the added weight (especially when scavenging apparatus is added) may increase the incidence of disconnections. Transfer tubing to the scavenging interface (Chapter 13) might become entangled with other objects. The valve will be difficult to adjust during head and neck surgery. Finally, placing the valve at position B will cause a decrease in inspired heat and humidity (178).

During spontaneous ventilation, absorbent use is inefficient if the APL valve is downstream of the absorber (positions C and D) because vented gas will have passed through the absorber. If the APL valve is placed at

position C, fresh gas will be vented. If the APL valve is in position D, exhaled gases will move retrograde in the inspiratory tubing during exhalation, causing an increase in dead space.

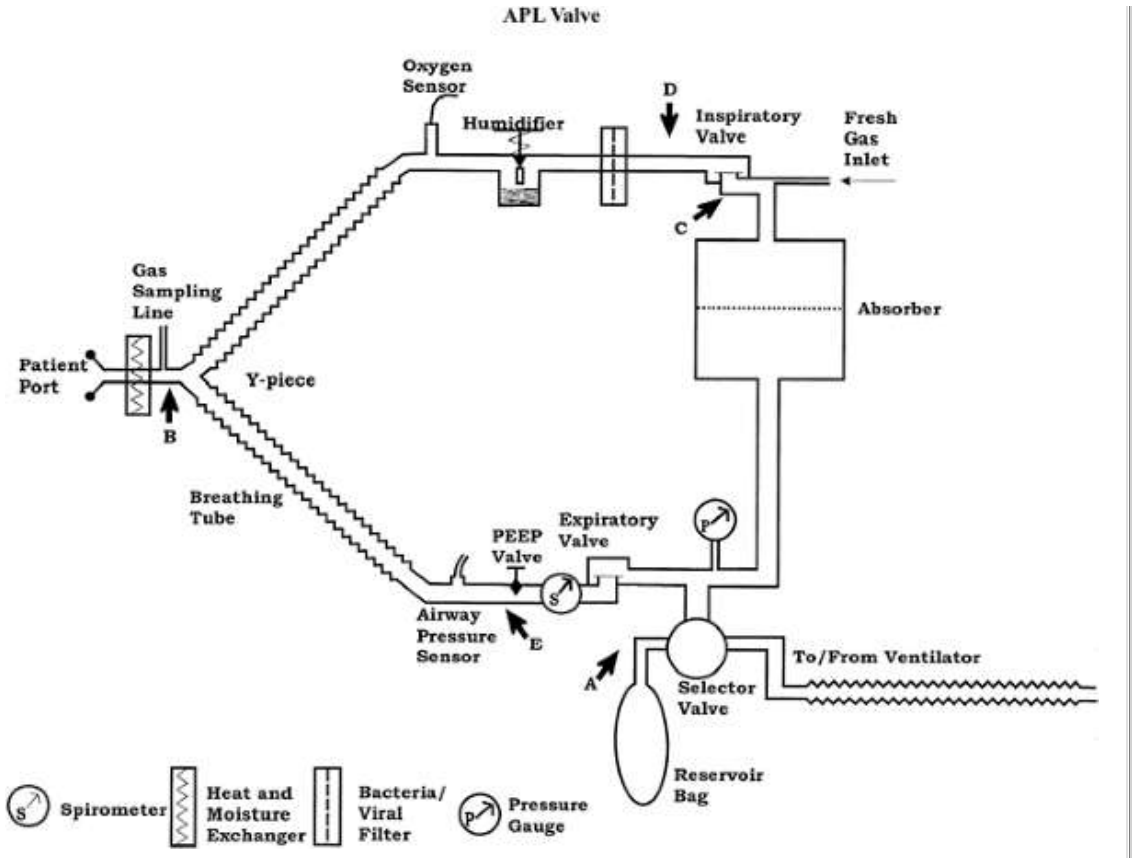

Figure 9.22 Possible locations for the adjustable pressure-limiting valve. (See text for details.) PEEP, positive end-expiratory pressure.

Filters

Figure 9.23 shows possible positions for a filter within the classic circle system. Most disposable systems do not allow a filter to be placed at position A or B. Convincing evidence that use of a filter prevents postoperative infection is lacking.

Position A is between the inhalation tubing and the Y-piece. A filter here will protect the patient from contamination and absorbent dust but will not protect system components or the operating room environment from contamination from the patient. If the filter is heavy or bulky, placing it in this position may be awkward. A filter should not be placed in this location if a humidifier is located upstream.

Position B is between the Y-piece and the exhalation tubing. In

this position, the system components and operating room will be protected. Water, mucus, or edema fluid can collect in the filter in this position, causing an increase in resistance or obstruction to gas flow. The bulk and weight of a filter may make it unsuitable for this location.

Position C is between the inspiratory tubing and the inspiratory unidirectional valve. The size or weight of the filter is not a problem in this position. If a humidifier is used, it should be downstream of the filter. A filter in this position will protect the patient from contamination from the absorber and its attached parts. It will catch absorbent dust. It will not protect circle system components or the operating room air from contamination from the patient.

Position D is between the exhalation tubing and the expiratory unidirectional valve. In this position, the filter will protect the system components from contamination. Because the filter is on the expiratory side, obstruction from fluid is possible, although less likely than with position B. This position may contribute to absorbent desiccation and production of Compound A and carbon monoxide as discussed earlier in this chapter.

Position E is between the Y-piece and the patient. In this position, the filter will protect the patient from the equipment and the equipment from the patient. This suggests a strategy for infection control in anesthesia (188). Using a new filter between the patient and the breathing system with each patient may permit reuse

of the breathing system. Potential problems with this site include increased dead space, increased possibility of disconnections, and increased resistance. The filter may become clogged with blood, secretions, or edema fluid.

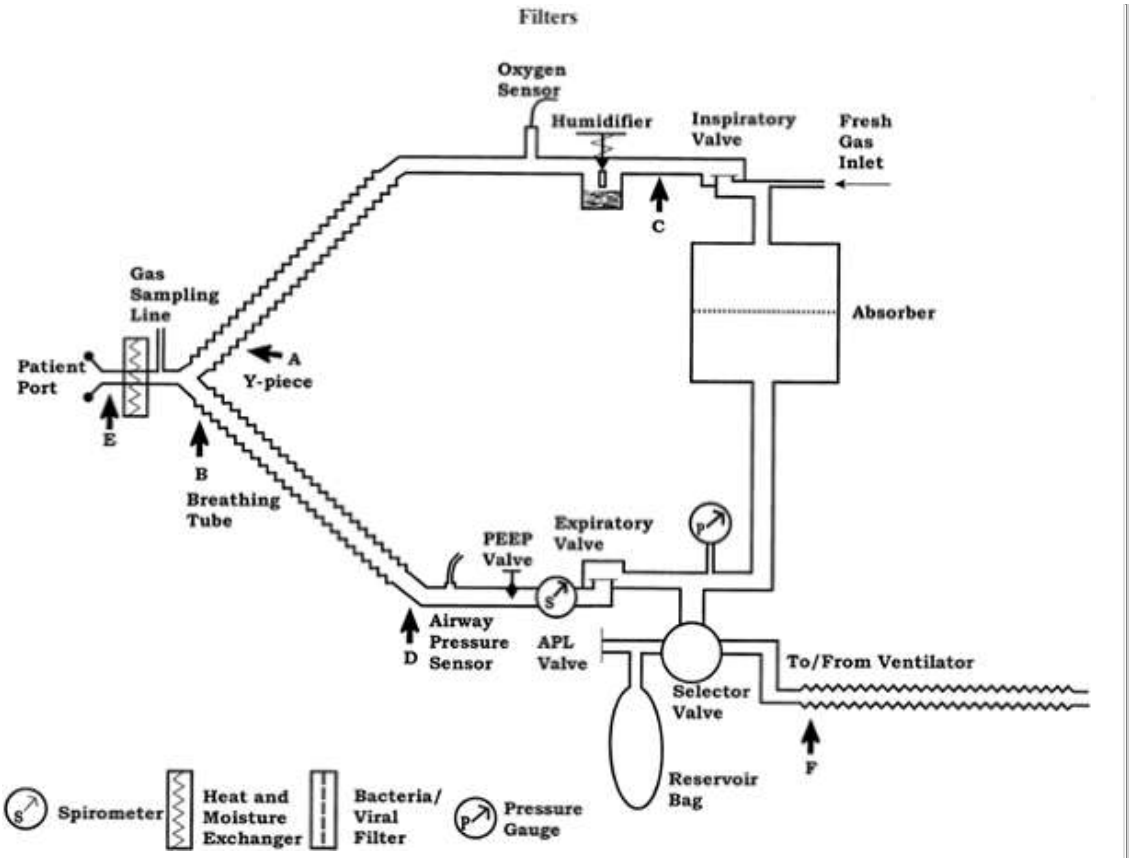

Figure 9.23 Possible locations for filters. (See text for details.) PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

Some filters act as HMEs. To function in this capacity, they must be positioned at location E. An HME that is located between the patient and the gas sample line will reduce the amount of moisture that enters the respiratory gas monitor (Chapter 22). Using an HME will decrease the humidity in the exhalation tubing, and this may contribute to dehydration of the absorbent.

Position F is in the hose leading to the ventilator. This will protect the patient from the ventilator and the ventilator from the patient. Disposable hoses with filters are available.

Respiratory Gas Monitor Sensor or Sample Site

Oxygen Monitor

Figure 9.24 shows possible locations for a mainstream oxygen monitor sensor in the classic circle system. It may be fitted into the dome of a unidirectional valve (H), the top of the absorber assembly, or a T-shaped adapter. The sensor should be placed so that the membrane points downward to prevent water from accumulating on the membrane.

Positions A, F, and H are on the inspiratory side, whereas positions C, E, G, and I are on the exhalation side. Placing the sensor on the expiratory side will usually expose it to more humidity, but this is not a problem with most sensors. If low fresh gas flows are used, the reading on the expiratory side will be lower than on the inspiratory side, but even with a closed system, the inspired-expired difference is only 4% to 6%.

It has been advocated that the oxygen analyzer be placed near the Y-piece (position B, F, or G) so that it will alarm in the event of a disconnection between the breathing system and the tracheal tube or supraglottic device. However, an oxygen analyzer should not be relied on to detect a disconnection. Although this is the most common site for disconnections, they can occur in other locations. With a high fresh gas flow, the oxygen concentration may not fall sufficiently for the alarm to sound if a disconnection occurs.

Placing the sensor near the patient in position B, F, or G may make it difficult to maintain in an upright position. In addition, the cable to the monitor may become entangled with other tubings or stretched, resulting in a pull on the Y-piece. Placing it in position B, between the Y-piece and the tracheal tube or mask, will increase dead space.

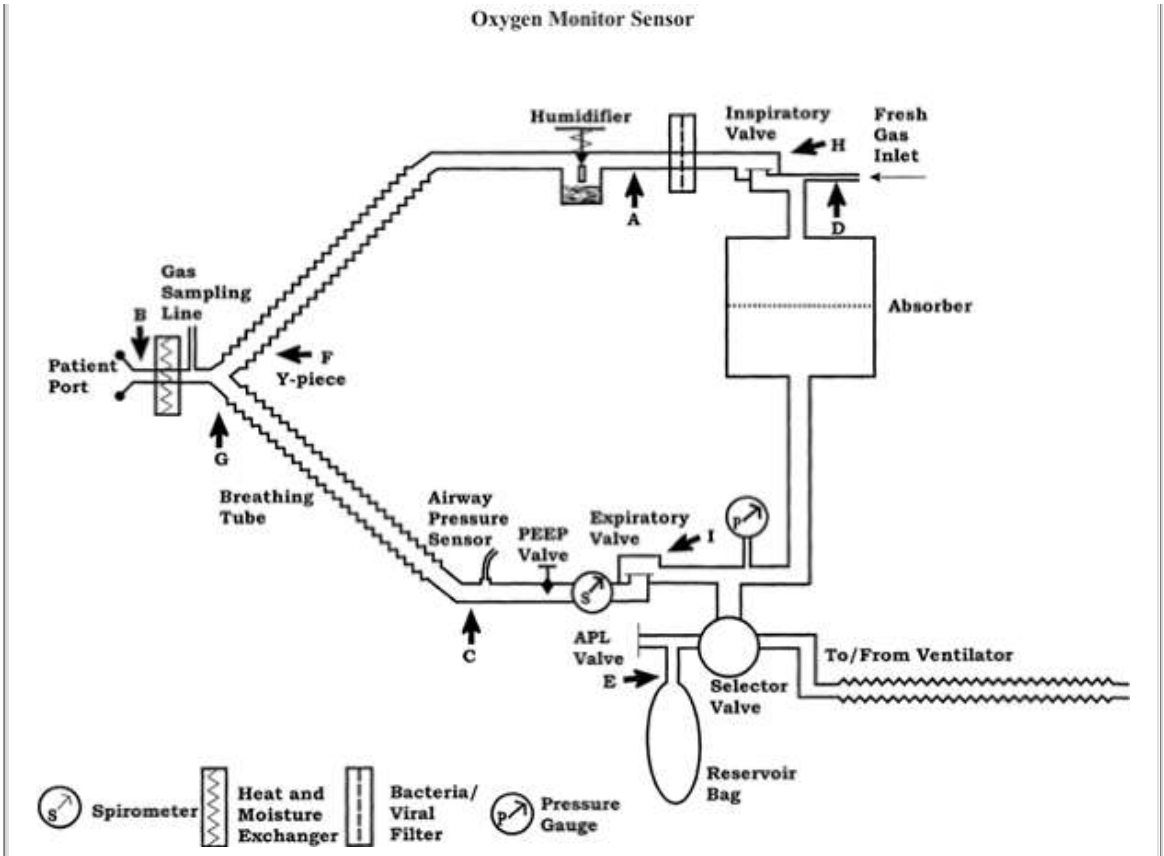

Figure 9.24 Possible locations for oxygen monitor sensor. (See text for details.) PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

With a sidestream monitor, position B is the preferred location because both inspired and exhaled gases can be monitored. The sampling site can be incorporated into other components so that it does not add dead space.

Position D is in the fresh gas line. This position will indicate only the concentration of oxygen in the gas mixture delivered to the breathing system and not that inspired by the patient.

Capnometer and Agent Monitor

Mainstream Devices

To obtain satisfactory exhaled values, a mainstream carbon dioxide sensor must be between the patient and the breathing

system (position B in Fig. 9.24), as close as possible to the patient. There are no mainstream agent monitors.

Sidestream Devices

Gases can be aspirated from an adaptor in the breathing system or from a port in a component. To obtain satisfactory samples of both inspired and exhaled gases, the site must be close to the patient (position B in Fig 9.24).

Respirometer

Figure 9.25 shows possible locations for a respirometer (Chapter 23) in the circle system. Some have special adaptors for attaching them securely at particular locations.

A respirometer is usually placed on the expiratory side on either side of the expiratory unidirectional valve (positions A and B). During spontaneous respiration, the volumes recorded will be accurate. During controlled respiration, a respirometer in this location will over-read inspired volumes because of the expansion of the breathing tubes and gas compression in the breathing system. If the respirometer can detect reverse flow, a malfunctioning unidirectional valve may be detected.

A respirometer placed between the patient and the Y-piece (position C) will record accurately during both spontaneous and controlled ventilation if it can read bidirectional flow. By measuring both inspired and exhaled volumes, problems such as a leaking tracheal tube cuff can be detected. If the patient is breathing spontaneously, it will not detect a disconnection between the sensor and the Y-piece. However, some respirometers are too bulky to be placed in this position, and the increase in dead space may be significant. If the respirometer does not measure bidirectional flow, it is of no value in this location. Using this position may result in increased likelihood of damage due to water condensation, mucus, edema fluid, and secretions. The weight of a mechanical respirometer could cause a disconnection or tracheal tube kinking.

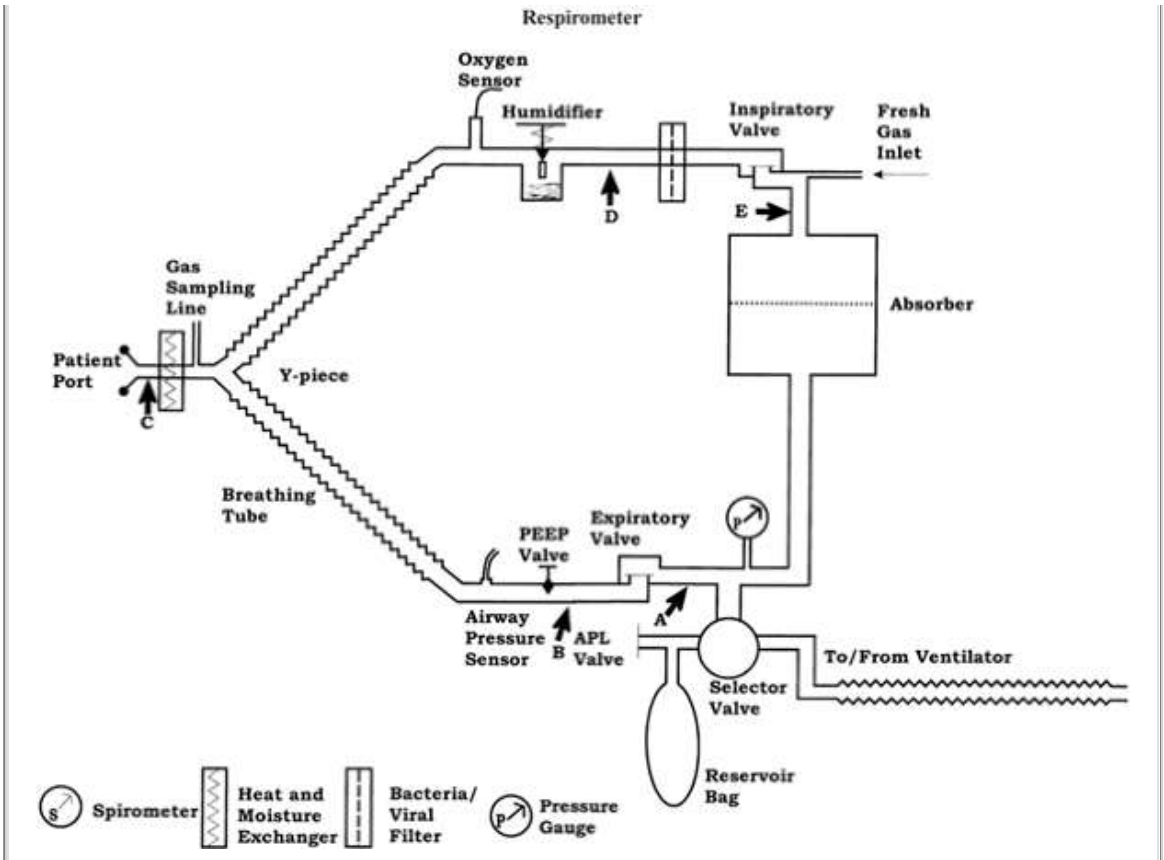

Figure 9.25 Possible locations for a respirometer. (See text for details.) PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

If the respirometer sensor is placed on the inspiratory side (position D), it will over-read during controlled or assisted ventilation because of the expansion of the tubings and leaks between the respirometer and the patient. This position can be of value if a second sensor is placed on the exhalation side (position C). This allows both inspiratory and expiratory tidal volumes to be measured. This combination is used with the Ohmeda 6900 series ventilators and Drager Apollo ventilator. These sites allow the ventilator to compensate for the fresh gas flow that is added to the breathing system during inspiration (Chapter 12). These sites also make it possible to gather the information necessary to produce flow-volume loops, which are discussed in Chapter 23.

A respirometer should not be located downstream of the absorber (position E), because the absorbed carbon dioxide will decrease the volume of gas measured.

Sensor for Airway Pressure Monitor

Possible positions in the classic circle system for an airway pressure sensor are shown in Figure 9.26. Placing the sensor in position C, between the patient and the breathing system, will ensure that the pressure measured is close to that of the patient's airway. The more distant the site is from the patient, the less useful it is as an estimate of airway pressure (189,190). Breathing system resistance, leaks, obstructions, and other mechanical factors may result in a measured pressure that differs substantially from the pressure in the patient's airway (191). Problems with this site include increased dead space, disconnections, tracheal tube kinking, contamination, and water buildup in the pilot line. It is necessary to connect the pilot line for every case.

Placing the sensor on the expiratory side (positions A and B) has an advantage over placement on the inspiratory side (position D). If there is gas flow obstruction in the inspiratory limb and the sensor for airway pressure is located upstream of the obstruction, the low pressure near the patient will not be sensed.

Position E, in the ventilator itself, was used in the past but is now not recommended. Certain circumstances may cause sufficient back pressure to develop, which will inhibit the low pressure alarm (191,192). Also, placement in the ventilator may result in failure to detect an incorrectly set bag/ventilator selector valve.

A combination of sites A and D is being used for machines equipped with the Datex-Ohmeda 6900 series

ventilators and the Drager Apollo ventilator. These sites can be used to generate information for a pressure-volume loops, which are discussed in Chapter 23.

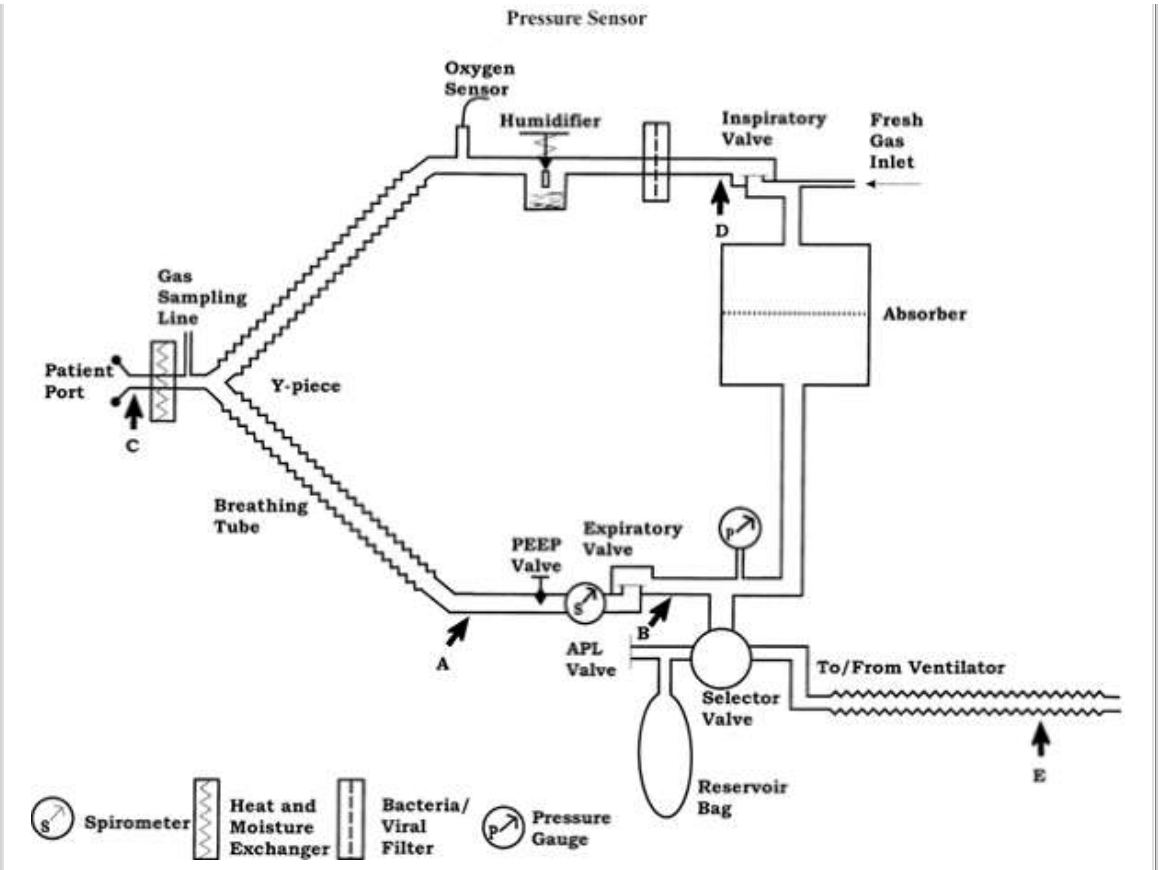

Figure 9.26 Possible locations for the sensor for an airway pressure monitor. (See text for details.) PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

Positive End-expiratory Pressure Valve

Possible positions for a PEEP valve are shown in Figure 9.27. A PEEP valve must be placed in the expiratory side of the breathing system. A disposable PEEP valve should be placed between the expiratory breathing tube and the expiratory unidirectional valve (position B). Built-in PEEP valves are usually situated downstream of the expiratory unidirectional valve and upstream of the absorber (position A). A bidirectional PEEP valve may be inserted between the anesthesia ventilator and breathing system (position C).

Pressure Gauge or Sensing Site

To measure PEEP accurately, the pressure gauge or sensing site must be on the same side (patient or absorber) of the unidirectional valves as the PEEP valve (193). On most older absorber assemblies, the pressure gauge is on the absorber side (position B). If a PEEP valve is added to the expiratory limb on the patient side of the unidirectional valve, PEEP will not register on the manometer gauge. Most new absorber assemblies have a built-in PEEP valve located on the absorber side of the unidirectional valve with the pressure gauge or sensing site in close proximity.

Ventilator

Possible locations for a ventilator are shown in Figure 9.28. Position A is upstream of the absorber, near the APL valve. If the ventilator location and other components are in the classic position (position A), gas flows do not differ from the classic circle system.

The other location for the ventilator is position B, upstream of the inspiratory unidirectional valve. When the ventilator is placed in this location, during inspiration, the gas must be prevented from flowing retrograde toward the bag and absorber. To accomplish this, an isolating valve is placed between the reservoir bag and the ventilator. The reservoir bag collects the fresh gas. This causes fresh gas decoupling, which is discussed in detail in Chapter 12.

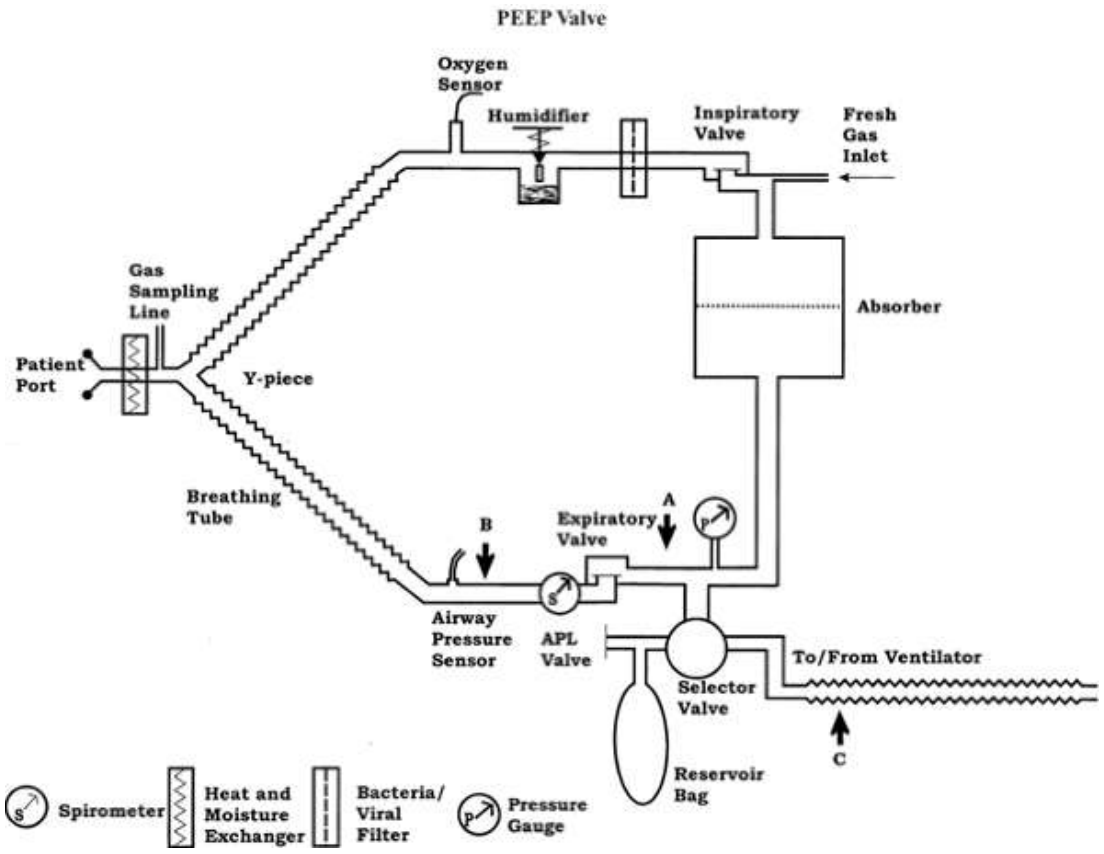

Figure 9.27 Possible locations for a positive end-expiratory pressure valve. (See text for details.) PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

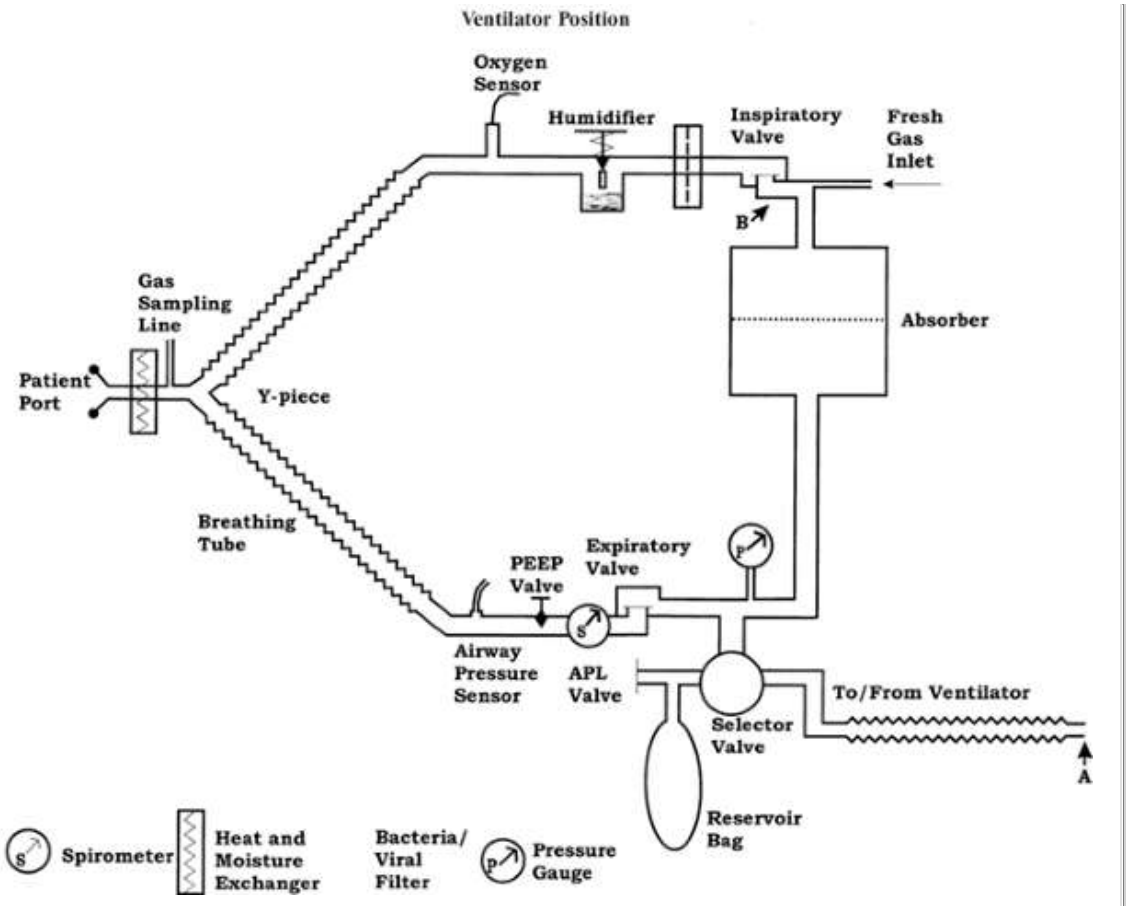

Figure 9.28 Possible locations for a ventilator. (See text for details.) PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

Gas Flows through the Breathing System

This section will examine the gas flow through different configurations of the breathing system that are currently commercially available during different modes of respiration. For this purpose, fresh gas refers to dry gas that has entered the system from the anesthesia machine.

Rebreathed gases are exhaled gases that may or may not have had the carbon dioxide removed. These gases have a higher humidity than fresh gas.

Retrograde gas flow indicates that gas is flowing in a direction

opposite to the flow directed by the unidirectional valves. Retrograde flow is important, because dry gas that is flowing through the absorber can potentially desiccate the absorbent. Experimental work to confirm that retrograde dry gas flow through the absorber during the various modes of the respiratory cycle contributes to desiccation has not been published. This needs to be studied, as there are a number of steps that can be taken to lessen desiccation during the respiratory cycle. The description of gas flows given here are assumed, given the configuration of the various elements of the breathing system and their interrelationships. The problems created by desiccated absorbent and anesthetic agents were discussed earlier in this chapter.

Classic Circle System

The classic circle system is shown in Figure 9.29. It has the ventilator in proximity to the reservoir bag. The classic circle system has been used for most of the Ohmeda anesthesia machines with the exception of the ADU. It has also been used on North American Drager Narkomed machines.

Spontaneous Breathing

Inspiration

During spontaneous inspiration (Fig. 9.29), gas flows from the reservoir bag and through the absorber, where it joins with the fresh gas and flows to the patient.

Exhalation

During exhalation (Fig. 9.30), exhaled gases pass into the reservoir bag until it is full. Then excess gases are vented through the APL valve. Since the inspiratory unidirectional valve is closed, fresh gas entering the breathing system flows in a retrograde direction through the absorber, pushing the gas in the absorber toward the APL valve. The first gas to be vented through the APL valve will be previously exhaled gas containing carbon dioxide that was in the tubing between the APL valve and the absorber. If the fresh gas flow is high, some gas that was in or has passed through the absorber will flow retrograde and pass into the reservoir bag or be expelled through the APL valve. If the fresh gas flow is high enough, fresh gas may also be lost

through the APL valve. Low fresh gas flows may not flow retrograde into the absorber.

Manual Ventilation

Inspiration

During manual ventilation (Fig. 9.31), excess gases are vented through the partially open APL valve during inspiration. The gas flowing through the absorber and ultimately to the patient will be a mixture of fresh gas and exhaled gases. The amount of fresh gas will depend on the fresh gas flow and the degree that retrograde flow occurred during the previous exhalation.

Exhalation

During exhalation with manually controlled ventilation (Figs. 9.32, 9.33), exhaled gases flow into the reservoir bag. Fresh gas flows retrograde through the absorber. If the fresh gas flow is low (Fig. 9.32), fresh gas may not enter the absorber. If the fresh gas flow is high (Fig. 9.33), some fresh gas may flow retrograde through the absorber and even enter the bag.

Mechanical Ventilation

Inspiration

During inspiration, gas flows from the ventilator through the absorber and inspiratory unidirectional valve to the patient. The gas in the ventilator bellows will consist of exhaled gas and, if the fresh gas flow is high, fresh gas that has passed retrograde through the absorber.

Exhalation

During exhalation (Fig. 9.34), exhaled gases will flow into the ventilator bellows. Fresh gas will pass retrograde through the absorber. Excess gases are vented through the spill valve in the ventilator in the latter part of exhalation. The longer the exhalation time and the higher the fresh gas flow, the more likely that fresh gas will pass retrograde through the absorber.

Continuous Fresh Gas Flow

A continuous flow of fresh gas can enter the circle system if a

flow control valve is left turned ON when the machine is not in use, such as between cases or at the end of the surgery schedule. Fresh gas flow may continue overnight or over a weekend.

There are two possible pathways that a continuous fresh gas flow can follow (Fig. 9.35). One is through the inspiratory unidirectional valve to the Y-piece and to atmosphere (Fig. 9.35A). The other pathway is through the absorber and out the open APL valve or bag mount (Fig. 9.35B). The fresh gas will take the path of least resistance. It is possible that both paths may be used.

In most cases, the path of least resistance will be past the inspiratory unidirectional valve and out through the Y-piece. However, a common practice to indicate that the

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breathing system on the machine is unused is to leave a plastic bag over the mask or inside the bowl (Fig. 9.36). If the plastic bag is tight, the resistance will be high, and the path of least resistance will be through the absorber if the APL valve is open (Fig. 9.35A). If the APL valve is closed (Fig. 9.35B), all of the gas will be directed down the inspiratory tubing. If the reservoir bag is removed, it is more likely that gas will flow retrograde through the absorber.

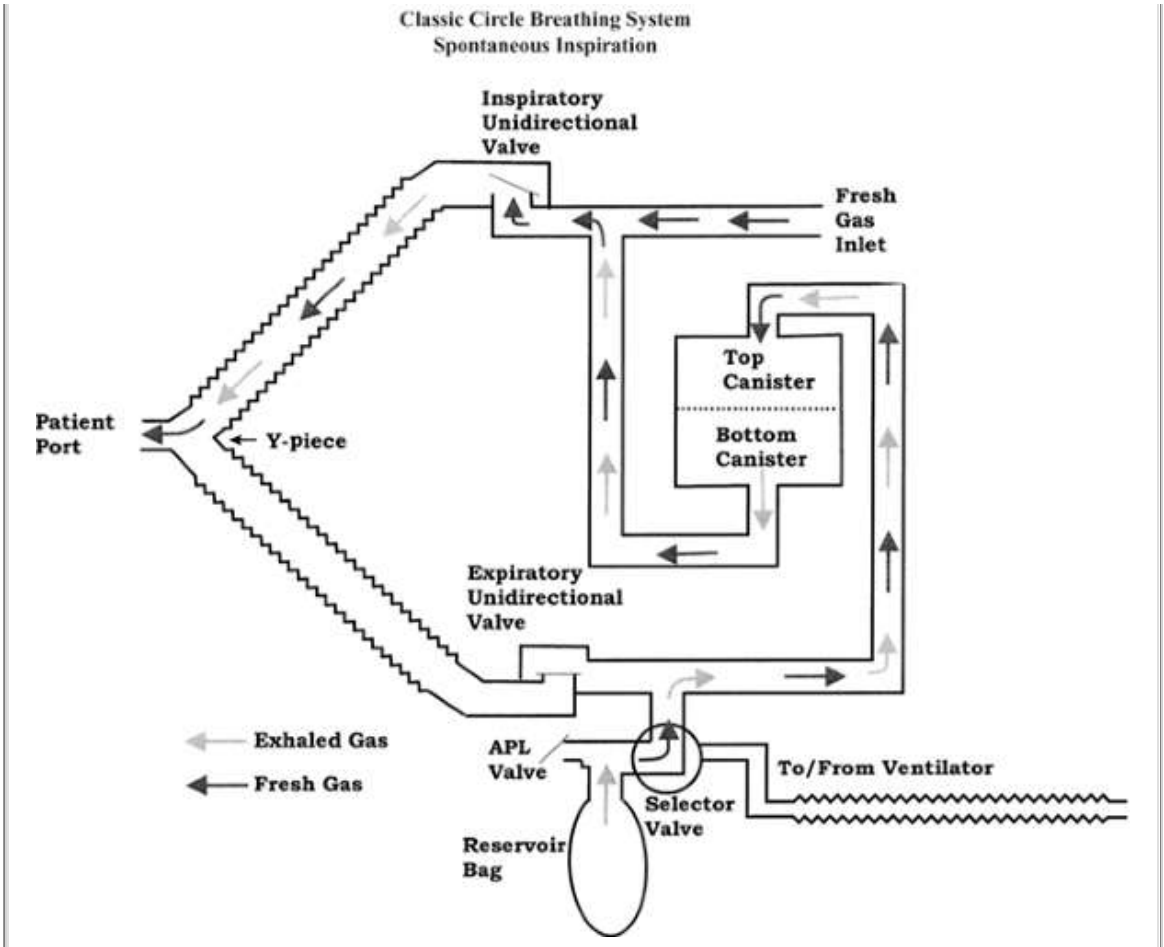


Figure 9.29 Gas flow through classic circle system during spontaneous inspiration. APL, adjustable pressure limiting.

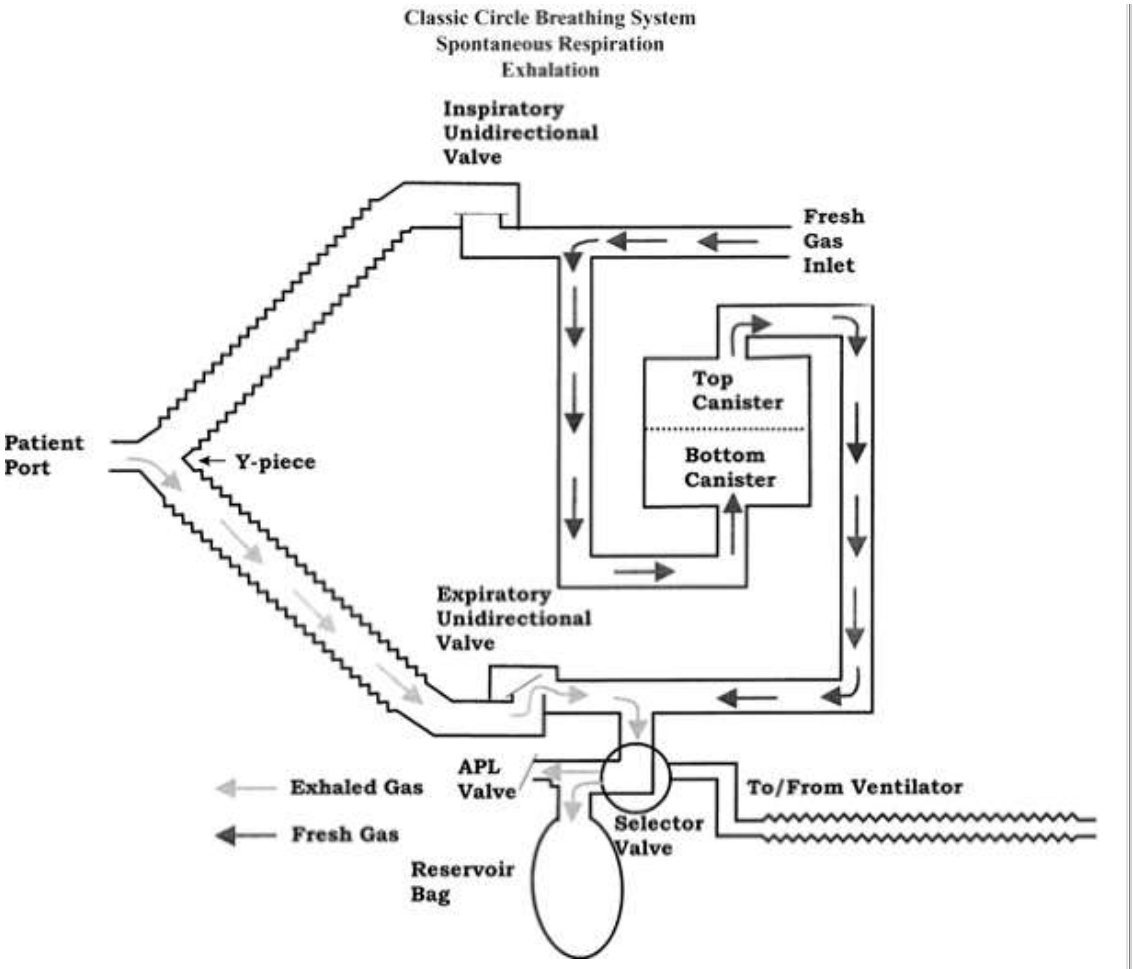


Figure 9.30 Gas flow through classic circle system during spontaneous exhalation. APL, adjustable pressure limiting.

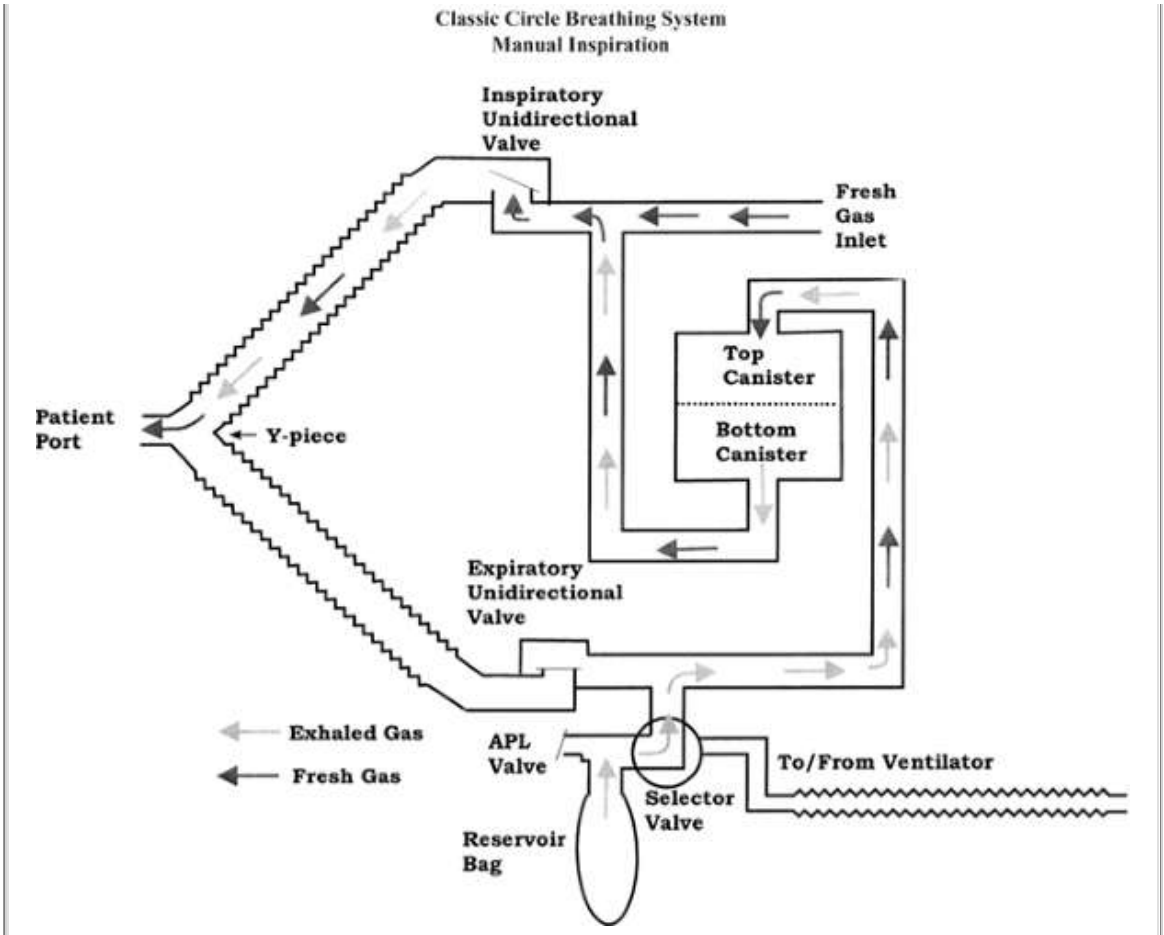


Figure 9.31 Gas flow through the classic circle system during inspiration with manual ventilation. APL, adjustable pressure limiting.

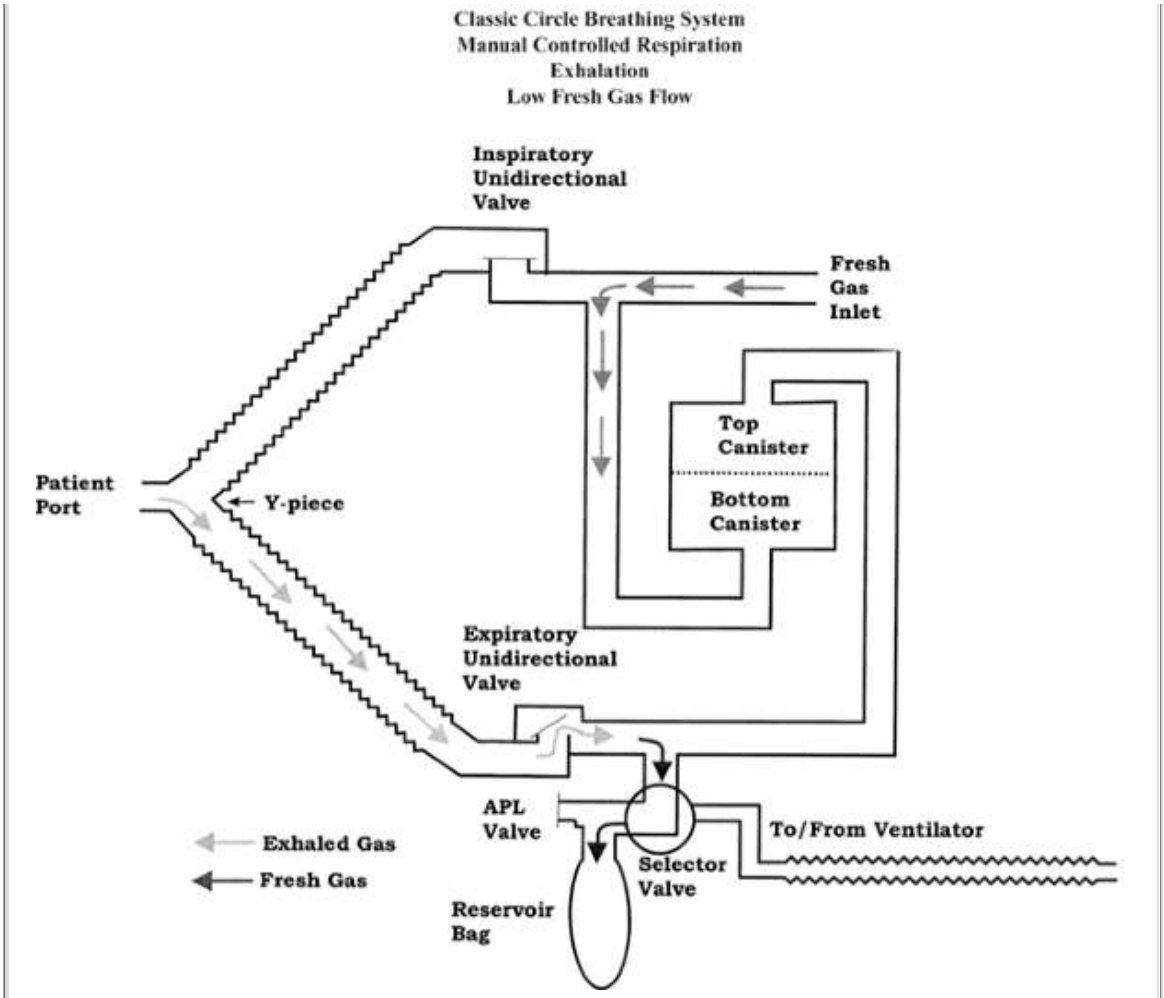


Figure 9.32 Gas flow through the classic circle system during exhalation with manual ventilation and a low fresh gas flow. APL, adjustable pressure limiting.

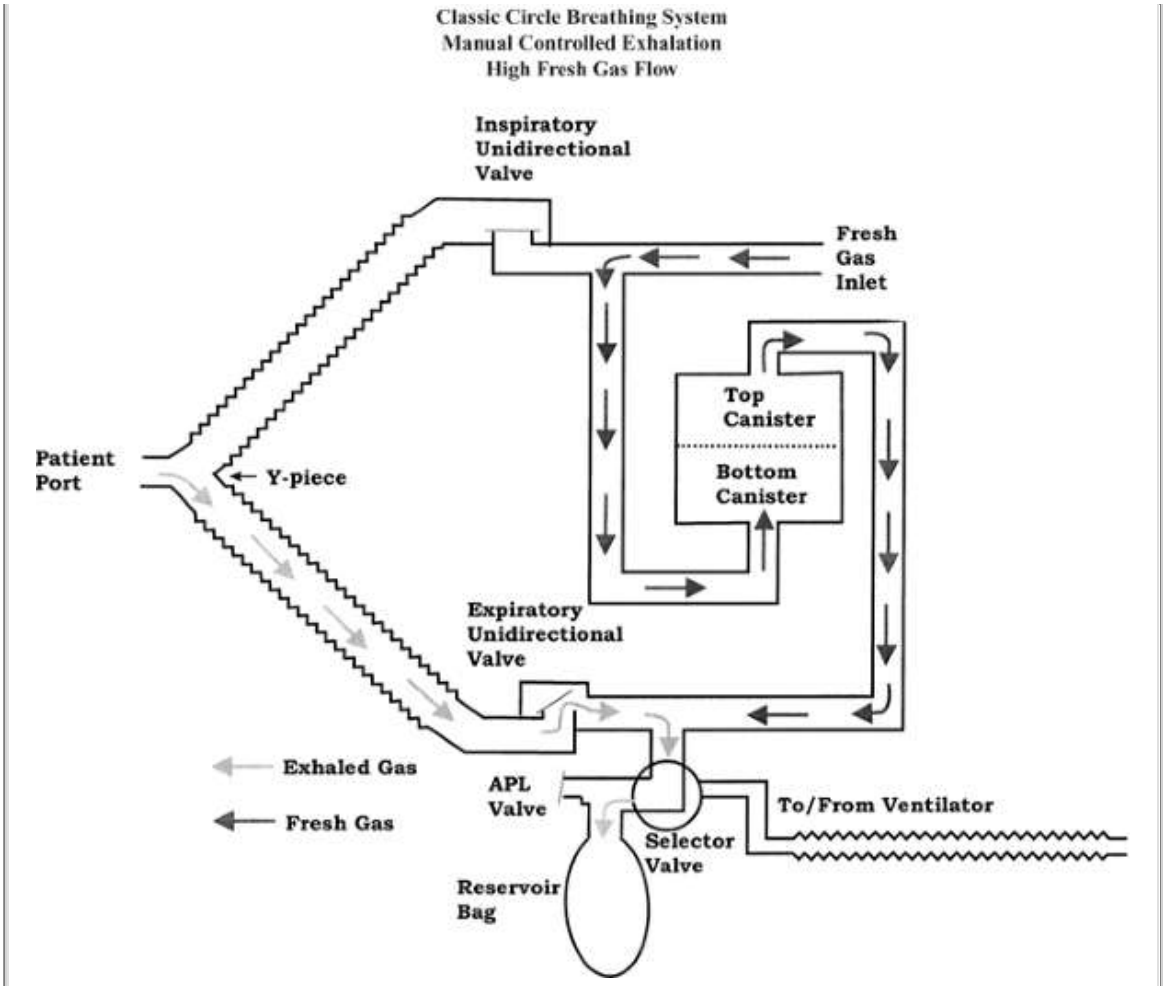


Figure 9.33 Gas through the classic circle system during exhalation with manual ventilation and a high fresh gas flow. APL, adjustable pressure limiting.

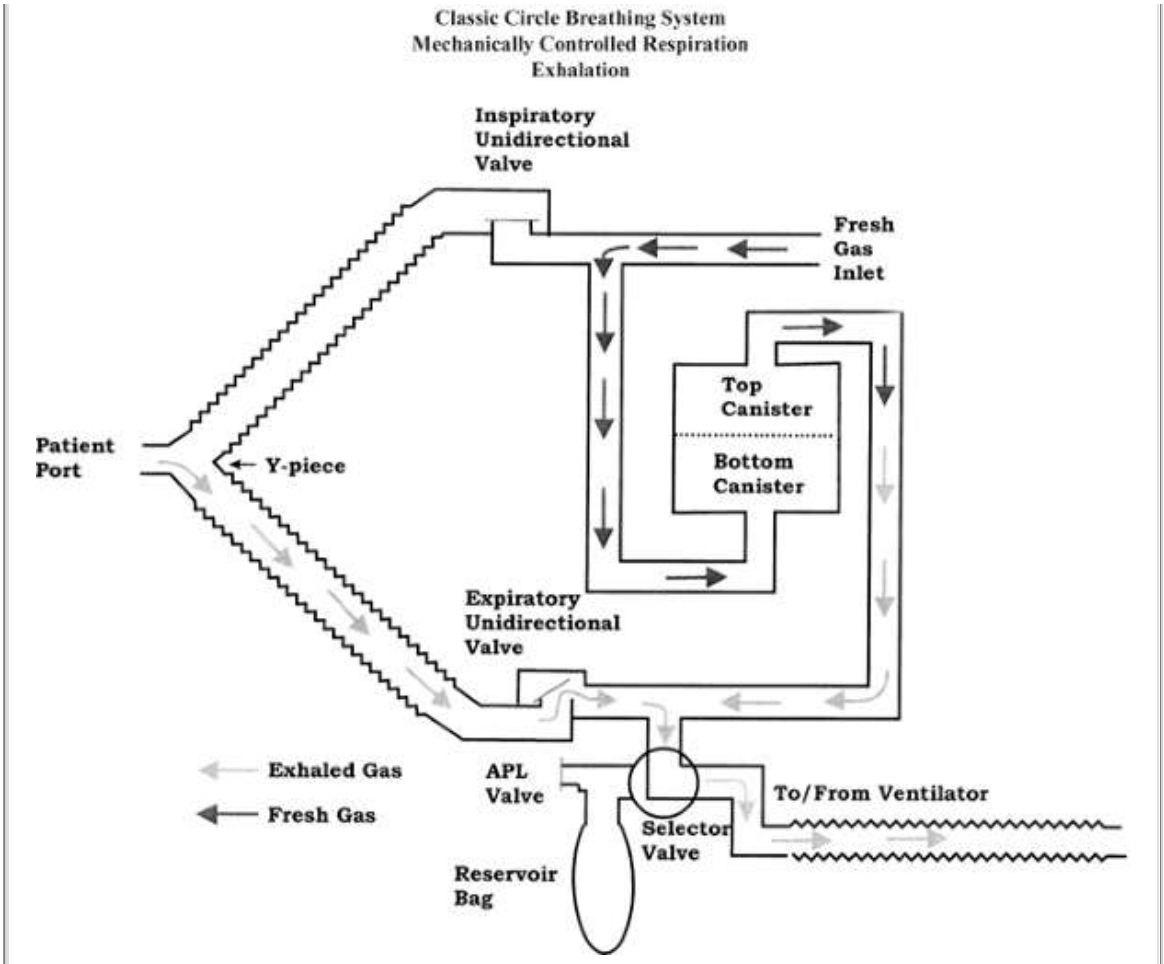
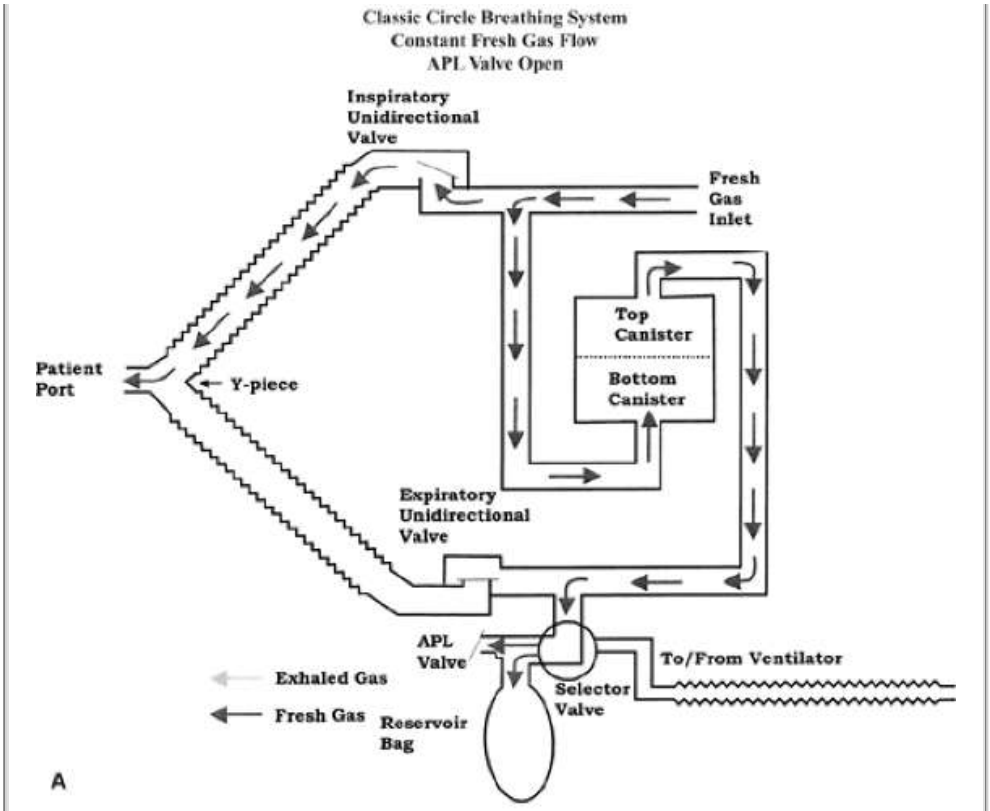


Figure 9.34 Gas through the classic circle system during exhalation with mechanical ventilation. APL, adjustable pressure limiting.


Classic Circle Breathing System
Constant Fresh Gas Flow
APL Valve Open
Inspiratory Unidirectional Valve
Fresh Gas Inlet
Top Canister
Bottom Canister
Patient Port
Y-piece
Expiratory Unidirectional Valve
APL Valve
To/From Ventilator
Exhaled Gas
Fresh Gas
Selector Valve
Reservoir Bag
A

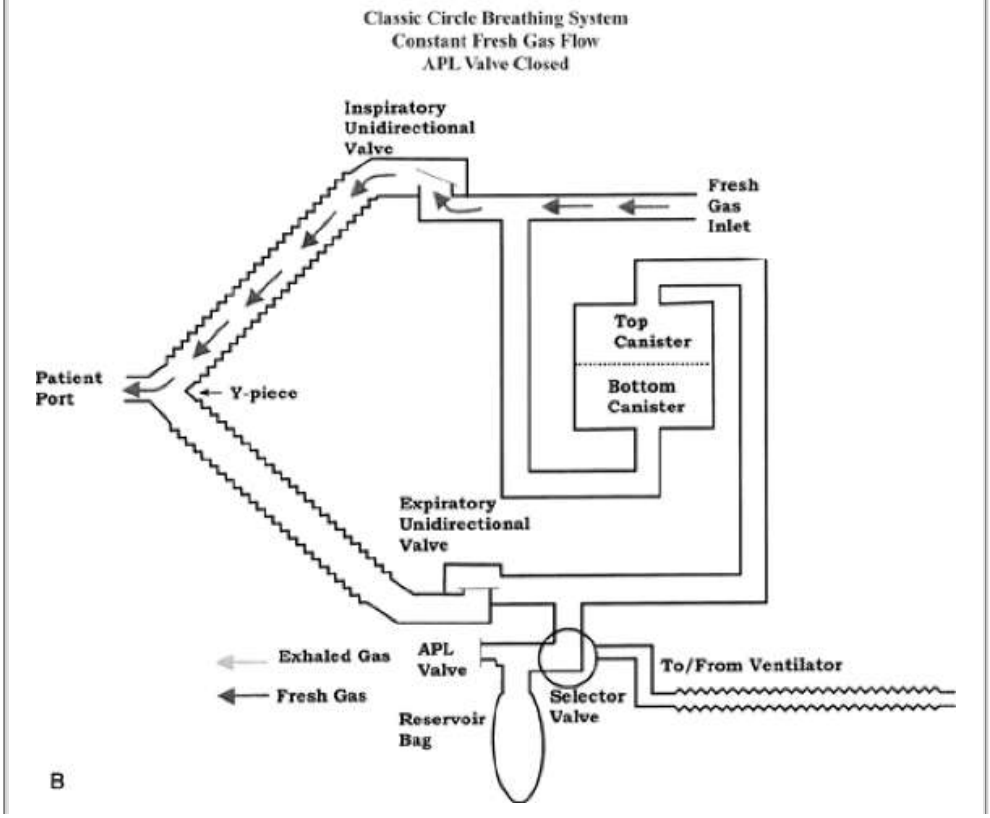

Classic Circle Breathing System
Constant Fresh Gas Flow
APL Valve Closed
Inspiratory Unidirectional Valve
Fresh Gas Inlet
Top Canister
Bottom Canister
Patient Port
Y-piece
Expiratory Unidirectional Valve
Exhaled Gas
APL Valve
To/From Ventilator
Fresh Gas
Selector Valve
Reservoir Bag
B

Figure 9.35 Possible paths of gas flow through the classic circle system during a period of nonuse, with a continuing fresh gas flow. APL, adjustable pressure limiting.

Figure 9.36 The plastic bag over the mask will cause increased resistance to gas flow. If the bag is not on the bag mount or the APL valve is open, fresh gas may flow retrograde through the absorber, causing the absorbent to become desiccated.

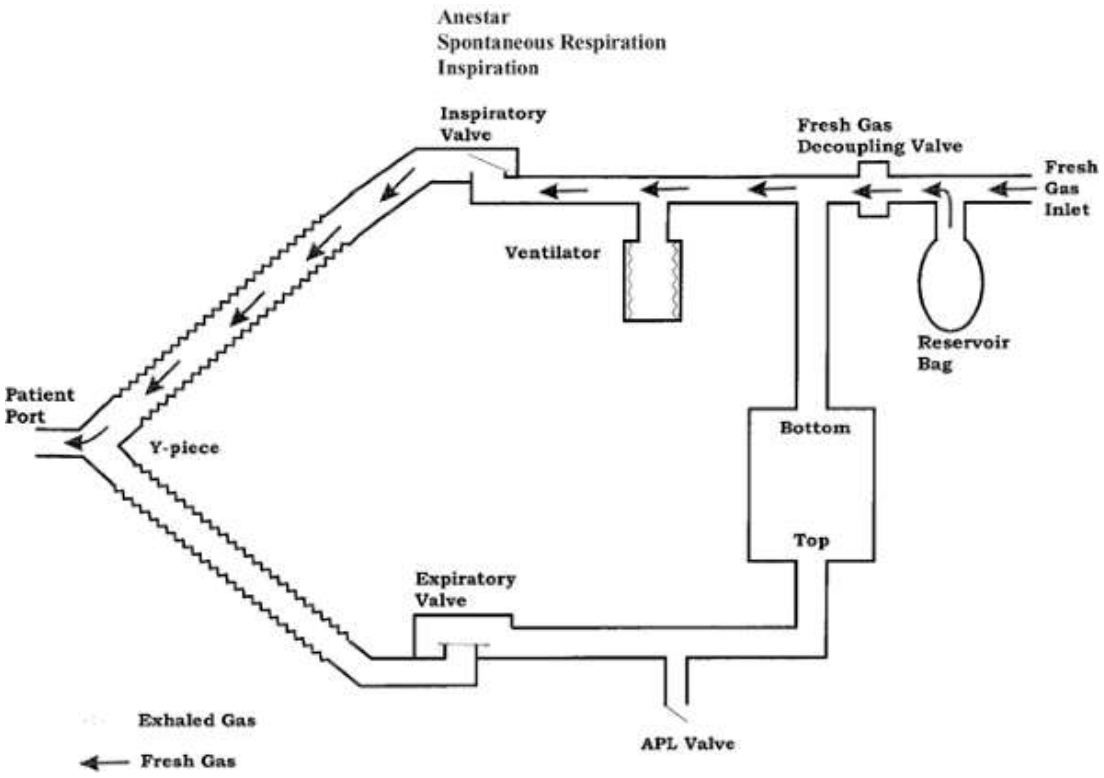


Figure 9.37 Gas flow through the Anestar breathing system during spontaneous inspiration. APL, adjustable pressure limiting.

Anestar Breathing System

The Anestar breathing system (Figs. 9.37,9.38,9.39,9.40,9.41,9.42,9.43,9.44) differs from the classic circle system. The reservoir bag is near

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the fresh gas inlet, and the ventilator is upstream of the inspiratory unidirectional valve. There is a fresh gas decoupling valve downstream of the reservoir bag. It is closed only during inspiration with mechanical ventilation.

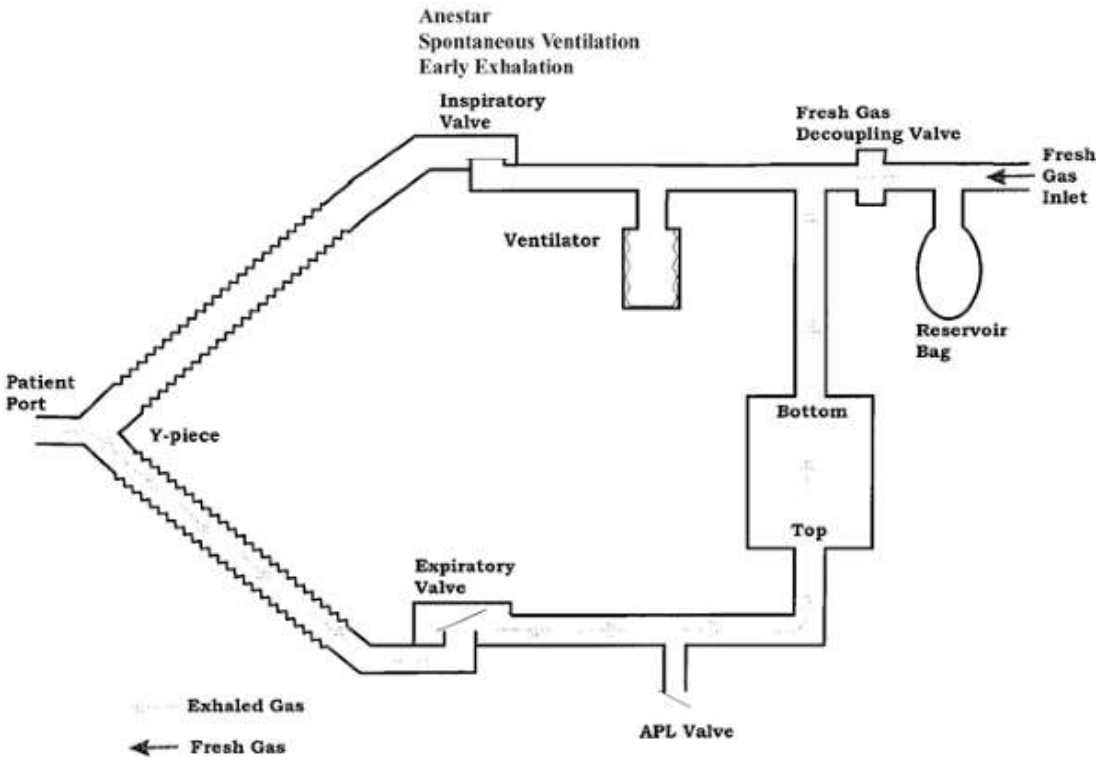

Figure 9.38 Gas flow through the Anestar breathing system during the early part of exhalation. APL, adjustable pressure limiting.

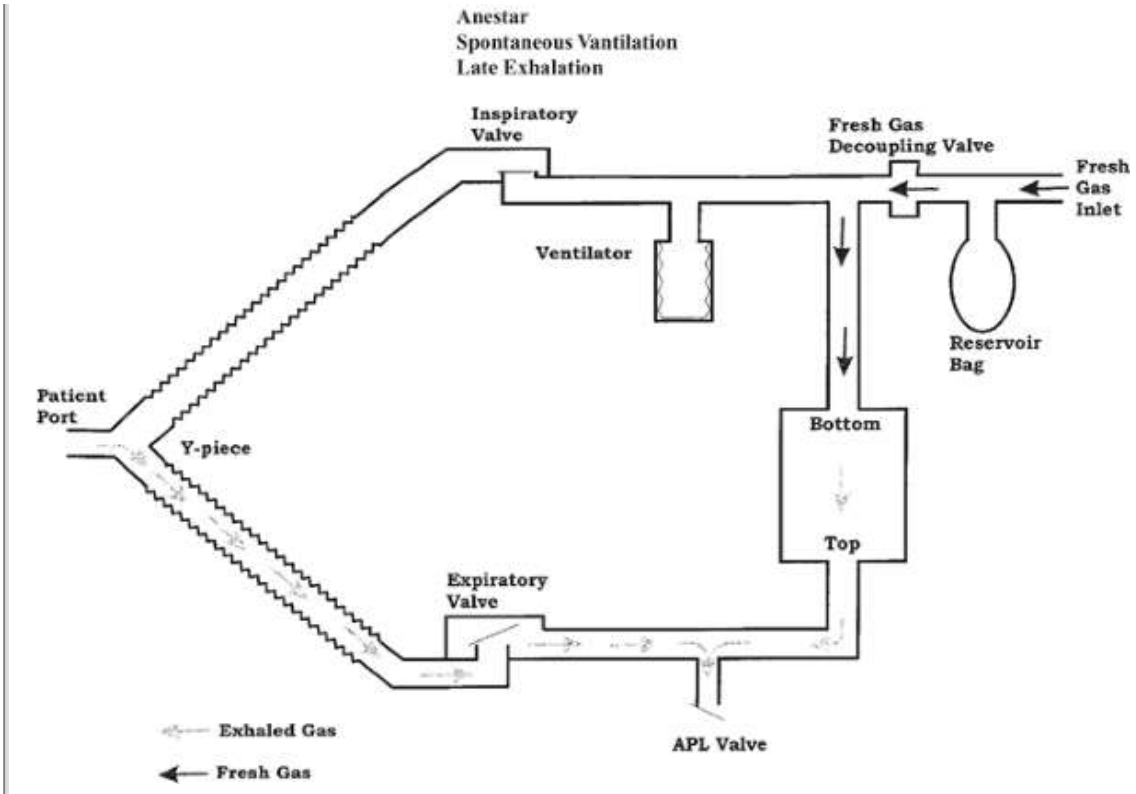

Figure 9.39 Gas flow through the Anestar breathing system during late exhalation. APL, adjustable pressure limiting.

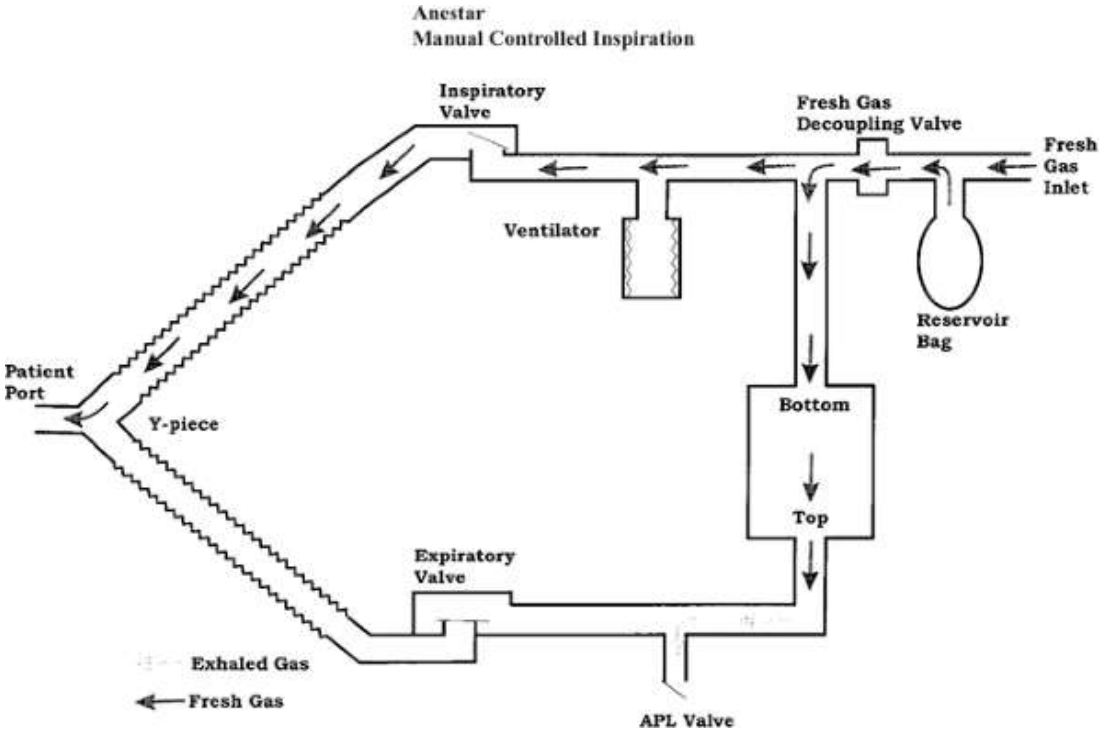

Figure 9.40 Gas flow through the Anestar breathing system during manual inspiration. APL, adjustable pressure limiting.

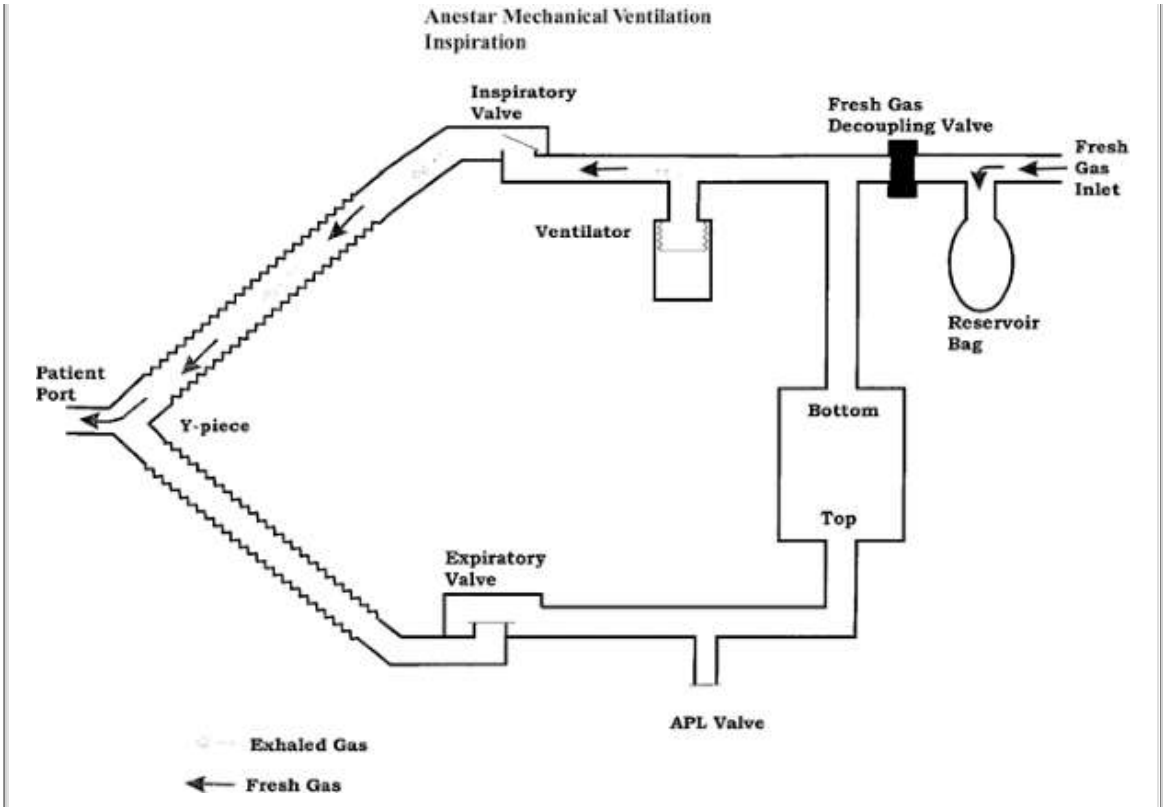

Figure 9.41 Gas flow through the Anestar breathing system during inspiration with mechanical ventilation. APL, adjustable pressure limiting.

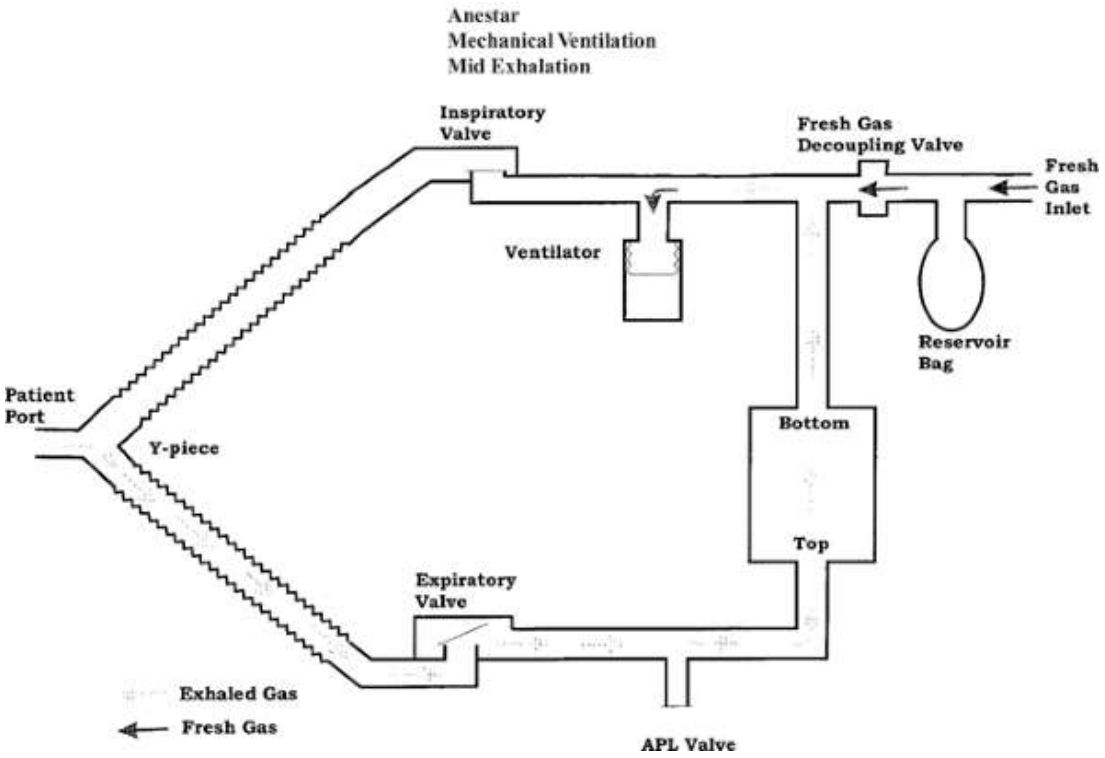

Figure 9.42 Gas flow through the Anestar breathing system during mid exhalation with mechanical ventilation. APL, adjustable pressure limiting.

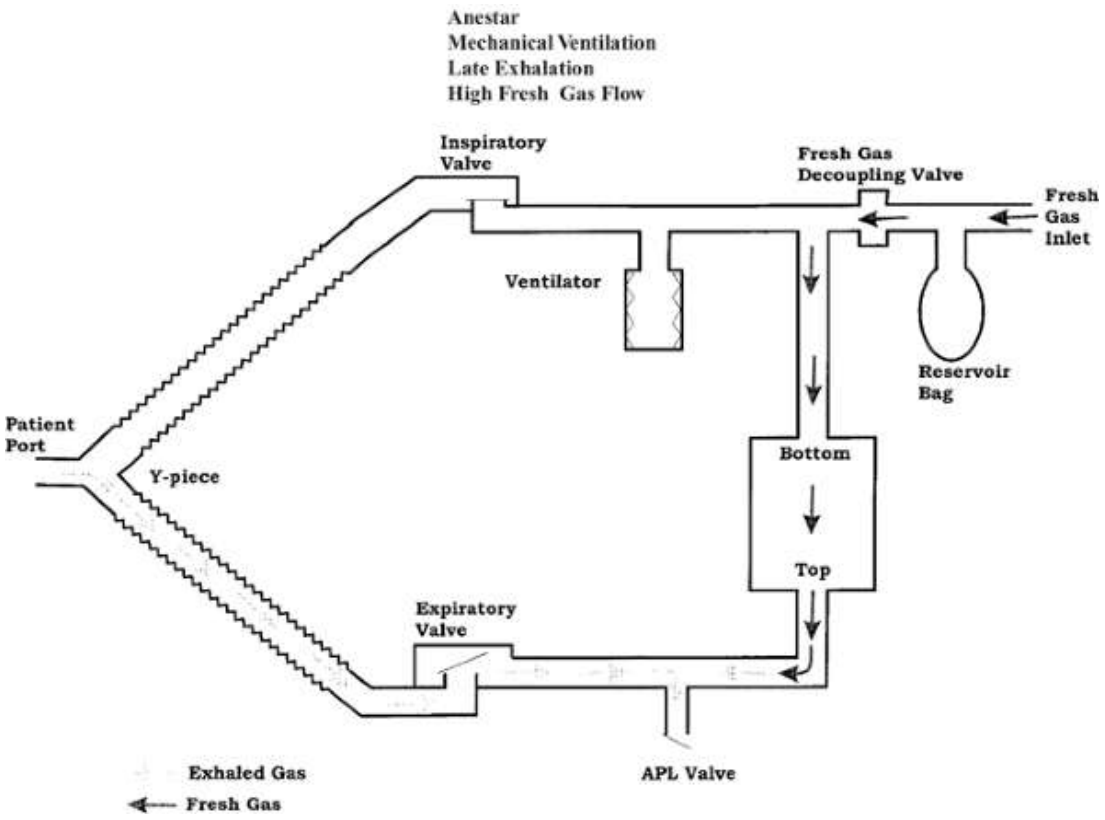

Figure 9.43 Gas flow through the Anestar breathing system during late exhalation with mechanical ventilation. APL, adjustable pressure limiting.

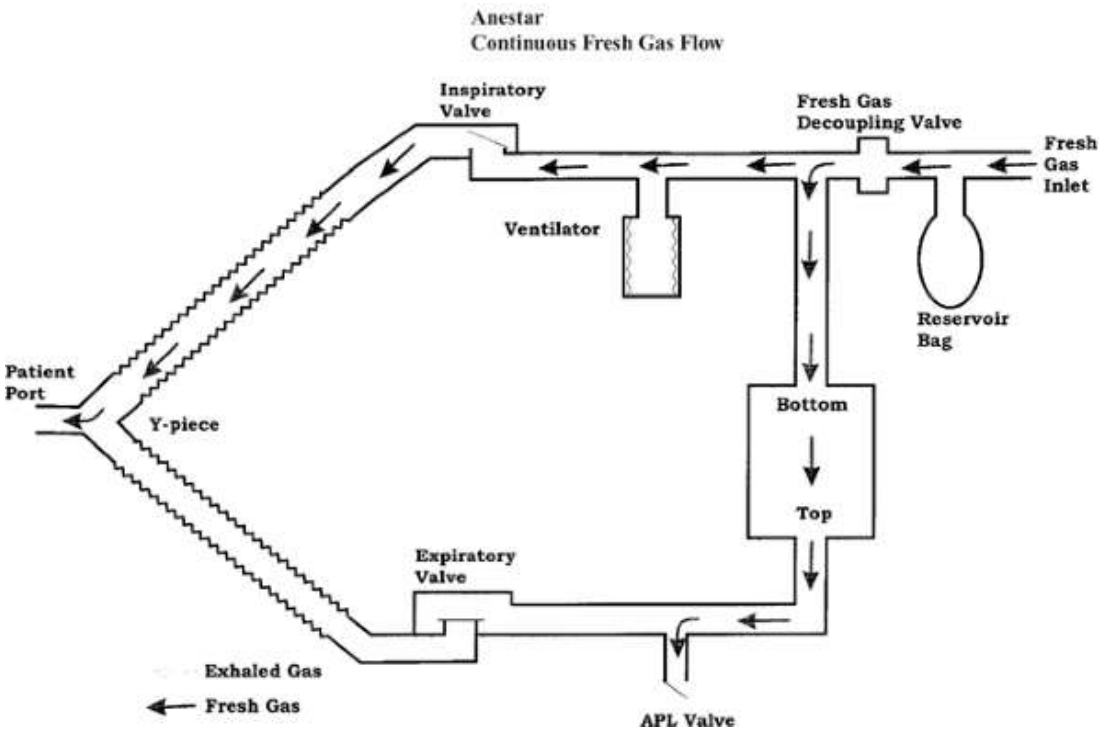

Figure 9.44 Gas flow through the Anestar breathing system during nonuse with continuing fresh gas flow. APL, adjustable pressure limiting.

Spontaneous Breathing

During spontaneous inspiration (Fig. 9.37), gas flows from the reservoir bag, through the fresh gas decoupling valve, and past the inspiratory unidirectional valve to the patient. If the bag empties, a subatmospheric pressure valve opens, and air is drawn into the system.

During early exhalation (Fig. 9.38), exhaled gases flow through the expiratory valve and absorber to the reservoir bag, where they mix with the fresh gas from the anesthesia machine. During late exhalation (Fig. 9.39) when the bag is full, the APL valve opens, and exhaled gases flow through the open valve to the scavenging system. The fresh gas flow pushes gases retrograde through the absorber. If the fresh gas flow is high enough, dry fresh gas will flow into or through the absorber.

Manual Ventilation

During manually controlled inspiration (Fig. 9.40), the reservoir bag is squeezed, causing fresh gas and exhaled gas that has passed through the absorber and into the bag to flow to the patient. Excess gas will pass retrograde through the absorber, pushing gas out through the APL valve. During exhalation, gases flow through the expiratory valve and absorber to the bag.

Mechanical Ventilation

With mechanical ventilation (Fig. 9.41), the fresh gas decoupling valve closes during inspiration, causing fresh gas to enter the reservoir bag and excluding it from the rest of the system. A mixture of fresh and previously exhaled gas flows from the ventilator bellows through the inspiratory unidirectional valve to the patient.

During the early and mid portion of exhalation (Fig. 9.42), exhaled and fresh gases flow into the ventilator bellows. After the bellows has filled (Fig. 9.43), the APL valve opens. There will be retrograde gas flow through the absorberÏ€”first exhaled gases that have passed through the absorber, then fresh gas. The higher the fresh gas flow and the longer the expiratory time, the greater the amount of fresh gas that will flow retrograde through the absorber.

Continuous Fresh Gas Flow

If a continuous flow of fresh gas passes through the breathing system (Fig. 9.44), the gases will take the path of least resistance. If the reservoir bag is removed from the bag mount, it is likely that all the fresh gas will exit at this point. If there is a bag in place, gas may flow either through the inspiratory tubing and the Y-piece

or retrograde through the absorber and out through the APL valve, depending on whether or not the APL valve is open and the resistance at the patient port on the Y-piece.

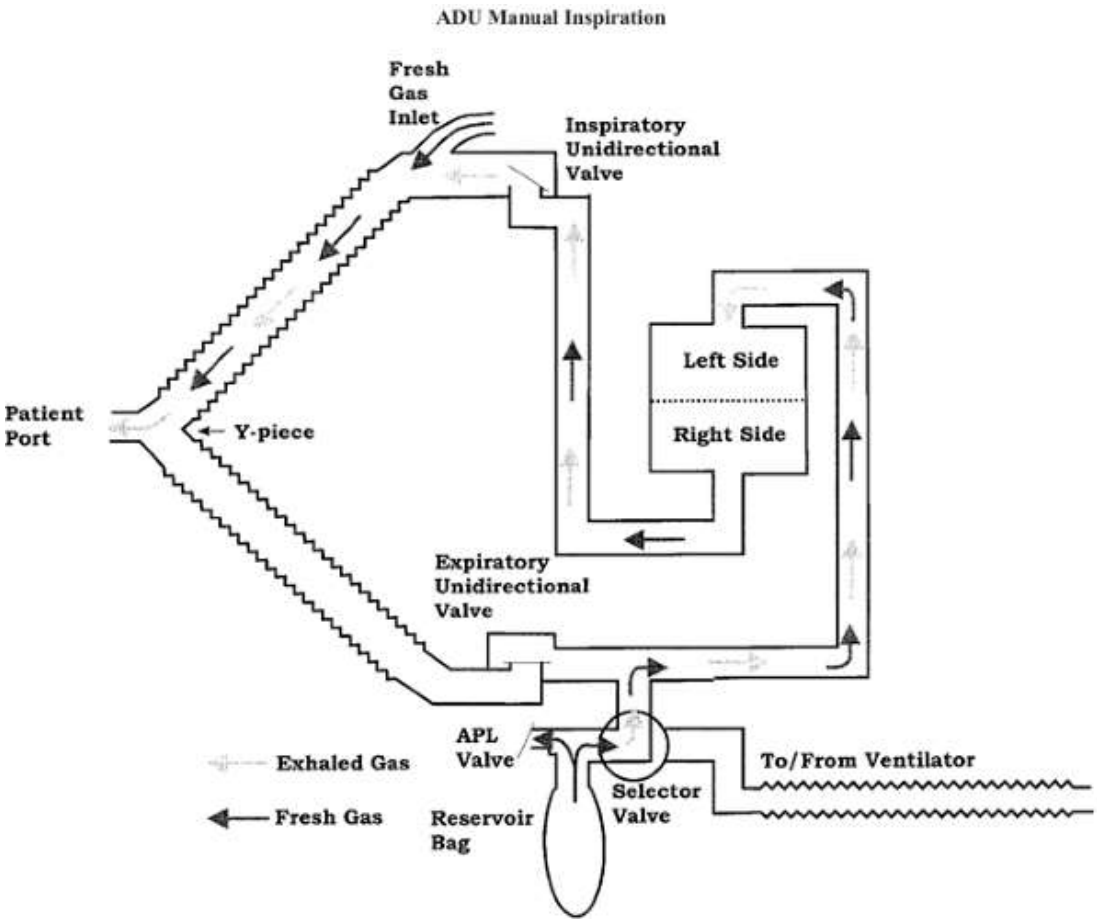

Figure 9.45 ADU breathing system during manual inspiration. APL, adjustable pressure limiting.

ADU Breathing System

In the Ohmeda ADU breathing system (Figs. 9.45,Figs. 9.46,Figs. 9.47,9.48), fresh gas enters the system between the inspiratory unidirectional valve and the Y-piece. The reservoir bag, APL valve, and ventilator with its spill valve are located as in the classic circle system position.

Spontaneous Breathing

During spontaneous inspiration, the patient draws gas from the reservoir bag, through the absorber and inspiratory valve. Downstream of the inspiratory unidirectional valve, the fresh gas

flow mixes with the exhaled gases.

During spontaneous exhalation, the bag fills with a mixture of fresh and exhaled gases. Excess gases are released through the APL valve.

Manual Ventilation

During inspiration with manually controlled ventilation (Fig. 9.45), gas passes from the bag and through the absorber to the inspiratory unidirectional valve. Some gas (both fresh and exhaled) is vented through the APL valve. During exhalation, fresh gas and exhaled gas from the patient pass through the expiratory unidirectional valve and into the bag.

Mechanical Ventilation

With mechanical ventilation during inspiration (Fig. 9.46), exhaled and fresh gases from the ventilator pass through the absorber and inspiratory valve, where they are joined by fresh gas on the way to the patient.

During exhalation (Fig. 9.47), fresh and exhaled gases flow to the ventilator, with the excess being vented through the ventilator spill valve during late exhalation.

Continuous Fresh Gas Flow

If there is a continuous flow of gases into the breathing system when the anesthesia machine is not in use (Fig. 9.48), the fresh gases have two possible pathways.

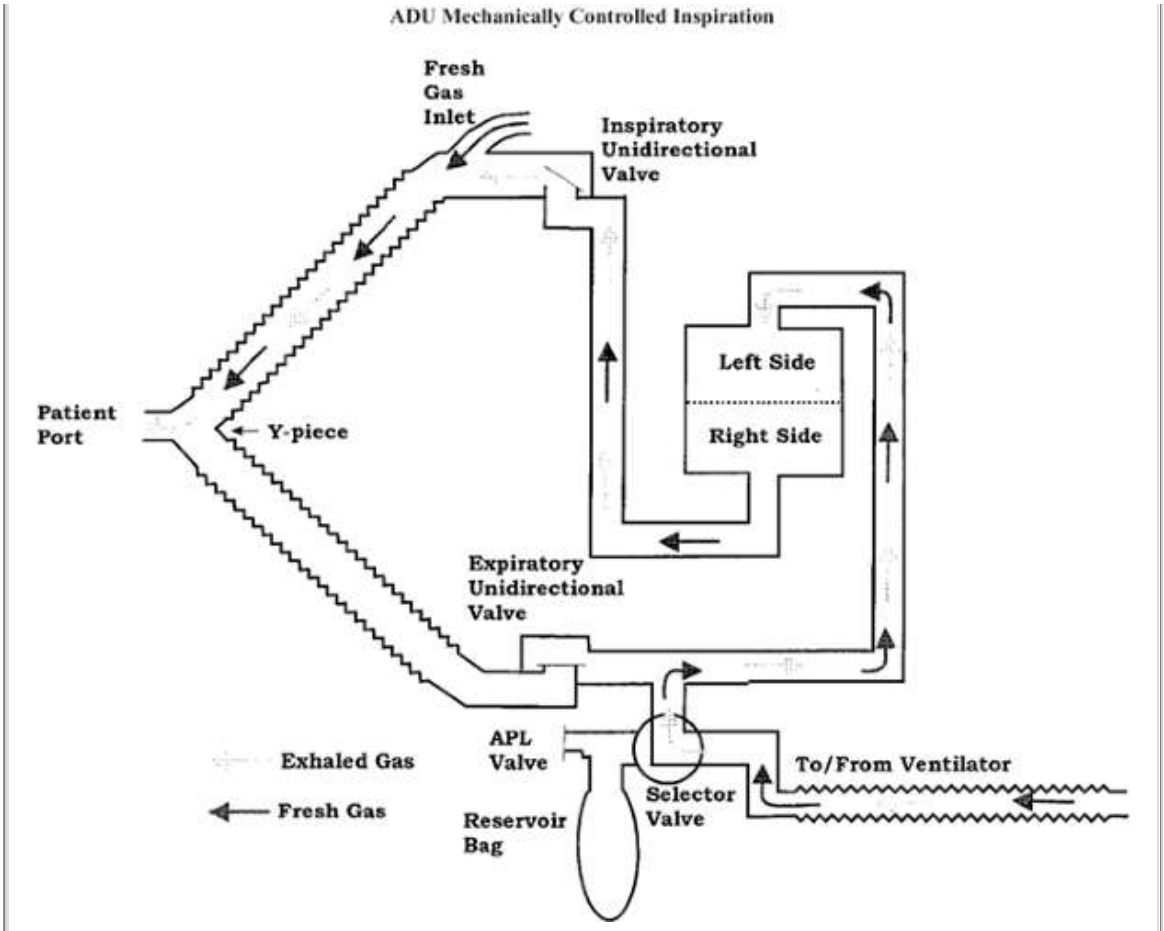

Figure 9.46 ADU breathing system during mechanically controlled inspiration. APL, adjustable pressure limiting.

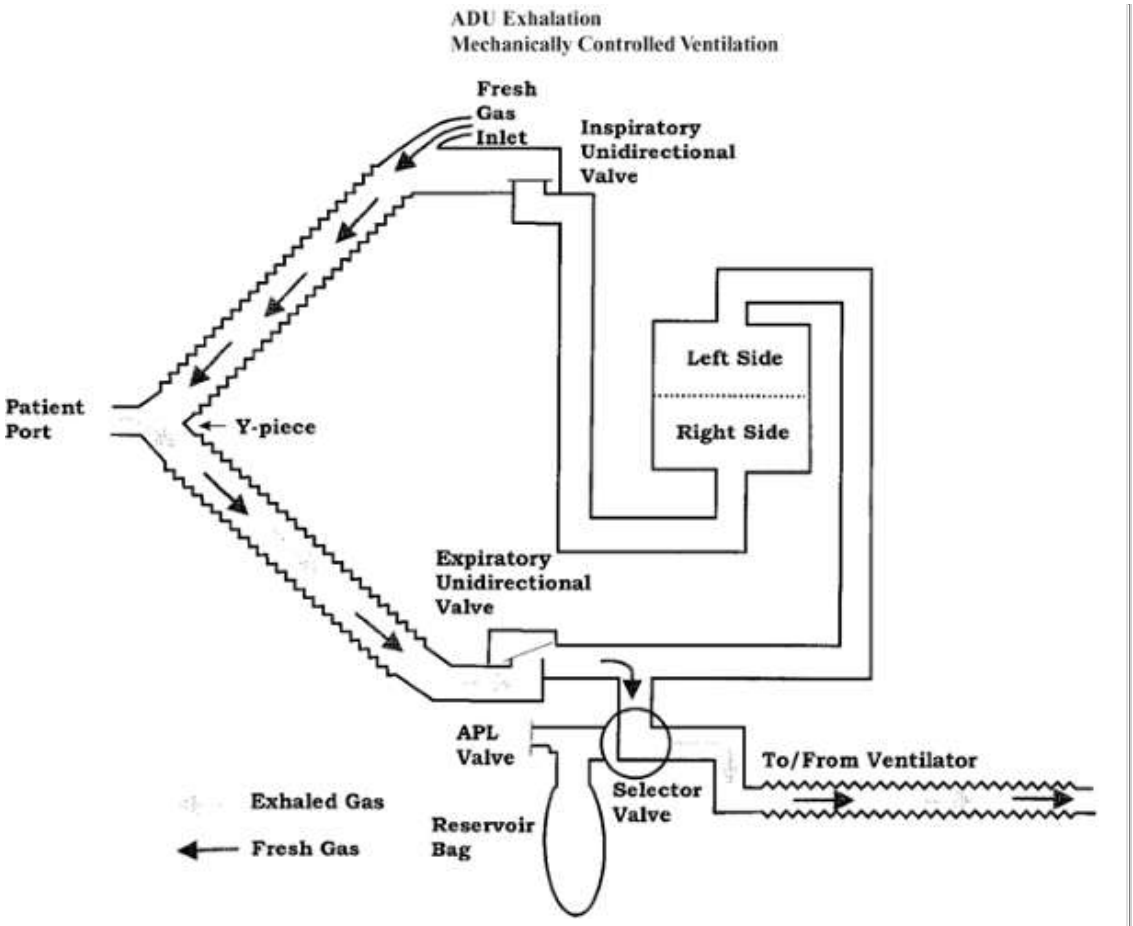

Figure 9.47 ADU breathing system during mechanically controlled ventilation. APL, adjustable pressure limiting.

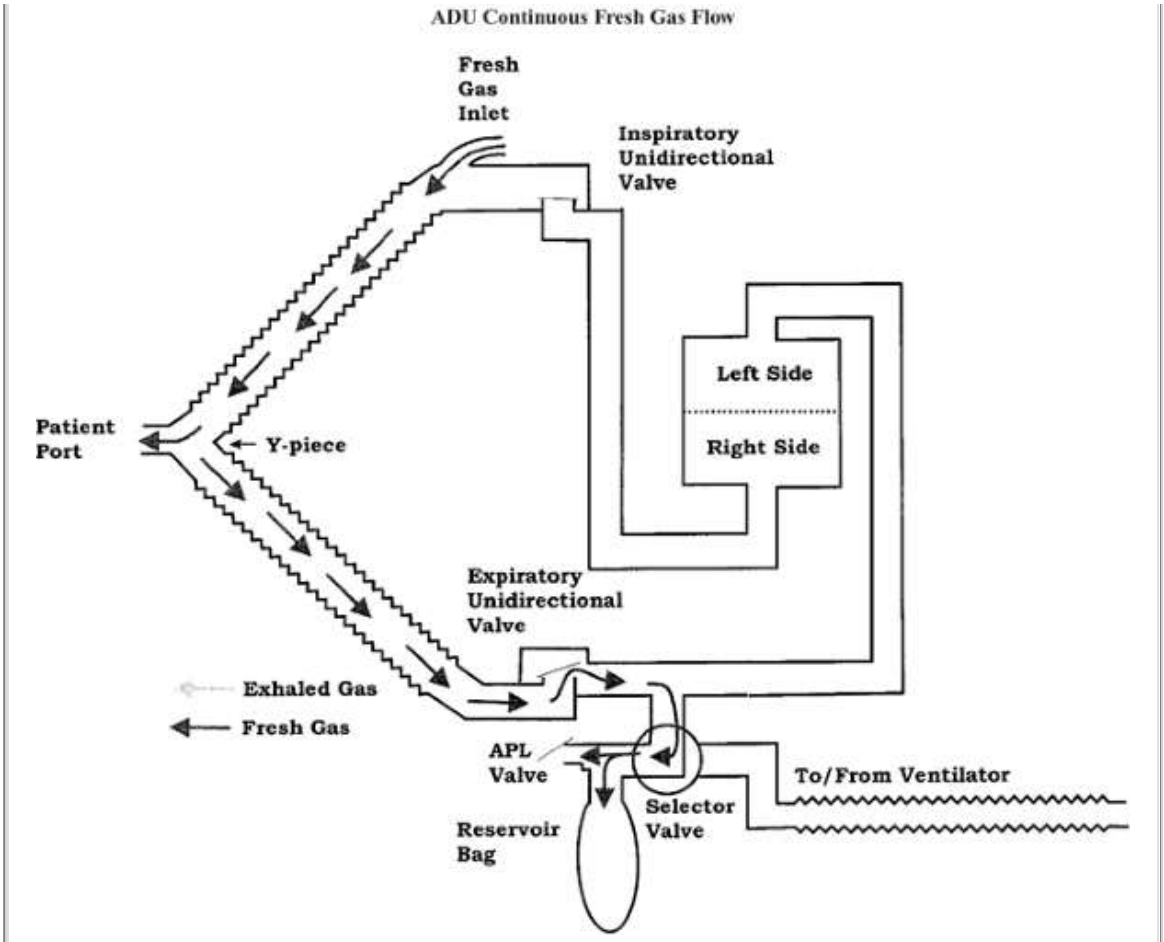

Figure 9.48 ADU breathing system with continuous fresh gas flow during nonuse. APL, adjustable pressure limiting.

If the Y-piece is not obstructed, this is the most likely exit point. If it is obstructed, gases can pass through the exhalation tubing past the expiratory unidirectional valve and out the APL valve, if it is open. If the bag is not in place, this may be the preferred pathway. Since the fresh gas enters downstream of the inspiratory unidirectional valve, the valve will be closed and not allow backflow. This means that there will be no retrograde fresh gas flow through the absorber during continuous gas flow.

Drager 6400 Breathing System

The Drager 6400 breathing system (Figs. 9.49,9.50,9.51,9.52,9.53,9.54,9.55,9.56) has the reservoir bag

near the fresh gas inlet, and the ventilator is on the exhalation side of the absorber downstream of the expiratory unidirectional valve. The APL valve and mechanical exhaust valve are also located on the exhalation side of the absorber.

Spontaneous Breathing

During spontaneous inspiration (Fig. 9.49), gases flow to the patient from the reservoir bag. The bag will contain a mixture of exhaled gases that have passed through the absorber into the reservoir bag during the previous exhalation and fresh gas from the anesthesia machine.

During exhalation, exhaled gases pass through the absorber and into the reservoir bag, where they are combined with fresh gas. When the bag is filled, the fresh gas flow will push gases retrograde through the absorber. These gases then exit through the APL valve.

Manual Ventilation

With manual ventilation (Fig. 9.50), squeezing the bag causes gases to flow toward the patient as well as retrograde through the absorber to the partially open APL valve. During exhalation, exhaled gases pass through the expiratory unidirectional valve and absorber to the bag.

Mechanical Ventilation

During mechanical inspiration, the reservoir bag and fresh gas inlet are isolated from the breathing system by the fresh gas control valve (Fig. 9.51). As the piston moves, gas is pushed through the absorber and

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inspiratory unidirectional valve to the patient. This gas will include fresh gas that has flowed retrograde through the absorber during exhalation. Meanwhile, fresh gas enters the reservoir bag.

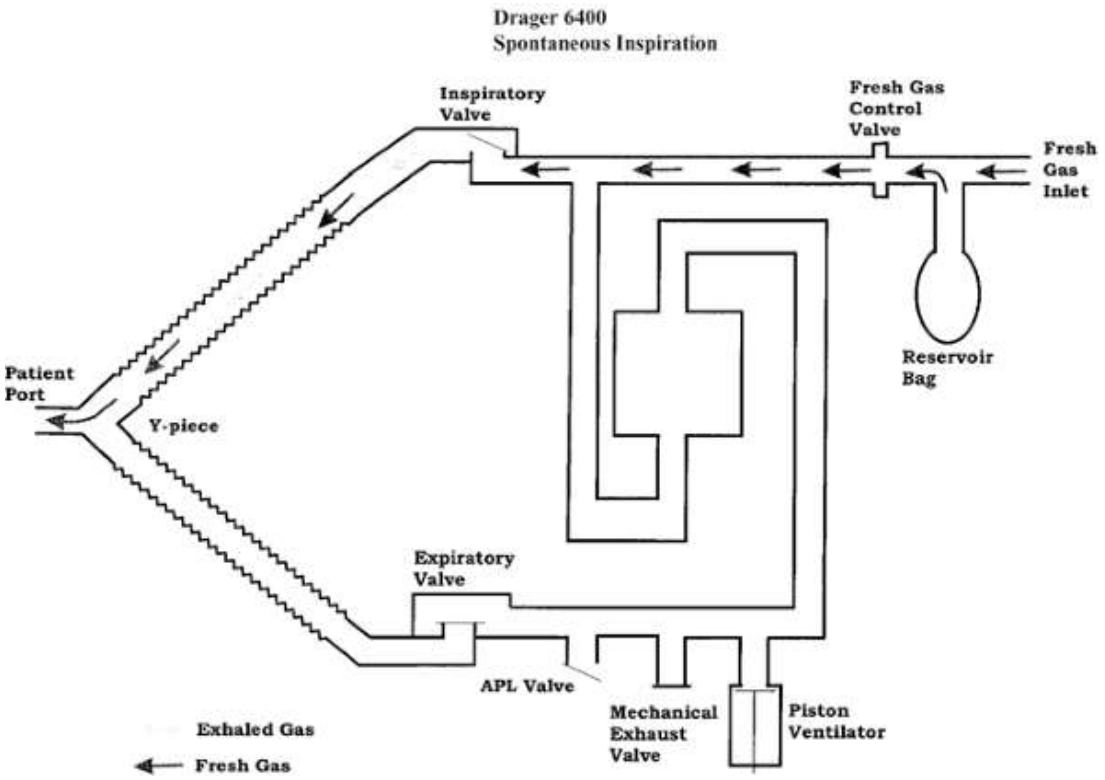

Figure 9.49 Drager 6400 breathing system during spontaneous inspiration. APL, adjustable pressure limiting.

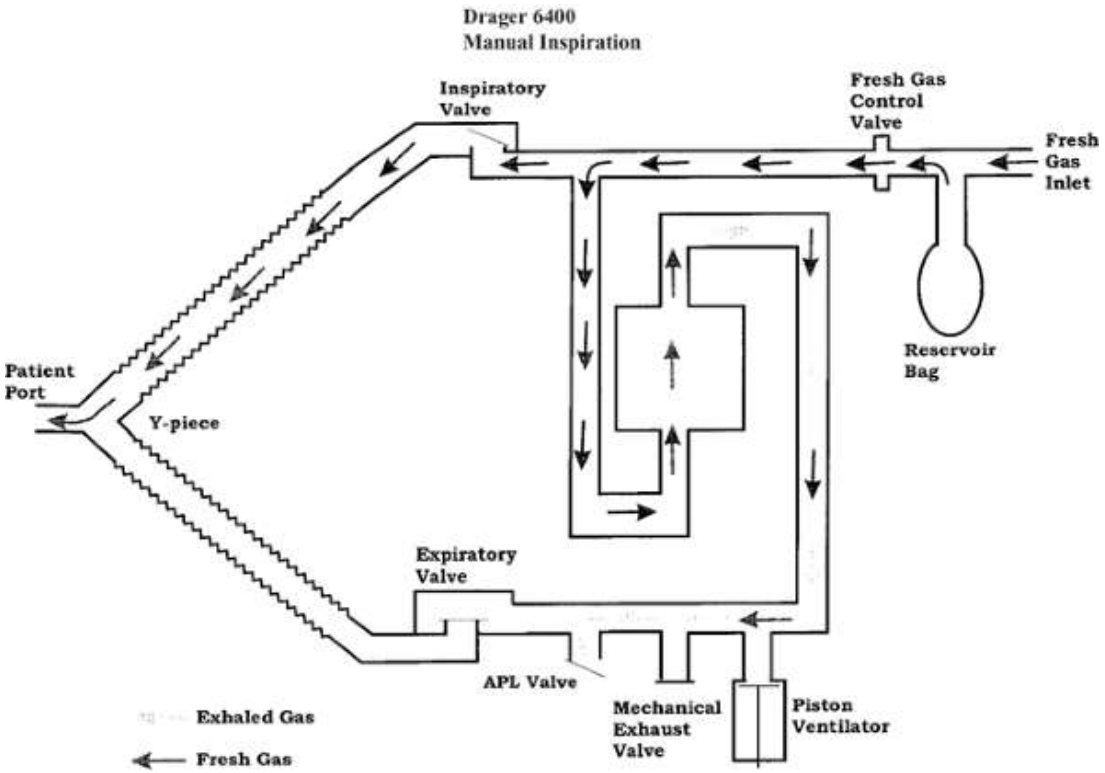

Figure 9.50 Drager 6400 breathing system during manual inspiration. APL, adjustable pressure limiting.

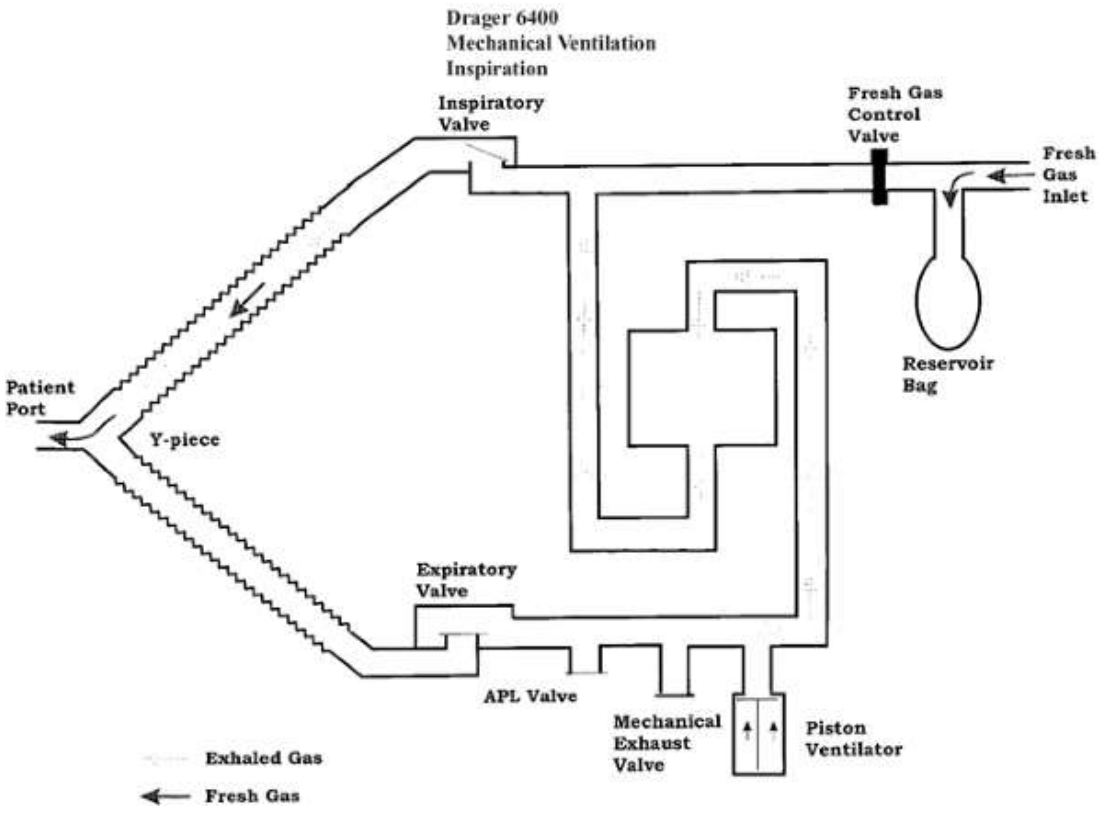

Figure 9.51 Drager 6400 breathing system during mechanical inspiration. APL, adjustable pressure limiting.

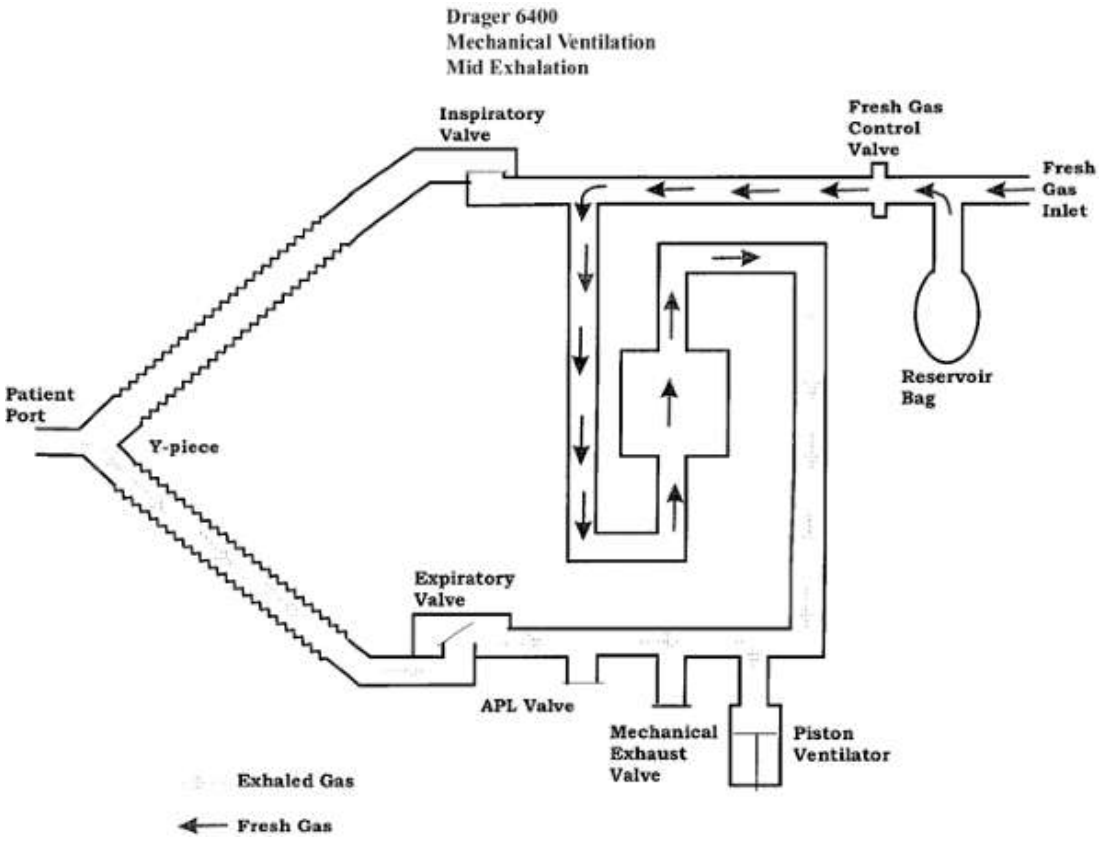

Figure 9.52 Drager 6400 breathing system during mechanical mid exhalation. APL, adjustable pressure limiting.

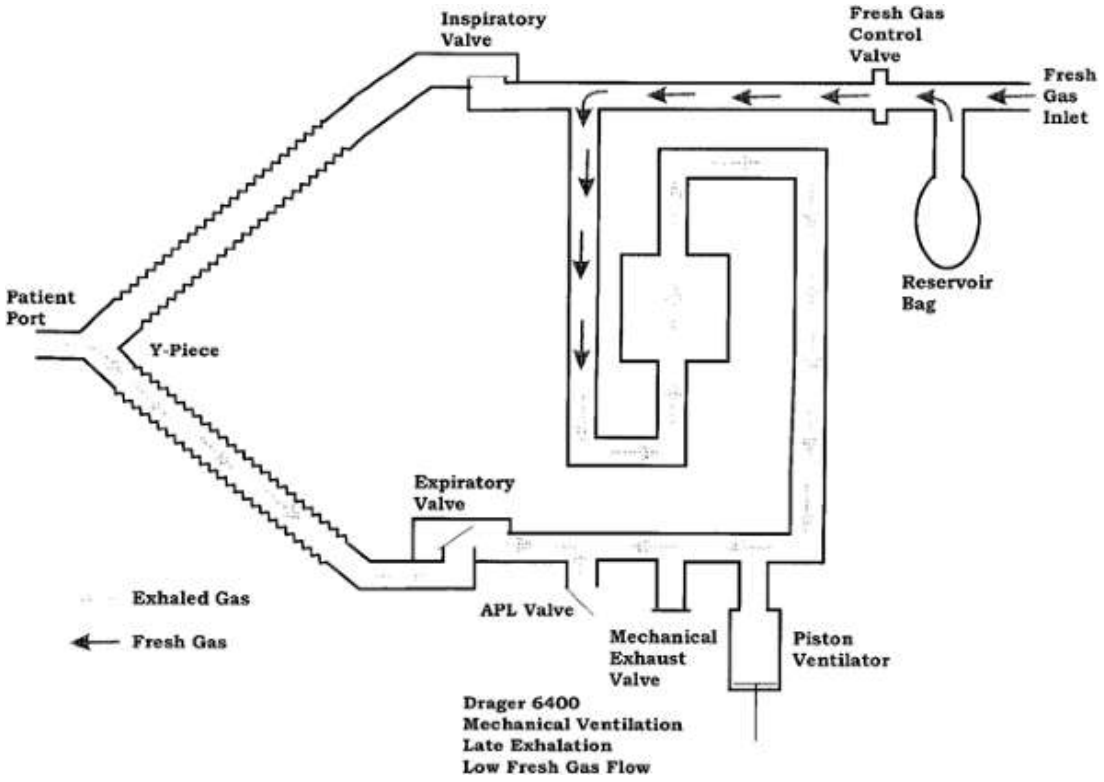

Figure 9.53 Drager 6400 breathing system during mechanical exhalation with low fresh gas flow. APL, adjustable pressure limiting.

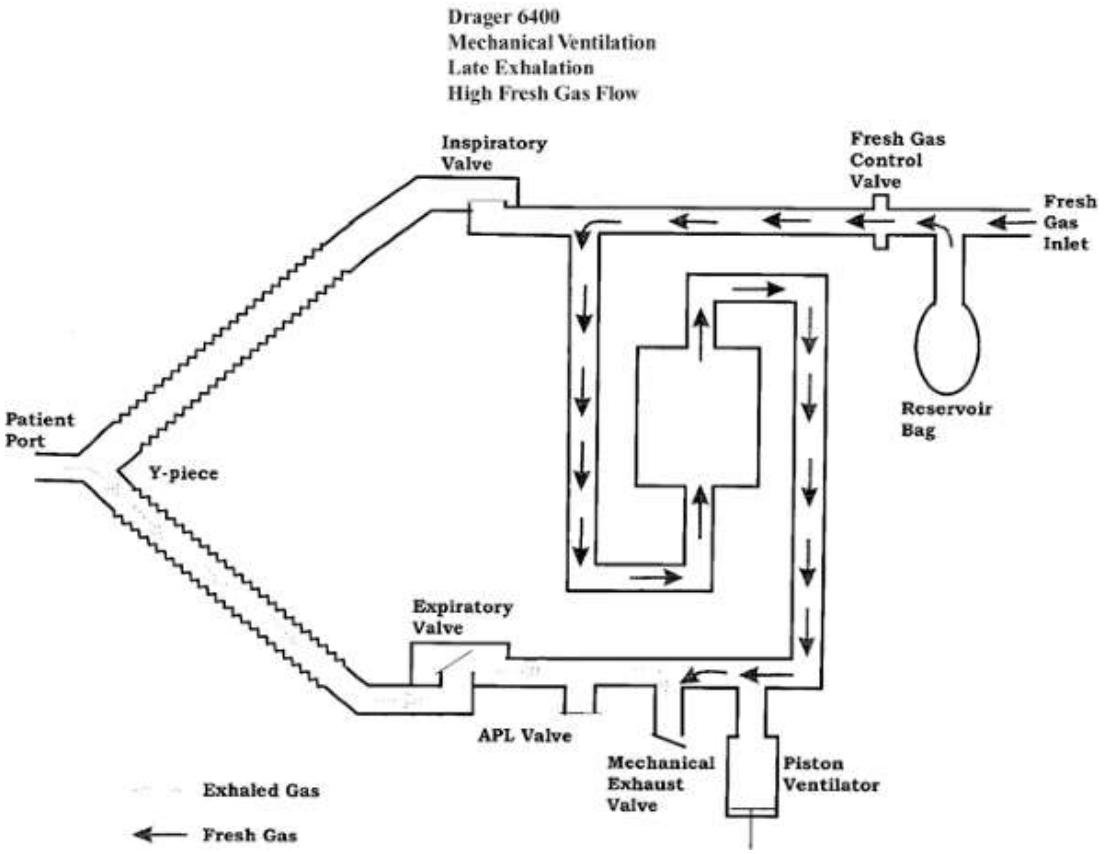

Figure 9.54 Drager 6400 breathing system during mechanical late exhalation with high fresh gas flow. APL, adjustable pressure limiting.

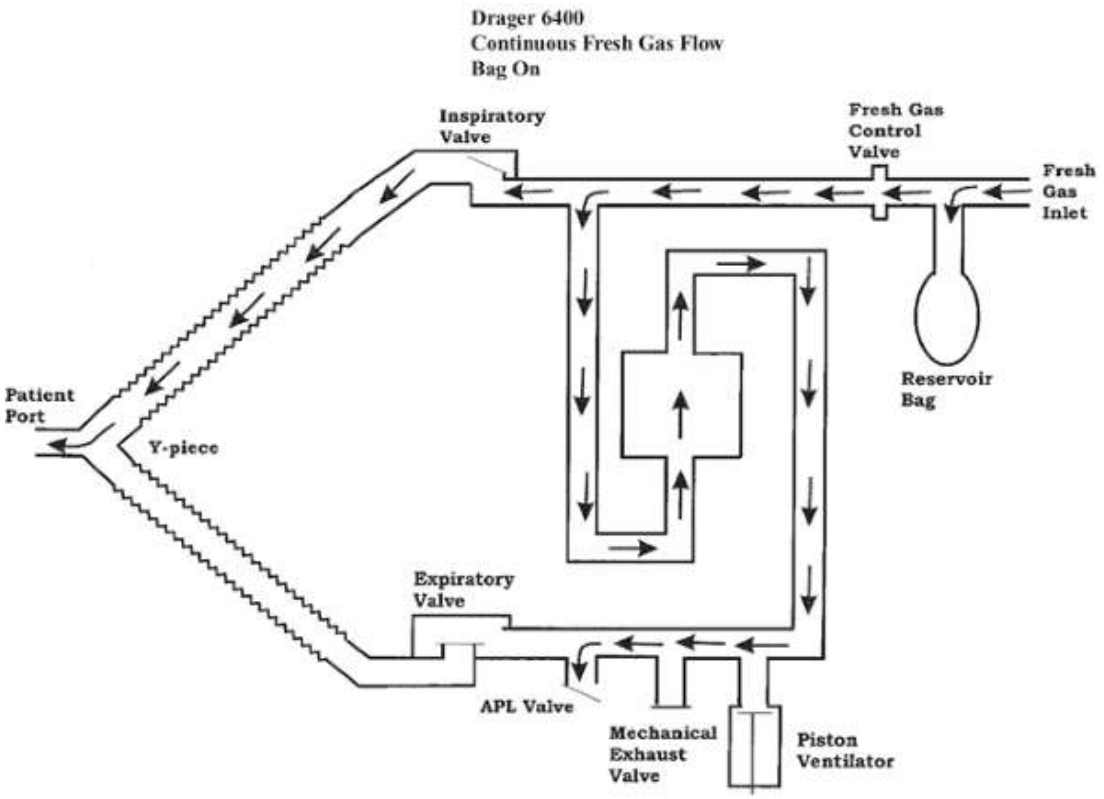

Figure 9.55 Drager 6400 breathing system with continuous fresh gas flow and bag on the bag mount. APL, adjustable pressure limiting.

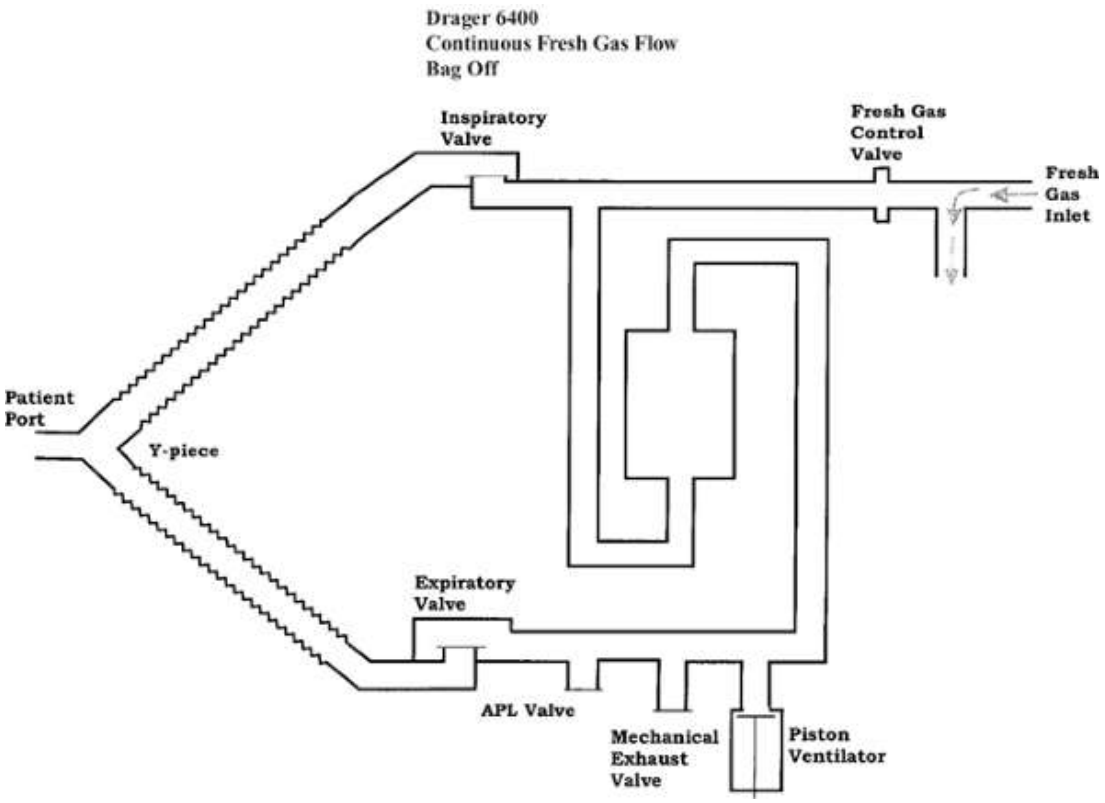

Figure 9.56 Drager 6400 breathing system with continuous fresh gas flow during nonuse and no bag on the bag mount. APL, adjustable pressure limiting.

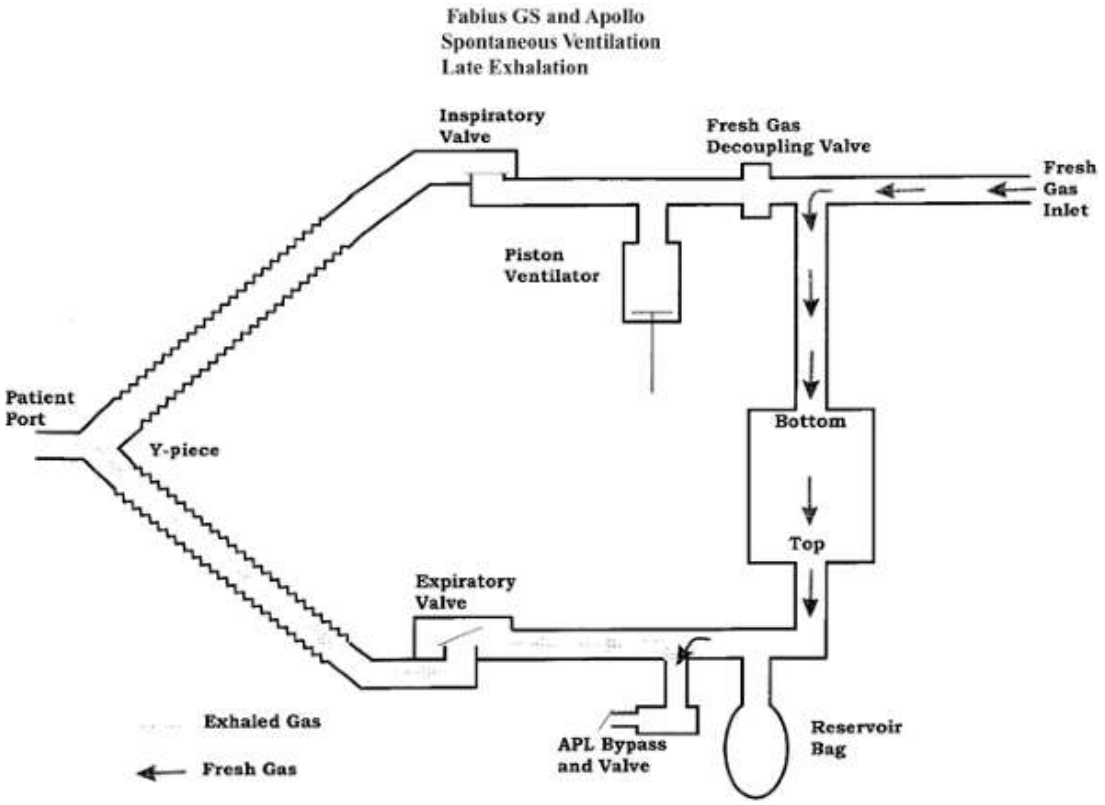

Figure 9.57 Fabius GS and Apollo breathing systems during spontaneous exhalation. APL, adjustable pressure limiting.

During mechanical exhalation, the piston retracts and exhaled gases fill the ventilator. Since the inspiratory valve is closed, fresh gas will flow retrograde through the absorber toward the ventilator (Fig. 9.52). The first gas to enter the ventilator will be exhaled gases. The magnitude of the fresh gas flow will determine how much fresh gas will reach the ventilator. During late exhalation (Figs. 9.53, 9.54), the piston is fully retracted, allowing excess gases to exit by way of the mechanical exhaust valve. The gas that exits the system will contain some exhaled gas and fresh gas that has passed retrograde from the absorber. If the fresh gas flow is high (Fig. 9.54), fresh gas penetration will be greater, and it is possible that some will exit through the exhaust valve.

Continuous Fresh Gas Flow

If a continuous flow of fresh gas enters the system when the system is not in use, there are three possible pathways for the gas to travel. One is through the inspiratory unidirectional valve to the Y-piece (Fig. 9.55). The other potential pathway is retrograde through the absorber and out an through an open APL valve (Fig. 9.55). The third possible pathway is through the bag mount if the bag is not present (Fig. 9.56). The gases will take the route of least resistance. If the reservoir bag is removed from the bag mount, the least resistance will be through the bag mount.

Fabius GS and Apollo Breathing Systems

In these systems (Figs. 9.57,9.58,9.59,9.60,9.61,9.62,9.63), the ventilator is between the fresh gas decoupling valve and the inspiratory unidirectional valve. The reservoir bag is between the expiratory unidirectional valve and the absorber.

Spontaneous Breathing

During spontaneous inspiration, gases will flow from the reservoir bag and fresh gas inlet through the inspiratory unidirectional valve to the patient.

During spontaneous exhalation (Fig. 9.57), exhaled gas passes though the expiratory unidirectional valve and into the reservoir bag. When the bag is full, the excess gases will exit through the open APL valve. Fresh gas flowing into the breathing system will flow retrograde through the absorber into the reservoir bag, with the excess vented through the APL valve. The amount of retrograde flow will depend on the fresh gas flow, respiratory rate, and length of the expiratory pause.

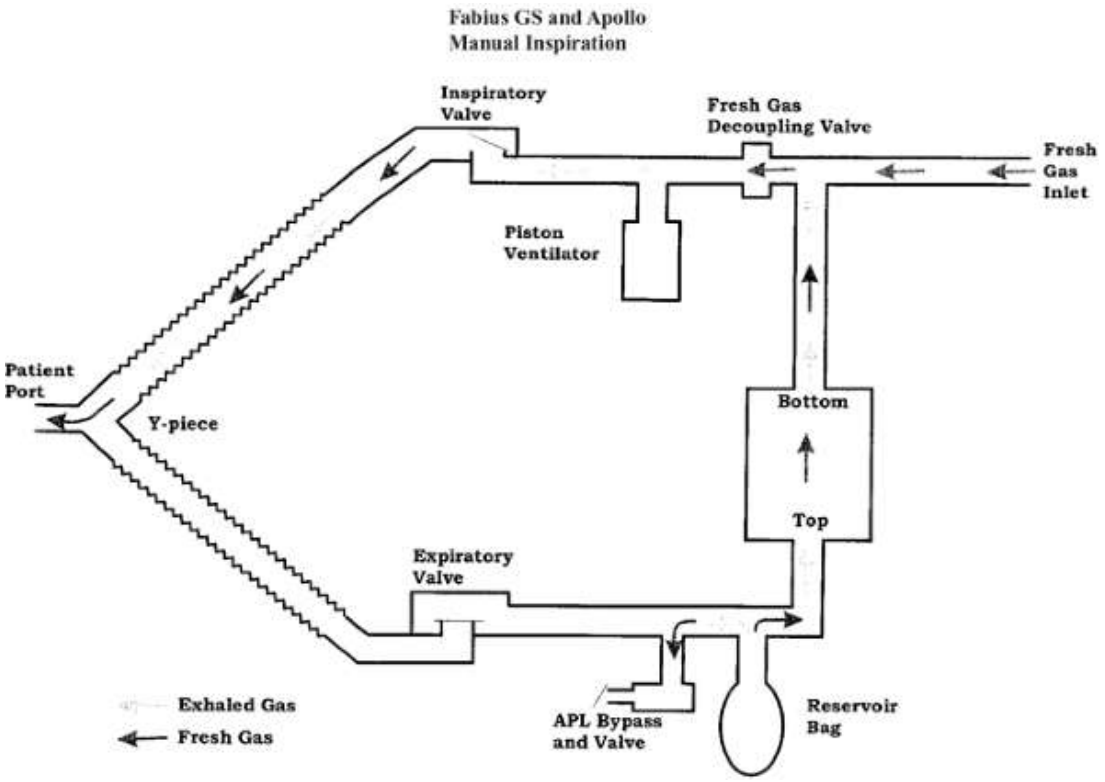

Figure 9.58 Fabius GS and Apollo breathing systems during manual inspiration. APL, adjustable pressure limiting.

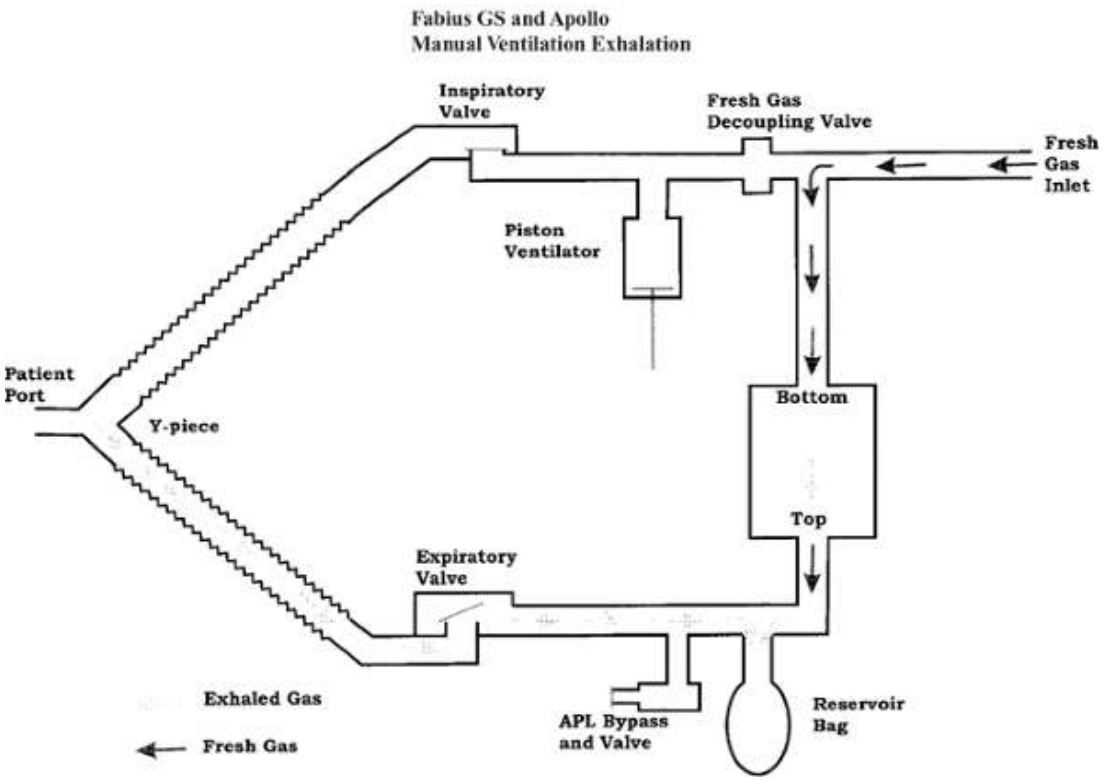

Figure 9.59 Fabius GS and Apollo breathing systems during manual exhalation. APL, adjustable pressure limiting.

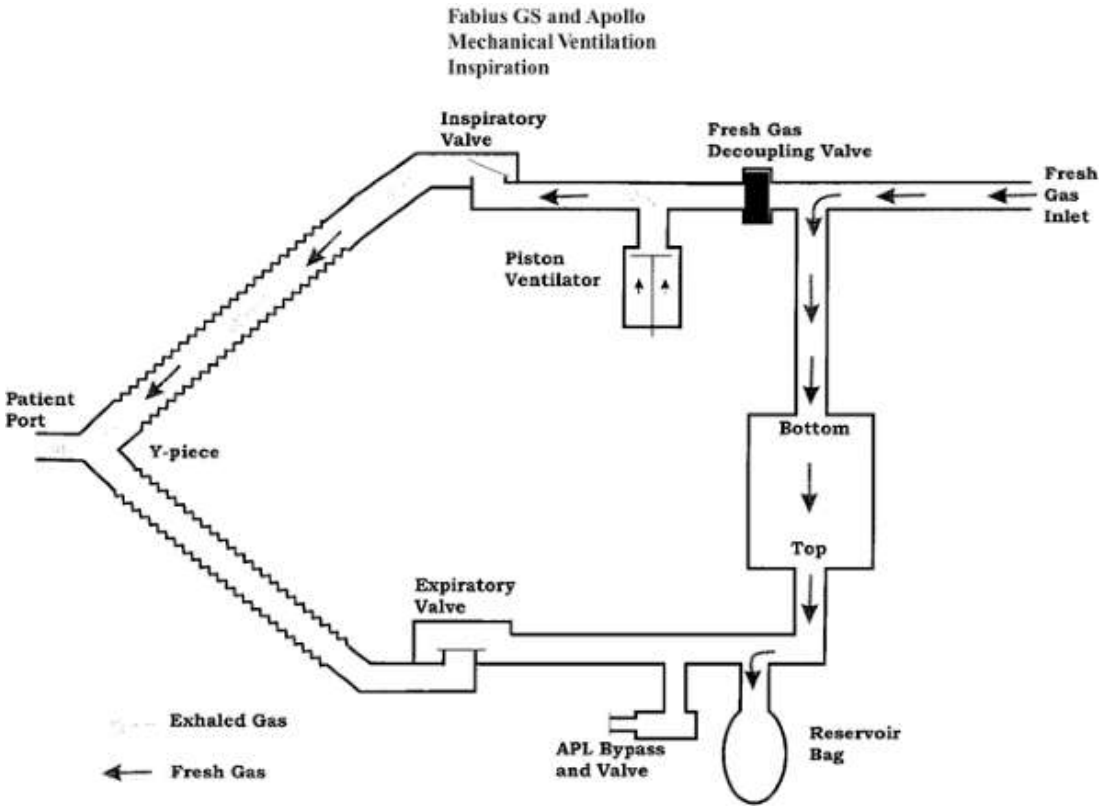

Figure 9.60 Fabius GS and Apollo breathing systems during mechanical inspiration. APL, adjustable pressure limiting.

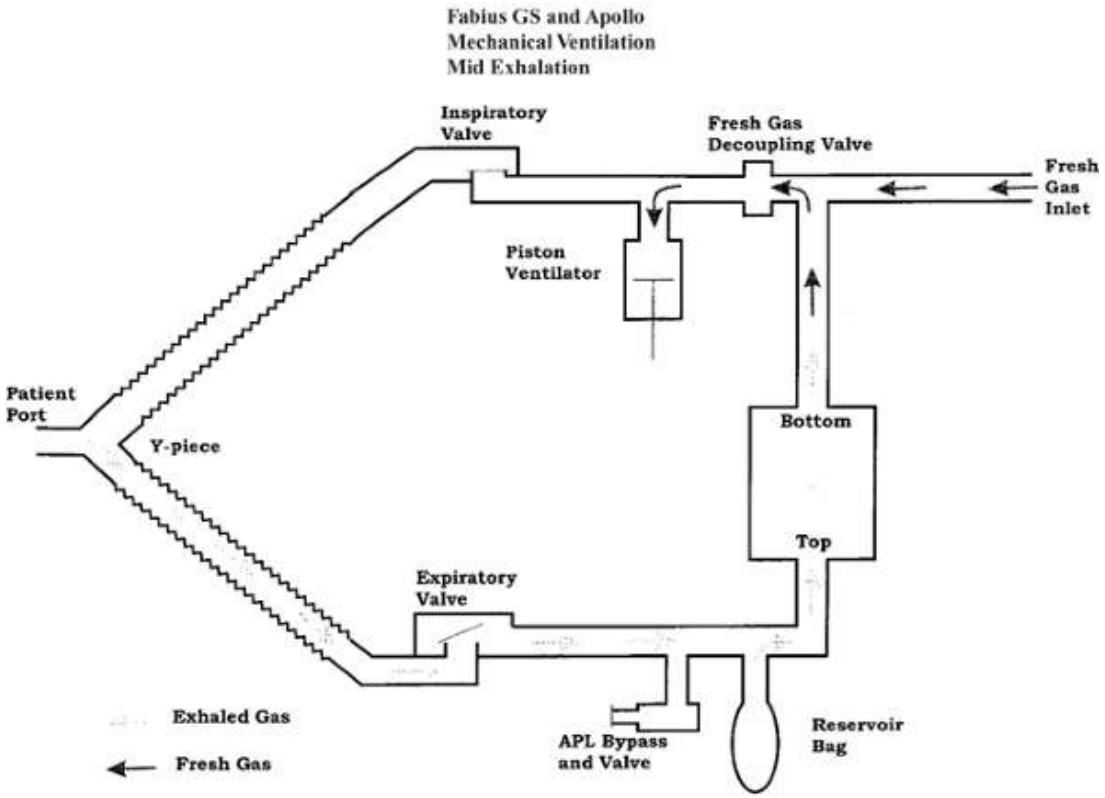

Figure 9.61 Fabius GS and Apollo breathing systems during mechanical mid exhalation. APL, adjustable pressure limiting.

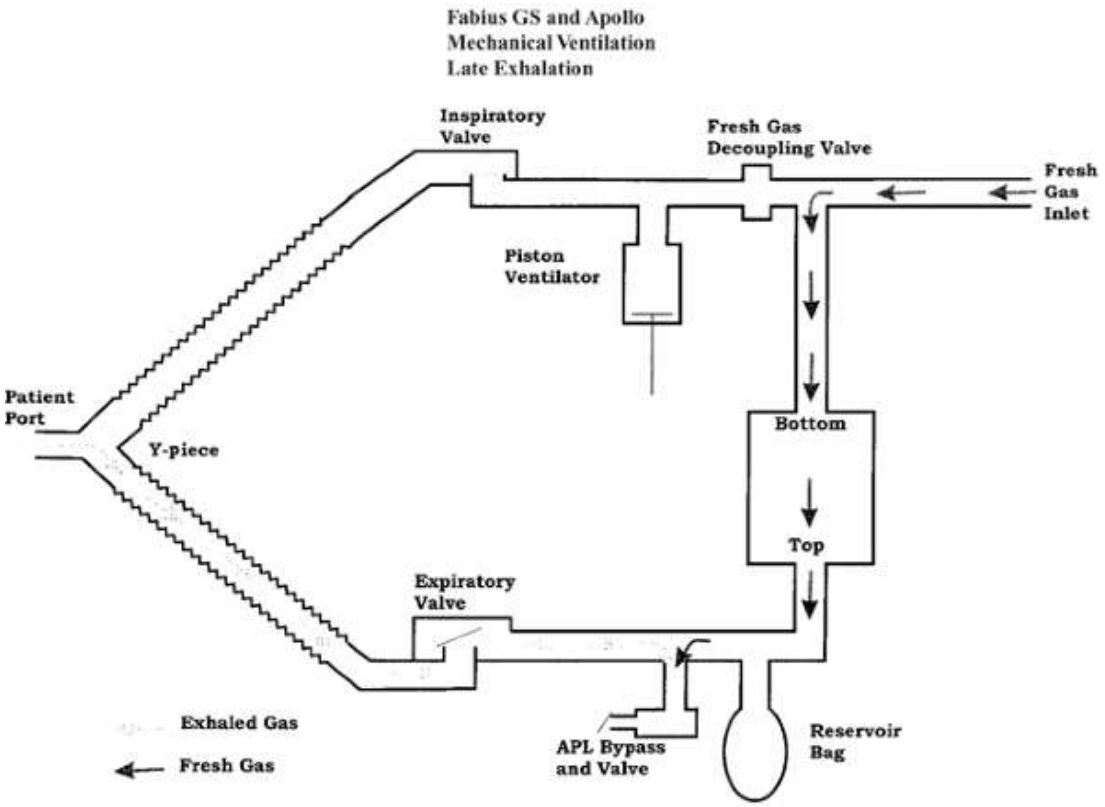

Figure 9.62 Fabius GS and Apollo breathing systems during mechanical late exhalation. APL, adjustable pressure limiting.

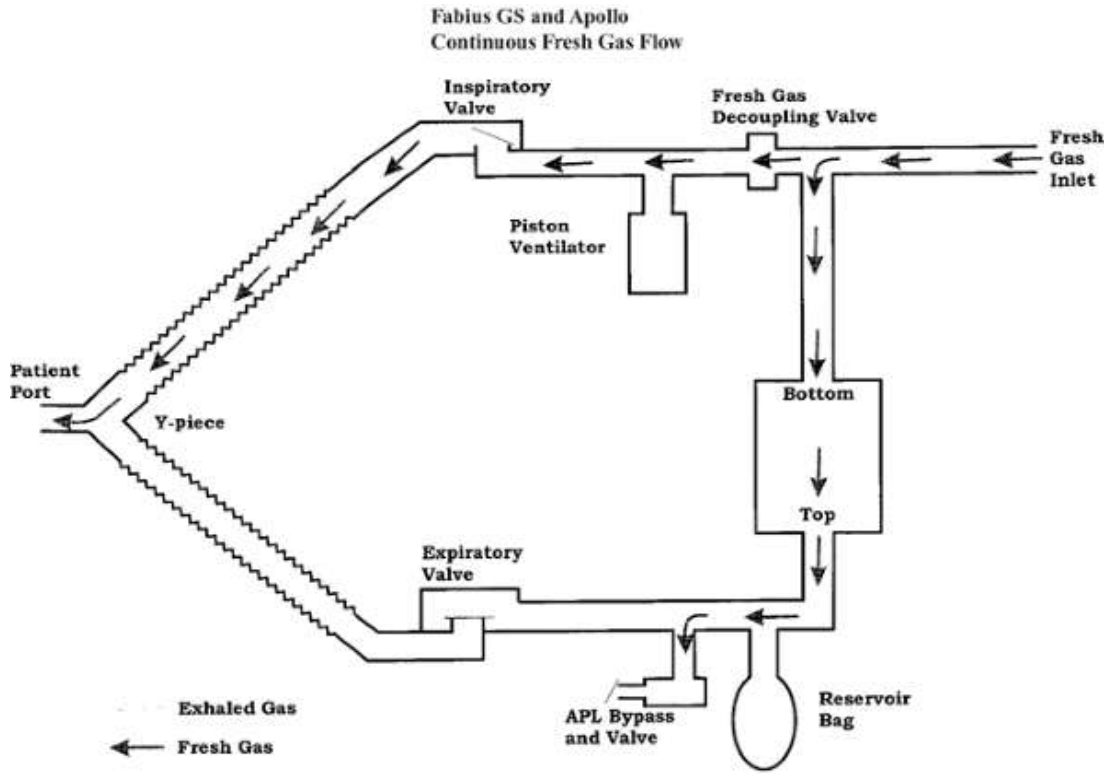

Figure 9.63 Fabius GS and Apollo breathing systems with continuous fresh gas flow during nonuse. APL, adjustable pressure limiting.

Manual Ventilation

During manual inspiration (Fig. 9.58), the bag is compressed, causing exhaled gas to pass through the absorber after which it is joined by fresh gas. The combined gases then pass through the inspiratory unidirectional valve to the patient. Some gas from the bag will also flow to the scavenging system through the APL valve.

During exhalation (Fig. 9.59), exhaled gases flow into the reservoir bag. At the same time, fresh gas will flow retrograde through the absorber toward the bag, pushing some exhaled gas toward the bag.

Mechanical Ventilation

With mechanical ventilation during inspiration (Fig. 9.60), the

fresh gas decoupling valve closes, isolating the fresh gas from the inspired gas. Fresh gas entering the breathing system will pass retrograde through the absorber to the reservoir bag. As the ventilator cycles, it will cause a mixture of fresh and exhaled gases that have passed through the absorbent to flow toward the patient.

During exhalation (Fig. 9.61), exhaled gases will pass through the expiratory unidirectional valve and the absorber and on to the ventilator. Fresh gas that has passed retrograde through the absorber during inspiration will be added to the continuing fresh gas flow that also fills the piston chamber. Late in exhalation (Fig. 9.62), after the piston has filled, exhaled gas will exit through the APL bypass valve. Fresh gas will flow retrograde through the absorber and exit the system at the APL bypass valve. The degree of retrograde flow will depend on the I:E ratio and the fresh gas flow.

Continuous Fresh Gas Flow

If a continuous flow of gas enters the system when the machine is not in use, the gas has two possible routes to exit (Fig. 9.63). One path is through the inspiratory valve and Y-piece. The other is retrograde through the absorber and an open APL valve or empty bag mount. The gas flow will take the path of least resistance. If the machine is in standby mode and there is still gas flow, a message to that effect will be displayed on the screen.

Resistance and Work of Breathing in the Circle System

In the past, one of the objections to using a circle system with small children was that it had a high resistance. However, investigations have shown that the resistance or work of breathing with the circle system is not significantly greater than with other breathing systems and may be less (194,195). Coaxial tubings increase resistance.

Dead Space of the Circle System

In the circle system, dead space extends from the patient port of the Y-piece to the partition between the inspiratory and exhalation tubings. A Y-piece with a septum will decrease dead

space. When exhalation or inhalation starts, the gases in the breathing tubes move in the opposite direction from their usual flow until stopped by closure of one of the unidirectional valves. This is referred to as *backlash* and causes a slight increase in dead space. If the unidirectional valves are competent, however, backlash will be clinically insignificant.

Heat and Humidity

In the circle system, moisture is available from exhaled gases, the absorbent, and water liberated from the neutralization of carbon dioxide. Gases in the inspiratory limb of a circle system are near room temperature. Even with low fresh gas flows, gases reach the Y-piece only 1ยฐC to 3ยฐC above ambient temperature (196).

The humidity of a standard adult circle system increases gradually with use and then stabilizes. A fresh gas flow of 0.5 to 2 L/minute will result in humidity between 20 and 25 mg H_2O/L at 60 minutes (197). Higher humidity results from lower fresh gas flows, increasing ventilation, locating the fresh gas upstream of the absorber, wetting the inspiratory tubing, and by using a humidifier, smaller canisters, or coaxial breathing tubes. Prior system use will result in an initially higher humidity that stabilizes in the same period of time and at the same final humidity. Using an HME (Chapter 11) will result in decreased humidity in the circle system but increased humidity in the inspired gases.

Relationship between Inspired and Delivered Concentrations

In a system with no rebreathing, the concentrations of gases and vapors in the inspired mixture will be close to those in fresh gas. With rebreathing, however, the concentrations in the inspired mixture may differ considerably from those in the fresh gas. The larger the breathing system's internal volume, the greater will be the difference between inspired and delivered concentrations. Canister size is the most important determinant of internal volume in the circle system.

Nitrogen

Nitrogen is important, because it hinders establishing high

concentrations of nitrous oxide and may cause low inspired oxygen concentrations. Before any fresh gas is delivered, the concentration of nitrogen in the breathing

system is approximately 80%. Nitrogen enters the system from exhaled gases and leaves through the APL valve, ventilator spill valve, and leaks.

Using high fresh gas flows for a few minutes to eliminate most of the nitrogen in the system and much of that in the patient is called *denitrogenation*. There is no set time or flow that will produce adequate denitrogenation in all cases (198). A tight mask fit is necessary for proper denitrogenation, as air will be inspired around a loose-fitting mask.

After denitrogenation, nitrogen elimination by the patient will proceed at a slower rate. In a closed system, the nitrogen concentration will gradually rise. Provided that denitrogenation has been carried out, even if all the body's nitrogen is exhaled, the concentration in the breathing system should not increase to more than 18% in the average adult (199,200). However, if a sidestream gas monitor directs gases back to the anesthesia circuit, nitrogen concentration may increase because many analyzers entrain air as the reference gas (201). A leak in the sampling line can result in air entrainment (202).

When delivering an air/oxygen mixture into the circle system, the inspired oxygen concentration will be lower than that set on the flowmeters when the fresh gas flow is low. To compensate for this, higher oxygen concentrations need to be administered at low flows (203).

In certain anesthesia machines, fresh gas compensation (decoupling) (Chapter 12) is accomplished by accumulating the fresh gas flow during inspiration in a reservoir bag and using a ventilator with a piston or descending bellows (164). This introduces the possibility of entraining room air into the gas circuit through a negative pressure relief valve.

Carbon Dioxide

With Absorbent

The inspired carbon dioxide concentration should be near zero, unless there is failure of one or both unidirectional valves,

exhausted absorbent, or a bypassed absorber (204). If one of these conditions exists, a high fresh gas flow will limit the increase in inspired carbon dioxide concentration.

Without Absorbent

If the circle system is used without absorbent, the inspired carbon dioxide level will depend on the fresh gas flow, the arrangement of components in the circle system, and ventilation.

Oxygen

The concentration of oxygen in the inspired mixture is affected by the rate of oxygen uptake by the patient, uptake and elimination of other gases by the patient, the arrangement of the components, ventilation, fresh gas flow, volume of the system, and the concentration of oxygen in the fresh gas. Because so many of these are unpredictable and uncontrollable, it is necessary to use an oxygen analyzer in the breathing system. Oxygen analyzers are discussed in Chapter 22.

Anesthetic Agents

Absorbents can remove volatile anesthetic agents by adsorption or degradation. This can result in slower inductions and exposure of subsequent patients to volatile agents. Dry absorbent removes more agent than wet (205,206,207,208). The relationship of absorbent and anesthetic agents was discussed earlier in this chapter. The following influence the concentration of anesthetic agent in the inspired mixture: uptake by the patient, uptake by components of the system, arrangement of system components, uptake and elimination of other gases by the patient, volume of the system, concentration in the fresh gas flow, degradation by the absorbent, and fresh gas flow. It is not possible to predict the concentration accurately unless a high fresh gas flow is used. Several devices are now available to measure the inspired anesthetic agent concentration (Chapter 22). The greatest variation occurs during induction, when anesthetic uptake is high and nitrogen washout from the patient dilutes the gases in the circuit. For this reason, most authors recommend that anesthesia be started with high fresh gas flows. The time interval until there is some equilibration between inspired and end-expired agent concentrations varies with the agent, being minimal with desflurane, intermediate with

sevoflurane, and greatest with isoflurane (209).

High flows are also commonly used at the end of a case to increase the elimination of anesthetic agent. The rate of elimination may be increased by bypassing the absorber (139,210).

When malignant hyperthermia is suspected, increasing the fresh gas flow is the most important measure that will aid in washing out anesthetic agents from the patient. Using a charcoal filter or changing the anesthesia machine and breathing system are of little or no clinical advantage (211).

Circle System with Low Fresh Gas Flows

Definitions

Low-flow anesthesia has been variously defined as an inhalation technique in which a circle system with absorbent is used with a fresh gas inflow of less than the patient's alveolar minute volume, less than 1 or 1.5 L/minute), 3 L/minute or less, 0.5 to 2 L/minute, less than

4 L/minute, 500 mL/minute, 500 to 1000 mL/minute, or 0.5 to 1 L/minute (212,213,214,215,216,217).

Closed system anesthesia is a form of low-flow anesthesia in which the fresh gas flow equals uptake of anesthetic gases and oxygen by the patient and system and gas sampling. No gas is vented through the APL valve.

Equipment

A standard anesthesia machine can be used, but it must have flowmeters that will provide low flows.

Vaporizers

Anesthetic agent can be added to the circle in two ways.

Calibrated Vaporizers

Vaporizers capable of delivering high concentrations and that are accurate at low fresh gas flows are required. Vaporizers are discussed in Chapter 6.

Liquid Injection

Anesthetic liquid can be injected directly into the expiratory limb (183,218,219,220). Care must be taken that only small amounts are injected at a time and that the syringe containing the liquid agent is not confused with those containing agents for intravenous injection. Liquid agent may cause deterioration of components in the system (221).

In-circle Vaporizer

In-system vaporizers are discussed in Chapter 6. They have been used successfully with both spontaneous and controlled ventilation (222,223,224,225).

Monitors

Continuous measurement of oxygen concentration should be mandatory. It is helpful to monitor other gases and vapors. With sidestream monitors, the fresh gas flow must be increased to compensate for gases removed by the monitor unless the gases are returned to the breathing system (226).

Techniques

Induction

Anesthetic induction by using low fresh gas flows can be accomplished by injecting measured amounts of liquid anesthetic directly into the expiratory limb of the circuit. Problems associated with this include the following: (a) large body stores of nitrogen will be released into the breathing system and will dilute concentrations of other gases; (b) if nitrous oxide is being used, it will take a prolonged period of time to establish concentrations high enough to have a clinical effect; and (c) rapid uptake of nitrous oxide and volatile agent as well as high oxygen consumption during this period mean that the anesthesia provider will have to make frequent injections and adjustments at a time when he or she is likely to be busy with other tasks.

More commonly, induction is accomplished by using high flows to allow denitrogenation, establish anesthetic agent concentrations, and provide oxygen well in excess of consumption. During intubation, the vaporizer should be left ON and the fresh gas flow turned to minimum or OFF (227,228). After gas exchange

has stabilized, lower fresh gas flows are used.

Maintenance

During maintenance, nitrous oxide and oxygen flows and vaporizer settings should be adjusted to maintain a satisfactory oxygen concentration and the desired level of anesthesia. If closed system anesthesia is used, a constant circuit volume is achieved by one of the following methods.

Constant Reservoir Bag Size

If the bag decreases in size, the fresh gas flow rate is increased; if the bag increases in size, the flow is decreased.

Ventilator with Ascending (Upright or Standing) Bellows

Constant volume can be achieved by adjusting the fresh gas flow so that the bellows is below the top of its housing at the end of exhalation. It is important that no negative pressure be transmitted to the bellows from the scavenging system, as this could cause the bellows to be held aloft in the presence of inadequate fresh gas flow (229).

Ventilator with Descending (Inverted or Hanging) Bellows

The fresh gas flow should be adjusted so that the bellows just reaches the bottom of its housing at the end of exhalation.

If a rapid change in any component of the inspired mixture is desired, the fresh gas flow should be increased. If, for any reason, the integrity of the circle is broken, high flows with desired inspired concentrations should be used for several minutes before returning to low flows. If closed system anesthesia is used, it is recommended that high flows be used for 1 to 2 minutes at least once an hour to eliminate gases such as nitrogen and carbon monoxide that have accumulated in the system.

Emergence

Recovery from anesthesia will be slower if low flows are used. High flows are usually needed at least briefly to clear nitrous

oxide. Coasting, in which anesthetic administration is stopped toward the end of the operation and the circuit is maintained closed with enough oxygen flow to maintain a constant end-tidal volume of the ventilator or reservoir bag, can be used. A charcoal filter placed in the inspiratory or expiratory limb will cause a rapid decrease in volatile agent concentration (230).

Advantages

Economy

Significant savings can be achieved with lower flows of nitrous oxide and oxygen, but the greatest savings occurs with the potent volatile agents (217,231,232,233,234,235,236,237,238,239). These are partly offset by increased absorbent usage, but this cost is small. Individual feedback and education regarding volatile agent use are effective in getting anesthesia providers to reduce fresh gas flows (240).

Reduced Operating Room Pollution

With lower flows, there will be less anesthetic agent put into the operating room. However, the use of low-flow techniques does not eliminate the need for scavenging, because high flows are still necessary at times. Since less volatile agent is used, vaporizers have to be filled less frequently so that exposure to anesthetic vapors during filling is decreased.

Reduced Environmental Pollution

Fluorocarbons and nitrous oxide attack the earth's ozone layer, and nitrous oxide contributes to the greenhouse effect (241,242,243,244,245,246,247). With low flows, these ecological dangers are reduced.

Estimation of Anesthetic Agent Uptake and Oxygen Consumption

In a closed system without significant leaks, the fresh gas flow is matched by the patient's uptake of oxygen and anesthetic agents (248,249,250,251). Changes in volume may be attributed principally to uptake of oxygen or nitrous oxide because the

volume contributed by the potent inhalational agents is usually not significant.

Buffered Changes in Inspired Concentrations

The lower the fresh gas flow, the longer it takes for a change in concentration in the fresh gas flow to cause a comparable change in the inspired concentration.

Heat and Humidity Conservation

With lower gas flows, inspired humidity will be increased, and the rate of fall in body temperature reduced (178,252,253,254,255,256). The incidence of shivering is lowered (257).

Less Danger of Barotrauma

High pressures in the breathing system take longer to develop with lower flows.

Disadvantages

More Attention Required

With closed system anesthesia, fresh gas flow into the system must be kept in balance with uptake. This requires frequent adjustments.

Inability to Quickly Alter Inspired Concentrations

The use of low fresh gas flows prevents the rapid changes in fresh gas concentration in the breathing system that occurs with high gas flows. As a result, it may be more difficult to control acute hemodynamic responses (258). This is a significant disadvantage only if the user insists on using low flows at all times. The clinician who uses low flows should accept that when it is necessary to change inspired concentrations rapidly, higher flows should be used.

Danger of Hypercarbia

Hypercarbia resulting from exhausted absorbent, incompetent

unidirectional valves, or the absorber being left in the bypass position will be greater when low flows are used.

Accumulation of Undesirable Gases in the System

The accumulation of undesirable gases is most likely only a problem with closed-circuit anesthesia, because low flows provide a continuous system flush. With closed system anesthesia, flushing with high fresh gas flows once an hour will decrease the concentration of most of these substances. Alternately, a diverting gas monitor with the sample gas scavenged instead of being returned to the circle system can be used to remove small amounts of gas (212).

Carbon Monoxide

Carbon monoxide from the interaction of desiccated absorbent and anesthetic agent was discussed earlier in this chapter. Since low-flow anesthesia tends to preserve the moisture content of the absorbent, it may protect against the production of carbon monoxide resulting from desiccated absorbent (113). However, if desiccated absorbent is present, low flows tend to increase the amount of carbon monoxide present in the system. Carbon monoxide produced from the breakdown of hemoglobin or exhaled by smokers can accumulate in the closed circle system (138,259).

Acetone, Methane, Hydrogen, and Ethanol

Acetone, methane, and hydrogen accumulate during closed system anesthesia (260,261,262). However, dangerous levels are reached only after hours of closed system anesthesia (263). Methane can disturb infrared analyzers (260,262). The common intoxicant ethanol can also accumulate.

Compound A

The safety of using sevoflurane with low flows is still under investigation. At the time of writing,

the FDA was still recommending that sevoflurane not be used with fresh gas flows of less than 2 L/minute. This recommendation has been revised to suggest that flow rates of 1

L/minute are acceptable but should not exceed 2 minimum alveolar concentration (MAC)-hours. Some investigators feel that Compound A should not be a real clinical concern and that restricting the use of low fresh gas flows with sevoflurane cannot be justified (45).

Argon

If oxygen is supplied from an oxygen concentrator (Chapter 4), there will be an accumulation of argon with low fresh gas flows (264).

Nitrogen

Even with initial denitrogenation, nitrogen will accumulate in the closed breathing circuit (199). If oxygen is being supplied by an oxygen concentrator, malfunction of one of the concentrators can cause nitrogen to appear in the product gas (264). Infrared monitors (Chapter 22) add air to the sample gas after the sample is analyzed (212,265). If the gas exhausted is returned to the breathing system, nitrogen accumulation will be greater than expected.

Other

An acrylic monomer is exhaled when joint prostheses are surgically cemented (266). During this period, the system should be vented to prevent rebreathing of this chemical.

Uncertainty about Inspired Concentrations

One of the effects of rebreathing is that the inspired concentrations cannot be accurately predicted. However, absolute or near-absolute knowledge of inspired anesthetic agent concentrations is not necessary for safe anesthesia conduct, because patients' responses to drugs vary widely.

Faster Absorbent Exhaustion

The lower the fresh gas flow, the faster the absorbent is exhausted.

Circle System for Pediatric Anesthesia

It was once believed that small patients required special

breathing circuits and ventilators. However, studies show that adult circle systems can be used even in small infants and with low fresh gas flows (194,195,235,267,268,269,270,271,272,273,274,275,276).

It is important not to add devices with large dead space or resistance between the Y-piece and the patient. Use of an HME/filter (Chapter 7) in this location causes the dead space to be unacceptably high for the spontaneous breathing infant (277).

One problem with the circle system is its large gas volume. The compression of that gas makes it difficult to determine the actual minute ventilation that the patient is receiving, unless measurements are done at the Y-piece (278). In the past, special pediatric circle systems with small absorbers were used. These are no longer commercially available. What is referred to as a pediatric circle system today is usually a standard absorber assembly with short, small-diameter breathing tubes and a small bag. This allows a rapid and easy changeover from an adult to a pediatric system and allows use of equipment with which most anesthesia providers are familiar.

Using the Circle System to Deliver Oxygen

In some institutions, supplemental oxygen may be delivered to patients by attaching the oxygen tubing to a mask or nasal prongs to the Y-piece of a circle system. Studies show that this method is less accurate than use of an auxiliary flowmeter (279). A hazard is that nitrous oxide or a volatile agent may be accidentally administered (149). Another disadvantage is that this may lead to absorbent desiccation. Also, the continuous positive pressure that results may cause activation of airway pressure alarms. Supplemental oxygen should be delivered by using an auxiliary flowmeter or a flowmeter attached to the piped oxygen system.

Advantages

1. Low fresh gas flows can be used with the physiological, economic, and environmental advantages of rebreathing.
2. $PaCO_2$ depends only on ventilation, not fresh gas flow. It may be the best system for patients with malignant hyperthermia (280).

Disadvantages

1. The circle system is composed of many parts that can be arranged incorrectly or may malfunction and a large number of connections that can become disconnected or leak.
2. Some components are difficult to clean. However, modern circle systems are designed to make disassembly and disinfection easier (Fig. 9.64).
3. The system is relatively bulky and not easily moved.
4. The compliance of the circle system is high compared with other systems. This may make consistent ventilation more difficult than with the Mapleson D or F systems (281). The trend toward smaller absorbent canisters will reduce the internal volume of the breathing system and reduce the system compliance.
5. The use an absorbent may result in formation of carbon monoxide or Compound A.

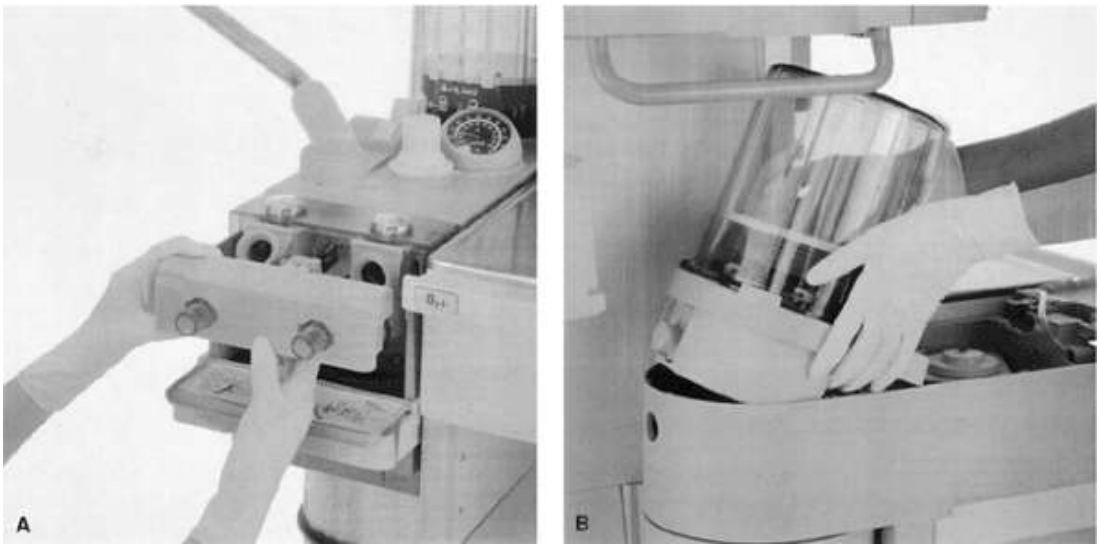

Figure 9.64 A,B: Modern circle systems are easier to disassemble and clean than older ones.

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Questions

For the following questions, select the correct answer.

1. Concerning degradation of sevoflurane by absorbent,

A. It is degraded more as the length of the anesthetic increases

B. More degradation occurs at lower temperatures

C. More degradation occurs with lower concentrations

D. Desiccated absorbent decreases degradation

E. Low fresh gas flows decrease degradation

View Answer

2. The most common location for the fresh gas inlet in the classic circle system is

A. Just upstream of the inspiratory unidirectional valve

B. Between the pressure manometer and the absorber

C. Between the inspiratory unidirectional valve and the Y-piece

D. Between the spirometer and the expiratory unidirectional valve

E. Between the inspiratory unidirectional valve and the PEEP valve

View Answer

3. The most common location for the reservoir bag in the classic circle system is

A. Just upstream of the inspiratory unidirectional valve

B. Between the inspiratory unidirectional valve and the absorber

C. Between the inspiratory unidirectional valve and the Y-piece

D. Between the expiratory unidirectional valve and the absorber

E. Between the Y-piece and the spirometer

View Answer

4. Which anesthetic agent is associated with the highest level of carbon monoxide formation?

A. Halothane

B. Enflurane

C. Isoflurane

D. Desflurane

E. Sevoflurane

View Answer

5. Which position of the fresh gas inlet will not result in absorbent desiccation?

A. Between the absorber and the inspiratory unidirectional valve

B. Between the APL valve and the absorber

C. Between the inspiratory unidirectional valve and the Y-piece

D. Between the Y-piece and the expiratory unidirectional valve

E. Between the expiratory unidirectional valve and the APL valve

View Answer

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

6. Which statements correctly reflect the flow through a carbon dioxide absorber?

A. Flow is continuous

B. It makes no difference if the flow is from bottom to top or from top to bottom

C. Larger canisters do not allow more carbon dioxide absorption

D. Absorption takes place first at the inlet and along the sides of the canister

View Answer

7. Baffles in the absorber

A. Increase resistance

B. Separate the absorbent into different compartments

C. Increase the path of travel for gases in the absorber

D. Act as a buffer for dust and water generated in the canister

View Answer

8. Bypassing the absorber

A. Increases the inspired carbon dioxide

B. Allows the absorbent to be changed during an anesthetic

C. Can be especially dangerous when used during low-flow anesthesia

D. Allows the absorbent to regenerate

View Answer

9. Which statement(s) concerning the size and shape of granules in soda lime are correct?

A. Small granules provide a greater surface area for absorption

B. Small granules may cause more resistance and caking

C. Granules used today range in size between 4 and 8 mesh

D. Small granules decrease channeling

View Answer

10. Concerning the hardness of soda lime granules,

A. If the granule is too soft, it will fragment easily and produce dust

B. Dust may be blown into system components

C. Dust will increase resistance and channeling

D. A coating on the granule will produce a film that will adhere to dust particles

View Answer

11. The absorbent in the canister should be changed when

A. Carbon dioxide appears in the inhaled gases

B. There is no heat production with low fresh gas flows

C. Heat is generated in the downstream canister

D. Color change is seen in the downstream canister

View Answer

12. Concerning the storage and handling of carbon dioxide absorbents,

A. They should not be stored at freezing temperatures

B. Absorbent dust can be irritating to the eyes, respiratory tract, and skin

C. When filling the canister with absorbent, a small space should be left at the top

D. Absorbent dust will cause the seals to warp

View Answer

13. Which of the following are objectives in the arrangement of components of the circle breathing system?

A. Maximal humidification of inspired gases

B. Low resistance

C. Minimal consumption of carbon dioxide absorbents

D. Maximal inclusion of dead space gases in the inspired mixture

View Answer

14. Which position(s) of the APL valve in the circle system would cause inefficient use of the carbon dioxide absorbent during controlled ventilation?

A. Just upstream of the inspiratory valve

B. Between the inspiratory unidirectional valve and the Y-piece

C. At the Y-piece

D. Between the exhalation unidirectional valve and the absorber

View Answer

15. If a bacterial filter is located on the inspiratory side of a circle system downstream of the inspiratory valve,

A. The patient will be protected from bacterial contamination in the anesthesia machine and components of the breathing system

B. It will catch absorbent dust

C. If a humidifier is used, it should be placed downstream of this filter

D. Use of a filter in this position has not been shown to reduce the incidence of pneumonia after anesthesia.

View Answer

16. Sources of humidity in the circle breathing system include

A. Neutralization of carbon dioxide

B. Water content of the absorbent granules

C. Exhaled gases

D. The fresh gas flow

View Answer

17. Which techniques are used during the emergence from anesthesia with low fresh gas flows?

A. Turning off all anesthetics and allowing the patient to awaken slowly

B. Using a charcoal filter to remove volatile agents

C. Using high fresh gas flows to wash out anesthetics

D. Bypassing the absorber in order to increase carbon dioxide

View Answer

18. Humidity in the circle system is increased by

A. Low fresh gas flows

B. A reduction of carbon dioxide output from the patient

C. Increased minute ventilation

D. Cooling the canister

View Answer

19. Carbon dioxide in inspired gases may be caused by

A. Not activating the bypass mechanism

B. Failure of one or both unidirectional valves

C. High fresh gas flow

D. Exhausted absorbent

View Answer

20. What equipment is essential for performing low-flow anesthesia with a circle breathing system?

A. An oxygen analyzer

B. An anesthetic agent analyzer

C. Vaporizers with accuracy in the high range of the scale

D. A ventilator with a bellows that descends on exhalation

View Answer

21. Which gases may accumulate in the circle breathing system during closed circle anesthesia?

A. Carbon monoxide

B. Acetone

C. Toxic metabolites of anesthetic agents

D. Hydrogen

View Answer

22. At which location(s) in the circle system will a spirometer over-read the inspired volume?

A. Just upstream of the inspiratory unidirectional valve

B. Between the pressure manometer and the absorber

C. Between the inspiratory unidirectional valve and the Y-piece

D. Between the Y-piece and the expiratory unidirectional valve

View Answer

23. Concerning unidirectional valves,

A. Movement of the disc does not assure competence

B. The disc can obstruct gas flow through the valve

C. The valve on the exhalation side is more likely to be incompetent

D. Unidirectional valves are not positional and can be operated in a number of positions

View Answer

24. What are some of the advantages of low-flow anesthesia?

A. Less danger of barotrauma

B. Buffering of changes in inspired concentrations

C. Conservation of heat and humidity

D. Elimination of the need for scavenging

View Answer

25. Which of the following are commonly found in soda lime?

A. Sodium hydroxide

B. Potassium hydroxide

C. Calcium hydroxide

D. A hardening agent

View Answer

26. Problems with high-alkali absorbents include

A. They degrade enflurane and isoflurane in the normally hydrated state

B. They can react with volatile agents to form carbon

monoxide

C. Carbonic acid is an end product of carbon dioxide absorption

D. They are less able to absorb carbon dioxide when the moisture content is decreased

View Answer

27. There is no evidence of carbon monoxide formation with

A. High-alkali absorbents

B. Normally hydrated soda lime

C. Low-alkali absorbents

D. Alkali-free absorbents

View Answer

28. Which factors increase Compound A formation?

A. Low fresh gas flows

B. Increased absorber temperature

C. High concentrations of sevoflurane

D. Sodium- and potassium-free absorbents

View Answer

29. How can carbon monoxide formation be detected during an anesthetic?

A. Significant decrease in SpO_2

B. Decreased end-tidal carbon dioxide

C. Sevoflurane will be displayed as another agent

D. An unusually delayed rise or unexpected decrease in the inspired volatile agent concentration

View Answer

30. Which factors contribute to carbon monoxide formation?

A. High fresh gas flows

B. Anesthetic agent

C. Increased temperature of the absorbent

D. Desiccated absorbent

View Answer

31. Which procedures will help to prevent carbon dioxide absorbent from becoming desiccated?

A. Turning off the fresh gas flow after each case

B. Turning vaporizers OFF when not in use

C. Checking the negative pressure valve in a closed scavenging system for proper function

D. Changing the top canister at least once a week

View Answer

32. Which statements about changing carbon dioxide absorbent are accurate?

A. It should be changed when carbon dioxide is present in the inspired gas

B. Color change is an indication of desiccation in canisters that have high sodium and potassium contents

C. It should be changed when the temperature in the downstream canister is higher than that in the upstream canister

D. When changing a dual canister, the absorbent in the upstream canister is thrown away, the downstream canister is moved to the top position, and the canister with new absorbent is placed downstream

View Answer

33. Which of the statements about color indicators are correct?

A. When color change shows strongly, the absorbent is at or near exhaustion

B. Indicators do not become deactivated if stored in the dark

C. Absorbents without a strong base change color with desiccation

D. If the color change reverses itself, the absorbent is safe to use

View Answer

34. Which position(s) of the reservoir bag in the classic circle system would result in exhaled gases being rebreathed?

A. Between the inspiratory unidirectional valve and the Y-piece

B. Between the expiratory unidirectional valve and the absorber

C. Between the Y-piece and the expiratory unidirectional valve

D. Between the absorber and the inspiratory unidirectional valve

View Answer

35. Potential problems with placing a filter between the patient and the Y-piece include

A. Increased dead space

B. Increased resistance

C. Increased risk of disconnections

D. It may allow water to enter the gas sample line

View Answer

36. Which are the potential paths of least resistance in the classic breathing system used by fresh gas flow into the breathing system while the system is not in use?

A. Through the inspiratory pathway

B. Through the reservoir bag mount if the reservoir bag is removed

C. Through the APL valve if fully open

D. Through the expiratory pathway

View Answer

37. Sources of increasing nitrogen concentrations in a closed circle system include

A. A leak in the gas sample line

B. Excretion by the patient

C. Recirculated sample gas

D. Leaks in the ventilator bellows

View Answer

38. Problems with inducing anesthesia by using low fresh gas flows include

A. Rapidly changing uptake of nitrous oxide and volatile agent requires frequent adjustments

B. It takes a long time to establish adequate nitrous oxide concentrations in the breathing system

C. Large body stores of nitrogen will be released into the breathing system

D. It is difficult to extract gas from the system

View Answer

Chapter 10

Manual Resuscitators

Introduction

Breathing systems that use nonrebreathing valves have largely disappeared from anesthesia practice. However, these valves are still used in small portable manual resuscitators, which are used primarily for patient transport, suctioning, and emergency situations. They can also be used to administer anesthesia. A manual resuscitator may be adapted for use during magnetic resonance imaging (MRI) (1).

Manual resuscitators are also known as bag ventilators; bag-assist devices; bag-type resuscitators; bag-valve devices, units, or resuscitators; bag-valve-mask units, resuscitators, or ventilators; emergency manual ventilators; hand ventilators; hand-operated bag resuscitators; manual ventilators; hand-operated emergency ventilators; hand- or operator-powered resuscitators; handbag resuscitators; manual bag ventilators; manually operated resuscitators; manual pulmonary resuscitators; respiratory bags; resuscitator or resuscitation bags; self-inflating manual resuscitators; self-inflating respirator bags or resuscitators; ventilator bags; and self-inflating bag-valve devices.

Figure 10.1 Manual resuscitators. Note the pressure-limiting mechanism near the nonrebreathing valve on the smaller resuscitators. This can be overridden by placing a finger on top. Note also the air inlet and outflow valves between the self-refilling bag and the reservoir. (Picture courtesy of Hudson RCIยฎ.)

Examples of these devices are shown in Figure 10.1. Disposable

manual resuscitators that avoid the inconvenience and hazards associated with reprocessing and sterilization are commonly used. International and U.S. standards for resuscitators have been published (2,3).

Components

A typical manual resuscitator is shown diagrammatically in Figure 10.2. It has a compressible self-expanding bag, a bag inlet valve, and a nonrebreathing valve. The bag inlet and nonrebreathing valves are combined in some units. Optional components include a pressure-limiting device, oxygen-enrichment device, positive end-expiratory pressure (PEEP) valve, mechanism for scavenging, carbon dioxide detector, and a port for measuring airway pressure.

Self-expanding Bag

The self-expanding bag (ventilating or ventilation bag, self-inflating bag, self-refilling bag, compressible unit, compressible reservoir) is constructed so that it is inflated in its resting state. Some bags collapse like an accordion for storage. During exhalation, the bag expands. If the volume of oxygen from the delivery source is inadequate to fill the bag, the difference is made up by room air. The rate at which the bag reinflates will determine the maximum minute volume.

Nonrebreathing Valve

The nonrebreathing valve is sometimes called the directional control valve, exhalation valve, expiratory valve, inflating valve, inhalation-exhalation valve, inflating-exhalation valve, inspiratory-expiratory valve, nonreturn valve, patient valve, routing valve, or one-way inflating valve. It has a number of parts that ensure that gas flows out of the bag and into the patient port during inspiration and from the expiratory port without mixing with fresh gas during exhalation.

Body

Most nonrebreathing valves are T-shaped. It is preferable that the housing be transparent so that the internal mechanism movement can be observed.

The expiratory port is the opening through which exhaled gases

pass from the patient to atmosphere. It may have a means to deflect exhaled gas (Fig. 10.3). A PEEP valve may be connected at this point. The expiratory port may have a tapered 19- or 30-mm connector for attachment to a scavenging system transfer tube (Chapter 13). The American Society for Testing and Materials (ASTM) standard (2) requires that the connector for this port have a ridge (baulk) in its internal lumen so that it cannot accept a 22-mm male connector.

The patient connector is the part that connects to a tracheal tube, face mask, or supraglottic device. It has 15-mm female and 22-mm male coaxial fittings. It may be designed to swivel.

The inspiratory port is the opening through which gas enters the valve from the bag. It is usually permanently attached to the bag.

Unidirectional Valves

Unidirectional valves direct the gases from the bag to the patient during inspiration and exhaled gases from the patient to atmosphere. In order to accomplish this, there are usually two valves. During inspiration, gas is directed from the bag to the patient connection port. At the same time, the expiratory port is blocked. During exhalation, the expiratory port is open, and the inspiratory port is blocked so that the patient exhales to atmosphere. The valve may have a means to prevent air from entering when the patient is breathing spontaneously so that the patient will inhale gas only from the bag.

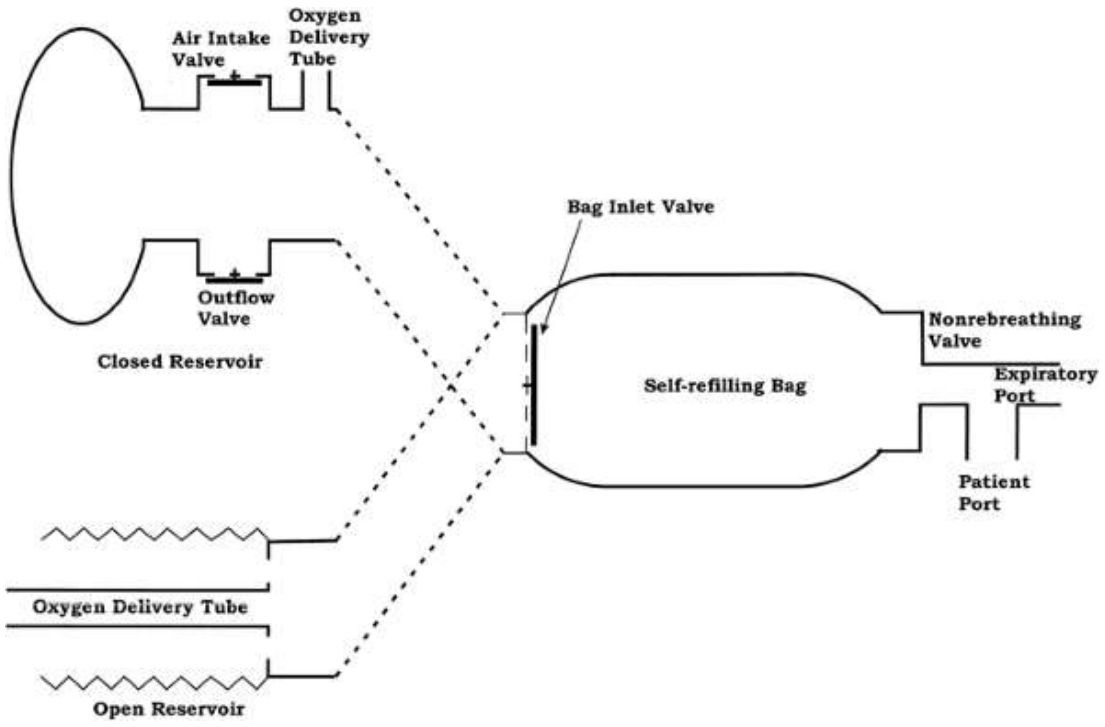

Figure 10.2 Components of a manual resuscitator. The nonrebreathing valve directs the gas from the bag to the patient during inspiration. During expiration, the nonrebreathing valve directs exhaled gases from the patient to atmosphere through the expiratory port, and the bag inlet valve opens to allow the bag to fill.

Spring-disc or Spring-ball Valve

Spring-disc valves are shown in Figures 10.4 and 10.5. In Figure 10.4, a spring holds the disc against the seat. When the pressure on the disc is great enough to overcome the force of the spring, the valve opens. As the pressure drops, the spring causes the disc to close the valve. Some unidirectional valves have a ball in place of the disc. The ball or disc may be held in place by gravity rather than a spring.

Figure 10.5 shows a T-shaped valve with a spring disc that alternately blocks the gas inlet or outlet. When the bag is compressed, the disc is pushed across the valve, connecting the inspiratory port with the patient port

while, at the same time occluding the expiratory port. When the bag is released, the disc moves back toward the bag and allows exhaled gas pass through the expiratory port. A guide pin keeps the disc centered. If the patient is breathing spontaneously, the disc will not close the exhalation port, and room air will be inhaled.

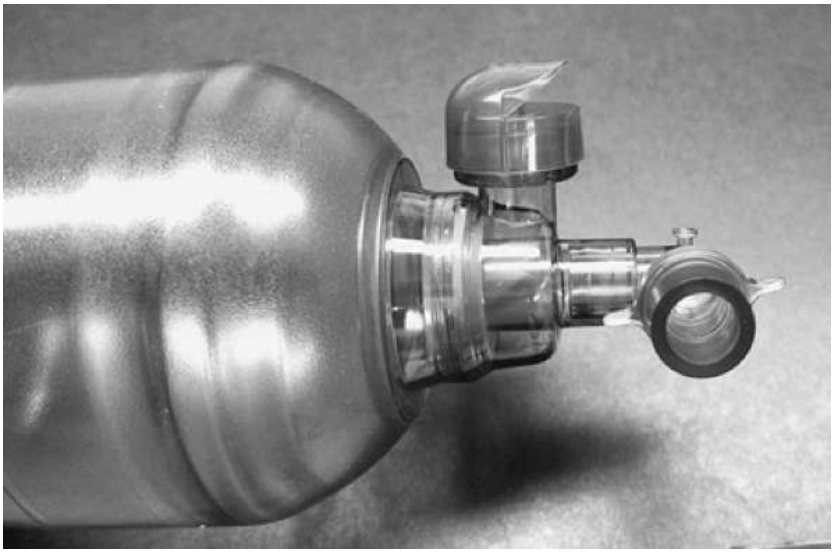

Figure 10.3 The exhalation port may have a means to deflect the exhaled gas away from the operator.

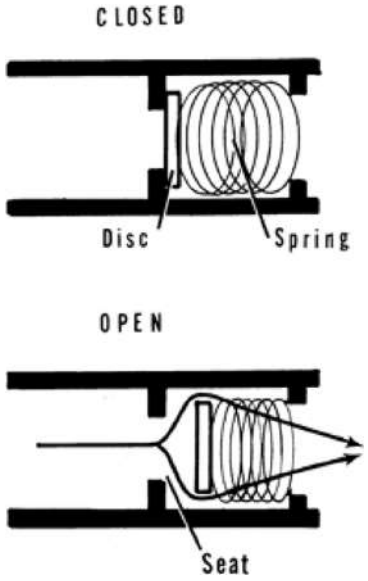

Figure 10.4 Spring-disc unidirectional valve. In the closed position, the spring holds the disc against the seat. When the pressure to the left of the disc increases above the pressure of the spring, the disc is forced away from the seat. When the pressure to the left of the disc drops, the valve closes.

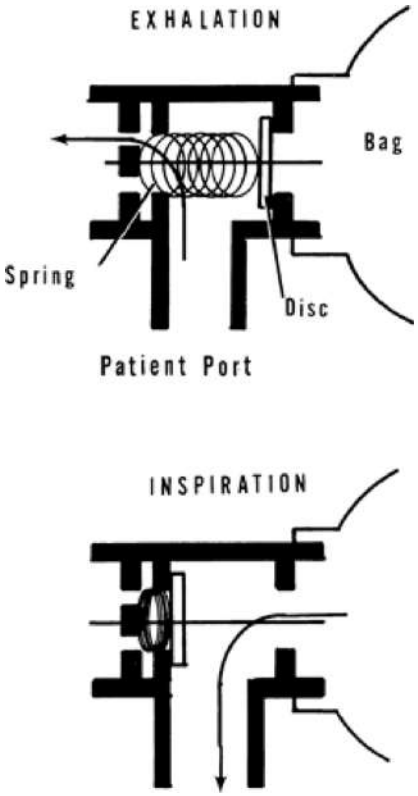

Figure 10.5 Spring-disc nonrebreathing valve. The disc is held on the seat by the spring. When the bag is squeezed, the disc moves to the left, closing the expiratory port. At the end of inspiration, the spring forces the disc to the right so that the patient exhales to atmosphere and not into the bag. A guide pin keeps the disc in the center. A spontaneously breathing patient can inhale room air unless a valve is placed over the expiratory port to prevent air entrainment.

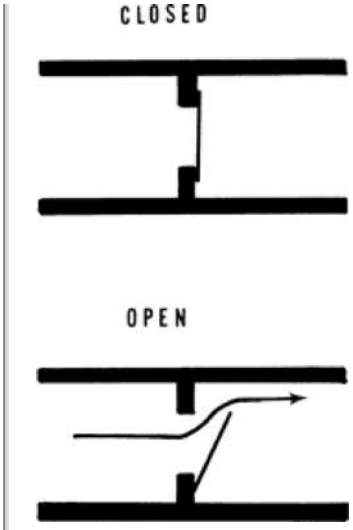

Figure 10.6 Edge-mounted flap unidirectional valve. Increased pressure upstream of the flap pushes the flap away from the seat, opening the valve. When the pressure downstream of the flap increases above the pressure upstream, the flap is forced back against the seat, blocking the flow of gas.

Flap Valve

The flap (leaf) valve has a rigid or flexible flap that moves. The flap may be fixed to the housing at the edge (Fig. 10.6) or the center (Fig. 10.7).

Figure 10.8 shows a nonrebreathing valve that incorporates two flap valves. During inspiration, the center-mounted

flap valve moves to the right. The peripheral flap valve covers the exhalation port. During exhalation, the flaps move to the left, preventing exhaled gas from re-entering the bag, and the exhalation ports are uncovered. The peripheral flap valve prevents inhalation of room air during spontaneous breathing.

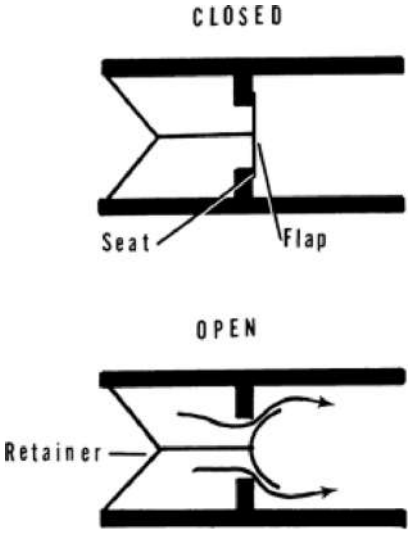

Figure 10.7 Center-mounted flap unidirectional valve. The flap valve is secured by a tab at the center. The tab is secured by a retainer, which is attached to the valve body.

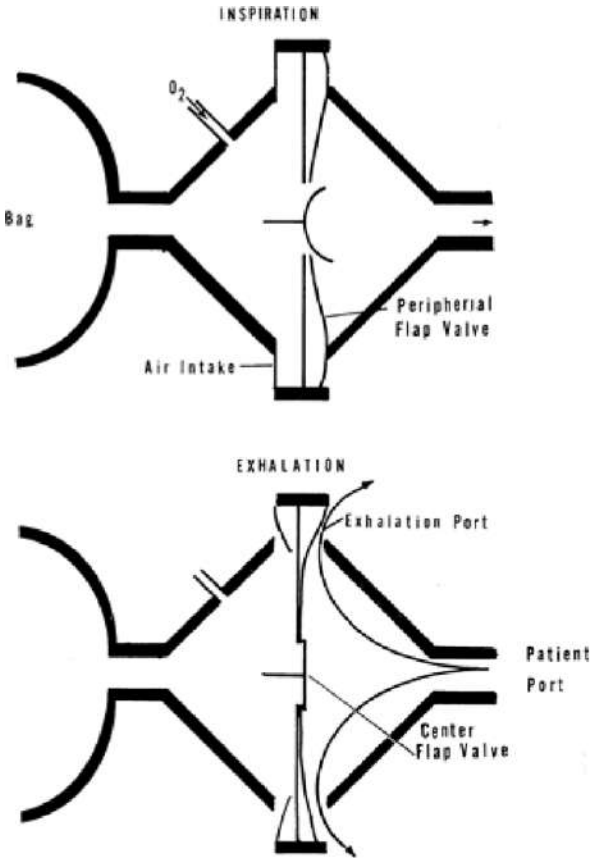

Figure 10.8 Nonrebreathing valve with two flap valves. During inspiration, the center-mounted flap valve opens, and the peripheral flap closes over the exhalation ports. During exhalation, the central flap valve closes, and the peripheral flap falls away from the exhalation ports. This valve has an oxygen inlet and two bag inlet valves, which open if the oxygen flow is not sufficient to prevent a negative pressure from developing in the space to the left.

Fishmouth Valve

The fishmouth (duck-bill) valve (Fig. 10.9) opens and closes like a fish's mouth. As pressure upstream of the valve increases, it opens at the slit in the center. An increase in pressure downstream pushes the leaflets together, closing the valve.

Diaphragm-flap Valve

A diaphragm-flap valve is shown in Figure 10.10. The diaphragm is attached at its periphery. When the bag is squeezed, the diaphragm is pushed to the left and occludes the expiratory port. Flap valves at the side of the diaphragm open, allowing gas from the bag to flow to the patient. When inspiration ends, the diaphragm returns to its resting position and the flap valves close, allowing the patient to exhale through the expiratory port. A spontaneously breathing patient may inhale room air through the exhalation port if there is no flap valve to block ambient air from entering the valve.

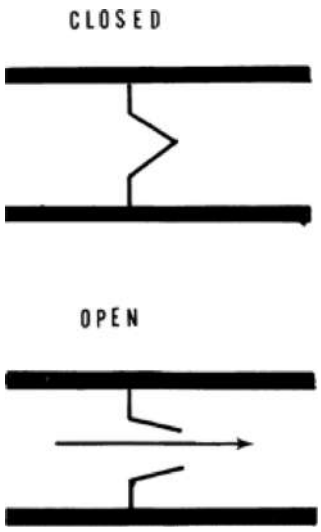

Figure 10.9 Fishmouth unidirectional valve. As pressure to the left increases, the leaflets open, allowing gas to flow through the valve. An increase in pressure to the right pushes the leaflets together, closing the valve and preventing backflow of gas.

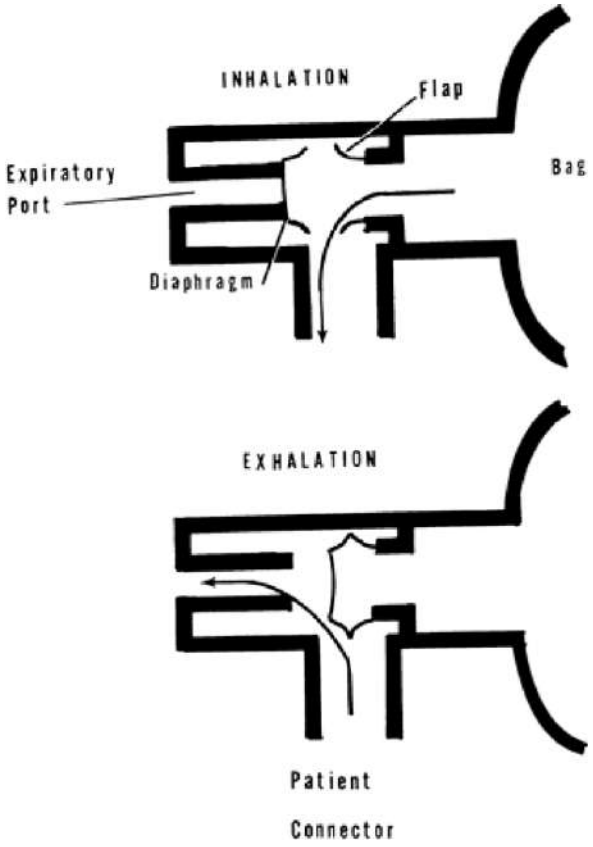

Figure 10.10 Diaphragm-flap nonrebreathing valve. During inspiration, when the bag is squeezed, the pressure to the right increases and the diaphragm is pushed to the left, closing the exhalation channel. At the same time, the flaps at the edge of the diaphragm open, allowing gas from the bag to flow to the patient connector. When inspiration ends, the diaphragm moves away from the exhalation channel and the flaps close, blocking the inspiratory port.

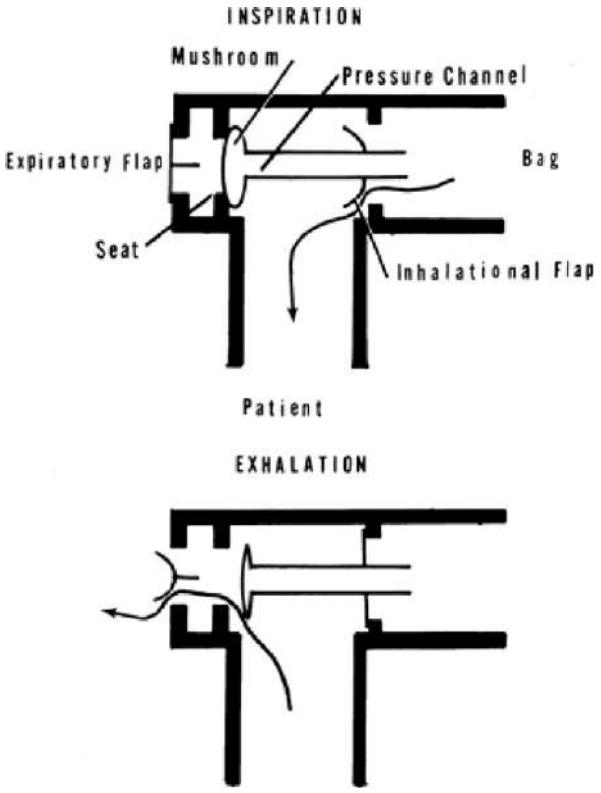

Figure 10.11 Mushroom-flap valve. This valve contains a mushroom-style diaphragm that is inflated when the pressure in the pressure channel increases. This occurs during inspiration. When the mushroom is inflated, it blocks the exhalation channel, allowing the lungs to be inflated. When the pressure inside the mushroom drops at the end of inspiration, it opens the channel and allows the exhaled gases to pass out of the exhalation channel. The flap valve prevents backflow of exhaled gases into the bag.

Mushroom-flap Valve

The valve illustrated in Figure 10.11 combines one mushroom and two flap valves. The inside of the mushroom is connected to a pressure channel. During inspiration, the mushroom is inflated against the seat, preventing flow of gas through the expiratory port and the inhalational flap opens. During exhalation, the inspiratory flap valve prevents flow back into the bag. The

mushroom collapses and opens the exhalation channel. A flap valve over the expiratory port prevents room air from being inhaled during spontaneous breathing.

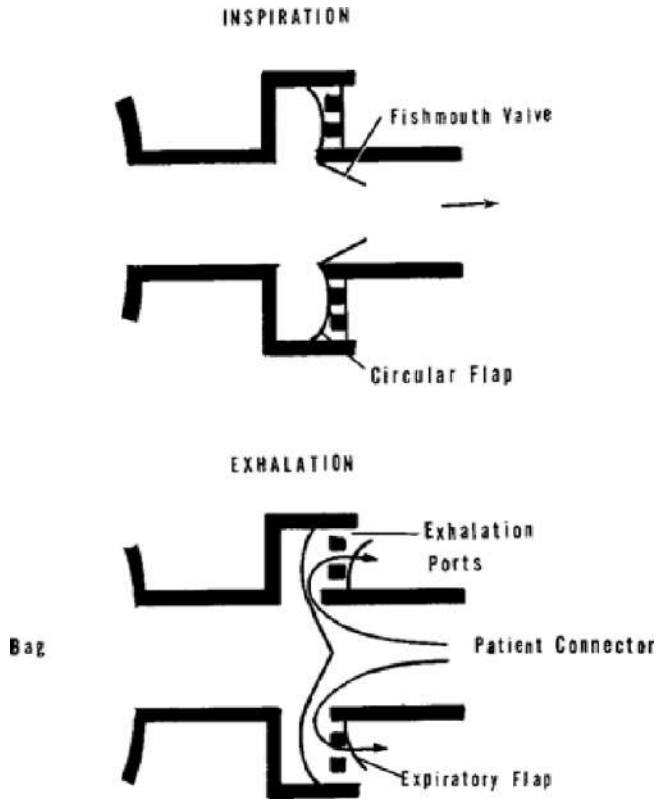

Figure 10.12 Fishmouth-flap nonrebreathing valve. The circular flap and fishmouth valves are attached, around the periphery. When the bag is squeezed, the flap valve is seated against the exhalation ports, and the fishmouth portion of the valve opens. During expiration, the fishmouth closes and the flap falls away from the exhalation channel. A second flap valve over the exhalation ports prevents air from being inspired during spontaneous respiration.

Fishmouth-flap Valve

The valve diagrammed in Figure 10.12 and pictured disassembled in Figure 10.13 has one fishmouth and two flap valves. The fishmouth and one circular flap valve are combined

into one piece. The flap valves surround the central fishmouth. Outside the main valve body is another circular flap valve. During inspiration, the fishmouth opens and the circular flap valve closes the exhalation port. The outside flap valve prevents room air from entering the valve during spontaneous breathing. During exhalation, the fishmouth section closes. The circular flap valve attached to it is lifted off the expiratory apertures, allowing exhaled gas to escape to atmosphere.

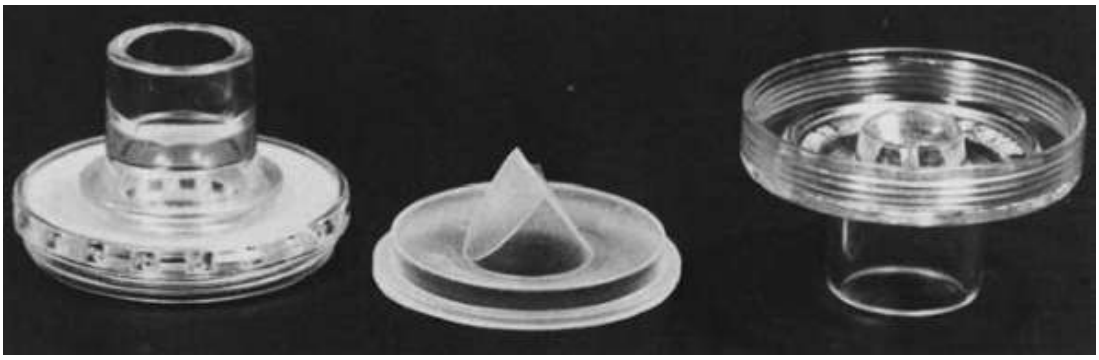

Figure 10.13 Components of the fishmouth-flap nonrebreathing valve. **Left:** The patient connection with the expiratory flap. **Center:** The fishmouth with its concentric flap. **Right:** The part of the housing closest to the bag.

Bag Inlet Valve

The bag inlet (refill) valve is a one-way valve that is opened by negative pressure inside the bag. When the bag is squeezed, the valve closes. This prevents escape of gas through the inlet. A simple flap (Figs. 10.2, 10.7) or spring-disc valve (Fig. 10.4) is most commonly used. This valve is usually located at the opposite end of the bag from the nonrebreathing valve but may be at the same end and may be combined with the nonrebreathing valve.

Pressure-limiting Device

The pressure-limiting device (pressure relief device, valve, or

system; overpressure limiting system; overpressure valve; pop-off valve; pressure limiting system) protects against barotrauma and may prevent gases from entering the stomach during manual ventilation (4).

A variety of devices have been used. One is a spring-loaded disc, with the tension on the spring adjusted so that it opens at the desired pressure. Another is a magnetic device, with the force of the magnet adjusted to open at the desired pressure. Some systems provide a small hole. The maximum pressure depends on the size of the hole and how firmly the bag is compressed. In order to override the device, it is usually necessary to place a finger over the outlet (Fig. 10.1). An override mechanism may cause confusion (5).

For adult resuscitators, the ASTM standard requires that if there is a device that limits the pressure to below 60 cm H_2O, there must be an override mechanism (2). If the override mechanism can be locked, it must be designed so that the operating mode (ON or OFF) is readily apparent to the user. It recommends that if a resuscitator is equipped with a pressure-limiting device, there should be an audible or visible warning to the operator when the pressure limiting device is operating. It also requires that with a pressure limiting device set at a fixed pressure, that pressure must be marked on the resuscitator.

The ASTM standard (2) requires a pressure-limiting system for infant and child resuscitators, with an opening pressure of 45 cm H_2O and an option for an override. The means that to create a higher inflation pressure is especially important in a resuscitator designed for infants, because the first few breaths may require pressures as high as 50 to 70 cm H_2O. The pressure needed to overcome flow resistance in a narrow tracheal tube and to expand the stiff lungs of a premature infant may exceed 30 to 40 cm H_2O. It is recommended that a manometer be used with neonatal resuscitation devices, because using these resuscitation devices can be associated with extremely high inspiratory pressures (6).

Oxygen-enrichment Device

Mechanisms to increase the inspired oxygen concentration above that of room air are present on nearly all resuscitation devices.

Oxygen Delivered Near the Bag Inlet Valve

Tubing from an oxygen flowmeter attached near the bag inlet valve is a simple means of increasing the concentration of oxygen in the bag. The oxygen does not enter the bag directly. The increase in oxygen concentration is limited because air can be drawn into the bag. The delivered oxygen concentration can be increased by increasing the oxygen flow, but this is of limited value. The higher the minute volume and the greater the inspiratory:expiratory (I:E) ratio, the lower the delivered oxygen concentration.

Oxygen Delivered Directly into the Bag

Oxygen can be delivered directly into the resuscitation bag. This method will result in high delivered oxygen concentrations without making the resuscitator cumbersome. However, provision must be made for venting excess oxygen to minimize the danger of the nonrebreathing valve locking in the inspiratory position. If the oxygen flow is less than the bag filling rate, the bag inlet valve will open and admit air.

Reservoir

Most units have a reservoir (accumulator) in which oxygen is stored when the bag is not filling. It may be a tube or a bag. When the resuscitation bag inlet valve opens, oxygen from the reservoir enters the bag. In general, resuscitators with reservoir bags provide a higher fraction of delivered oxygen than resuscitators with tubing reservoirs (7). The size of the reservoir may limit the oxygen concentration delivered. If the volume of the reservoir is less than that of the bag, the inflowing oxygen may not be sufficient to make up the difference, and room air will be drawn in. On the other hand, a large reservoir makes a resuscitator more cumbersome.

Open Reservoir

Open reservoirs are shown in Figures 10.14 (*left*) and 10.15. A piece of corrugated tubing or other material open to atmosphere is placed like a sleeve around the bag inlet valve. If the oxygen flow is high, oxygen will flow into atmosphere at the open end of the reservoir. If the oxygen flow is low or the reservoir is smaller than the tidal volume, air will be drawn into the bag along with

the oxygen. The highest possible concentration of oxygen will be administered if the reservoir is large and the oxygen flow is greater than the minute volume.

Figure 10.14 Left: A resuscitator with an open reservoir. **Right:** One with a closed reservoir.

Closed Reservoir

Closed reservoirs are shown in Figures 10.1, 10.14 (*right*), and 10.16. Each has an overflow valve that vents excess gases and an air intake valve that allows intake of ambient air if there is insufficient oxygen flow. A bag provides a visual indication of whether the reservoir is receiving sufficient oxygen. A deflated bag means that there is a problem with the oxygen supply or a hole in the bag.

Demand Valve

A demand valve connecting a compressed gas source to a self-expanding bag will consistently provide a high inspired oxygen concentration (8). A negative pressure in the bag triggers the flow of oxygen, which stops at a preset pressure. The demand valve may be manually activated with a push button.

Positive End-expiratory Pressure Device

A PEEP valve is available on some resuscitators and can be added to the expiratory port on others.

Scavenging Mechanism

A means for scavenging expired gases (Chapter 13) can be mounted on the expiratory port of some resuscitators.

Carbon Dioxide Detector

A manual resuscitator may have a built-in colorimetric carbon dioxide detector (7,9,10) (Chapter 22). A detector may also be attached.

Pressure Monitoring Port

A port for monitoring airway pressure is available on some manual resuscitators (11).

Functional Analysis

Respiratory Volumes

The minute volume will be determined by the tidal volume and respiratory rate. These will depend not only on resuscitator performance but also on the operator's skill. The volume delivered when the bag is compressed will vary with the size of the user's hand and whether one or two hands are used (12,13,14,15,16,17,18,19,20).

Tidal volume will be increased when a two-handed technique is used. Grip strength is the best predictor of delivered volumes and is more important when the tidal volume is delivered by a one-hand technique (20). Tidal volume may be increased by compressing the bag against a solid surface such as a thigh or the operating room table. Another method to increase the tidal volume is to compress the bag between the open palm and body

(21).

The respiratory rate may be limited by how fast the bag re-expands, which depends on the bag construction and the size of the bag refill valve inlet. The maximum compression rate may be reduced at low temperatures (13,22,23).

Delivered Oxygen Concentration

The ASTM standard (2) requires that a resuscitator for adults be capable of delivering an inspired oxygen concentration of at least 40% when connected to an oxygen

source supplying not more than 15 L/minute and at least 85% with an oxygen-enrichment device supplied by the manufacturer.

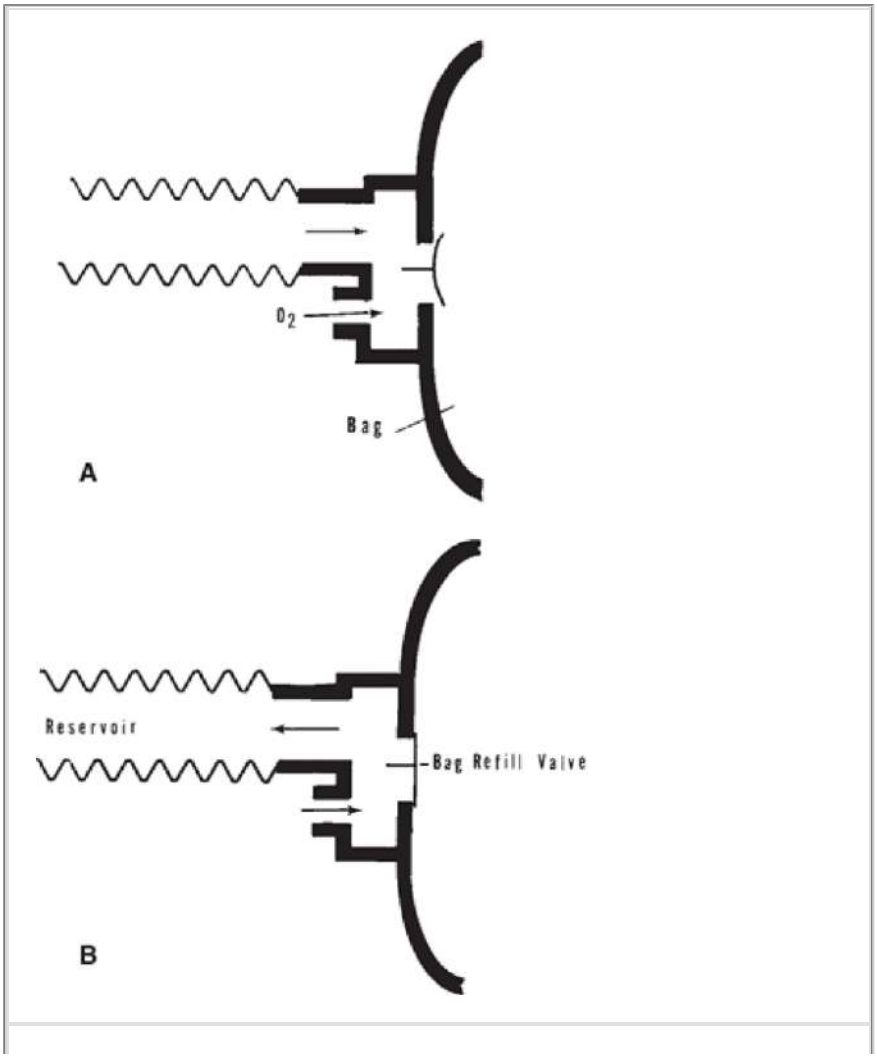

Figure 10.15 Open reservoir. **A:** The bag is filling. Oxygen from the delivery tubing as well as that in the reservoir flows into the bag. If the volume entering the bag exceeds that in the reservoir and flowing through the delivery tubing, room air will make up the difference. The size of the reservoir is, therefore, important. **B:** The bag inlet valve is closed. Oxygen from the delivery tubing flows into the reservoir. Because the reservoir is open to atmosphere, some oxygen will be lost if the flow is high.

The delivered oxygen concentration is limited by reservoir size and the oxygen flow (7). If the volume of the reservoir is greater than the volume of the bag and the oxygen flow is greater than the minute volume, the delivered oxygen concentration may approach 100%. If the tidal volume is greater than the reservoir volume plus the volume of oxygen delivered during inspiration, air will be drawn into the unit and reduce the delivered oxygen percentage (24).

Controlled Ventilation

The delivered oxygen concentration will be determined by the minute volume, the size of the reservoir (if present), the oxygen flow, and the technique used to squeeze and release the bag (25). If the bag is allowed to fill at its most rapid rate, all of the oxygen in the reservoir may be exhausted and air drawn in. If bag filling is manually retarded, the delivered oxygen concentration will be higher (8). This may be useful when low oxygen flows must be used or when the reservoir is small or not present, but it limits the respiratory rate that can be achieved. Furthermore, it may cause the nonrebreathing valve to jam in the inspiratory position. Activating the pressure-limiting device may cause the delivered oxygen concentration to decrease (26).

Spontaneous Ventilation

With spontaneous ventilation, inspired gas may come from the exhalation port as well as the bag. The inspired oxygen concentration can vary from 25% to 100% (24,27). Bags with fishmouth valves are associated with low inspired oxygen concentrations (24,28,29).

Rebreathing

If the nonrebreathing valve is competent, inhaled and exhaled gases should not mix. If the valve is incompetent, a back leak will allow exhaled gases to pass back into the resuscitator.

Use

A bag and mask that are the appropriate size for the patient should be selected. For adults, an oxygen flow of 10 to 15 L/minute is most commonly used. For children and infants, lower flows are recommended. Higher flows than those recommended by the manufacturer can result in significant levels of auto-PEEP (30).

If anesthetic gases are to be administered, the transfer tube (Chapter 13) from a scavenging system should be attached to the expiratory port.

A manual resuscitator can be adapted for manual ventilation during MRI by inserting an extension tube that is long enough to cover the distance between the patient and the person squeezing the bag between the nonrebreathing valve and the bag (1). An extension must not be placed between the patient and the nonrebreathing valve, as this will cause the dead space to be increased.

Hazards

High Airway Pressure

High airway pressure is a hazard mainly if the patient is intubated. A dangerously high pressure is less likely when a mask or supraglottic device is used.

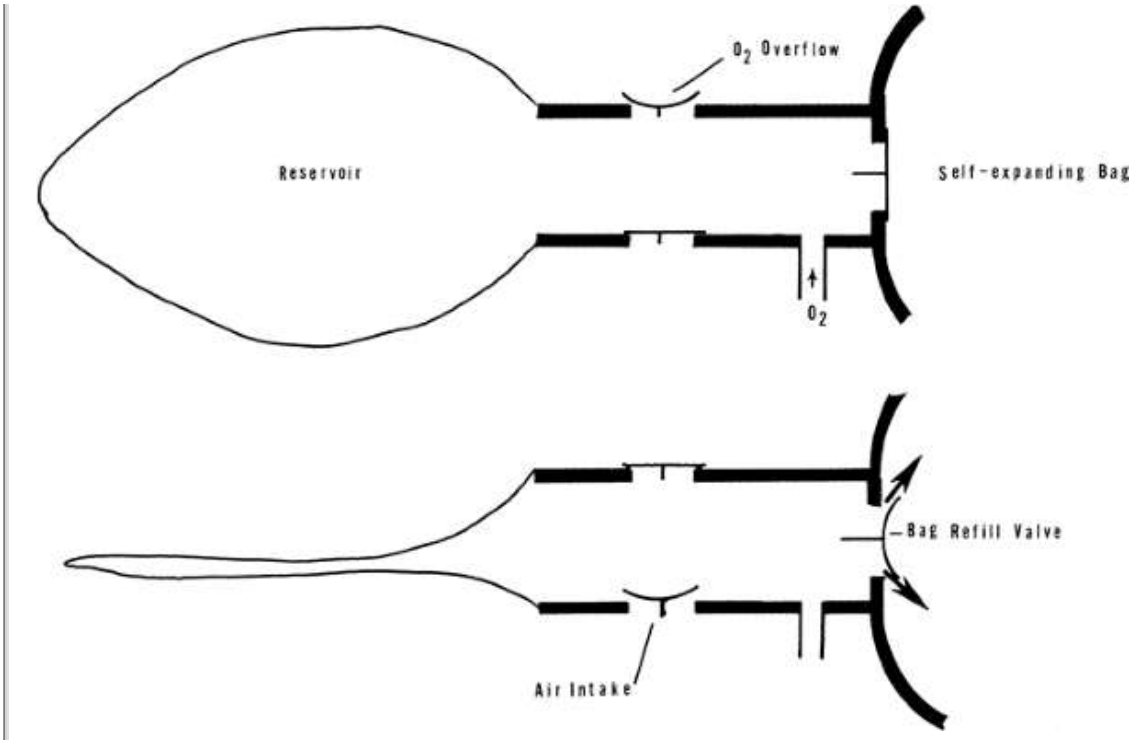

Figure 10.16 Closed reservoir. **Top:** The reservoir is full, and the pressure increases. Oxygen flows through the overflow valve. **B:** The resuscitator bag is filling. Because there is insufficient gas in the reservoir, air enters through the intake valve.

Nonrebreathing Valve Sticking in the Inspiratory Position

If the nonrebreathing valve sticks (locks up, jams) in the inspiratory position, the patient will be attempting to exhale against a closed outlet, and continued inflow will quickly cause a continuous and dangerous increase in pressure. A variety of other conditions can cause this, including interrupting manual ventilation for observation of spontaneous respiratory efforts, manually restricting bag refill, the valve becoming contaminated with foreign material, a small squeeze or bump on the bag causing the valve to lock up, coughing, improper assembly, attaching an oxygen inlet nipple without vent holes directly to the resuscitator, failure of the expiratory flap valve to open, and a kink in the reservoir tail (31,32,33,34,35,36,37,38,39,40,41).

High Oxygen Inflow

The ASTM resuscitator standard (2) requires that the valve not jam at an input flow of up to 30 L/minute. Infant resuscitators are especially prone to obstruction with high flows because the bag is so small. A case has been reported in which the pressure monitoring port was connected to an oxygen source (11). This distorted the inspiratory valve and resulted in excessive pressure.

Asynchrony between Patient Exhalation and the Demand Valve

Manually activating a demand valve while the patient is exhaling can cause dangerously high pressures (8).

Pressure-limiting Device Failure

Pressure-limiting devices often malfunction, opening well above an acceptable pressure (26,42,43).

Excessive Resistance

Resuscitators with high resistance can expose the patient with high expiratory flows to acute airway pressure elevations (44).

Rebreathing

Rebreathing exhaled gases can occur if the valve on the inspiratory limb from the bag is not competent or is improperly assembled (45,46). The fishmouth valve can become unseated, allowing rebreathing and/or insufficient pressure during inspiration (47). Extension tubing should not be added between the patient and the valve.

Hypoventilation

Studies show that it is more difficult to achieve satisfactory ventilation with a resuscitation bag and face mask

than with a supraglottic airway device or Combitube (48,49).

A defective nonrebreathing valve may have forward leak, so during inspiration part of the volume expelled from the bag escapes through the expiratory port (45,50,51). Unrecognized

venting through the pressure relief device may result in hypoventilation (52,53). If the fishmouth valve sticks or is absent, ventilation is not possible (53,54). The seal at the rear of the bag may not seat, allowing gas to exit (55). Hypoventilation can be caused by a disconnection or broken pieces on the resuscitator (56).

Pediatric bags will not provide adequate volumes when used with adults (57,58). Using an intermediate size bag may result in adequate ventilation with reduced risk of gastric inflation when using a face mask (59).

The operator is an important factor in determining the effectiveness of ventilation (60). Squeezing the bag may require considerable physical effort, and performance may deteriorate as the operator becomes fatigued. Operators with small hands may have difficulty delivering adequate tidal volumes. Squeezing the bag by using one hand instead of two tends to lower the delivered volume (12,17,18). Adequate tidal volumes are frequently not delivered when a mask is used unless two persons participate, one holding the mask and one squeezing the bag (15).

Because resuscitators are used away from the hospital, it is possible that they will be subjected to low temperatures. In this situation, the maximum cycling rate is often reduced, and the units may become inoperable or incapable of delivering satisfactory ventilation (61,62).

It may be possible to misassemble the resuscitator so that when the bag is squeezed, the contents are exhausted to atmosphere (45,63,64). The bag may become detached from the nonrebreathing valve (65).

If the pressure relief device is set incorrectly, it may open at a low pressure, causing hypoventilation (66,67). If a pediatric adaptor with a pressure relief device is present on an adult resuscitator, it will not allow adequate ventilation (53).

Decreased tidal volume may be seen with increased resistance or decreased compliance (12,18,68).

Low Delivered Oxygen Concentrations

Low delivered oxygen concentrations may be the result of insufficient oxygen flow, a detached or defective oxygen tubing,

or problems with the oxygen-enrichment device (7,25,69,70). A defect in the nonrebreathing valve may result in oxygen not flowing to the patient (71). The reservoir may be too small for the tidal volume. Low temperatures may result in low inspired oxygen concentrations being delivered (61).

During spontaneous ventilation, the patient may inhale room air from the expiratory port as well as oxygen-enriched gas from the bag. The inspired oxygen concentration can vary from 25% to 100% (24,27).

High Resistance

Some nonrebreathing valves offer high resistance to flow so that high negative pressures must be generated during spontaneous ventilation (24,27,44). The work of breathing may be quite high.

Contamination

Because these devices are often used on patients who have respiratory infections, they frequently become contaminated (72,73,74). Oxygen flowing through the valve may aerosolize bacteria and spread them into the surrounding air. For these reasons and because these devices are difficult to clean, disposable units have become popular. Bacterial/viral filters (Chapter 7) may be used.

Inhalation of Foreign Bodies

Part of the inside of the bag or parts of the nonrebreathing valve may break off and be inhaled (75,76).

Checking Manual Resuscitators

Before use, the resuscitation bag should be visually inspected for signs of wear such as cracks or tears. After the bag has been inspected, it should be checked for leaks. The patient port should be occluded and the bag squeezed. Pressure should build up rapidly to a point at which the bag can no longer be compressed. If there is a pressure limiting device, it can be checked by connecting a pressure manometer between the patient port and the bag by using a T-fitting. If there is an override mechanism on the pressure limiting device, this should be checked. This check also determines that the refill valve will close when the bag is squeezed.

To check that the bag refill valve opens, the bag should be squeezed, then the patient port occluded and the bag released. The bag should expand rapidly.

If the resuscitator has a closed reservoir, its function can be checked by performing several compression-release cycles with no oxygen flow into the reservoir. The reservoir should deflate, but the resuscitation bag should continue to expand.

A reservoir bag from a breathing system is placed over the patient port. Squeezing the resuscitation bag should cause the reservoir bag to inflate. After the reservoir bag has become fully inflated and the resuscitation bag has been released, the bag should deflate easily. This

tests the inspiration and exhalation parts of the valve and the exhalation pathway for patency. The reservoir bag should deflate easily.

Advantages

1. The equipment is inexpensive, compact, lightweight, and portable yet rugged.
2. The equipment is easy to use.
3. The equipment is simple with a small number of parts. Disassembly and reassembly are usually easily performed.
4. Dead space and rebreathing are minimal if the nonrebreathing valve functions properly.
5. With proper attention to the oxygen-enrichment device, oxygen flow, and ventilation technique, it is possible to administer close to 100% oxygen with most resuscitators.
6. During emergency situations in which a connection to a gas source is not readily available, the resuscitator can be used with room air until a source of oxygen becomes available.
7. The operator has some feel for pressures and volumes delivered. Barotrauma may be less likely with these devices than with gas-powered resuscitators, which do not allow the operator to sense when the patient's lungs are fully inflated.

Disadvantages

1. Some of the valves are noisy and stick, particularly when wet.
2. There may be considerable heat and humidity loss from the patient with prolonged use. Consideration should be given to using a heat and moisture exchanger with prolonged transport.
3. feel of the bag is different from that in other breathing systems. The user's hand must be re-educated.
4. The valve must be located at the patient's head. Its bulk may be troublesome, and its weight may cause the tracheal tube to kink or be displaced downward.
5. During infant resuscitation, manual resuscitators are unreliable as free-flowing oxygen delivery devices (77)

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Questions

For the following question, select the correct answer.

1. What determines the maximum minute volume delivered from a resuscitation device?

The rate of oxygen flow into the bag

The rate at which the bag reinflates

The size of the oxygen reservoir

The rate at which the bag is squeezed

View Answer

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

2. Measures that can increase the concentration of oxygen delivered from a resuscitation bag include

Increasing the oxygen flow

Low minute volume

Addition of a reservoir to the inlet

A lower I:E ratio

View Answer

3. Problems with delivering oxygen directly into the resuscitation bag include

Difficulty attaining high oxygen concentrations

Nonrebreathing valve locking in the inspiratory position

Excessive pressure

Inability to deliver adequate tidal volume because the flowmeter can only deliver up to 15 L/minute

View Answer

4. Characteristics of an open reservoir include

Oxygen flows into the reservoir during inspiration

If the tidal volume is high, air may be added to the gases entering the resuscitation bag

Oxygen enters the bag from the resevoir during exhalation

Ambient air can make up deficiencies in oxygen volume during inhalation

View Answer

5. Characteristics of the closed reservoir include

A valve to let in ambient air

A valve to vent excess gases from the reservoir

The presence of a bag

A valve to provide warning of excess oxygen pressure

View Answer

6. What minimum oxygen concentration must a resuscitation bag be capable of delivering?

Forty percent with up to 15 L/minute oxygen flow

One hundred percent if the reservoir is smaller than the tidal volume

Eighty-five percent with the addition of a reservoir

Ninety percent if the reservoir is larger than the tidal volume

View Answer

7. Benefits of manually restricting refill of the resuscitation bag include

A lower flow of oxygen may be used

A reservoir may not be needed to deliver high oxygen concentrations

Higher oxygen concentration will be delivered

Higher minute volume can be achieved

View Answer

8. Situations that can result in high airway pressure include

Nonrebreathing valve sticking in the expiratory position

High oxygen inflow

Kinking of the reservoir tail

Use of a demand valve as the patient exhales

View Answer

9. Causes of hypoventilation when using a manual resuscitator include

Incomplete closure of the expiratory port

Low temperature

Venting through the pressure relief device

No auxiliary air intake

View Answer

10. The ASTM standard on resuscitators includes the following provisions concerning pressure limiting devices:

In adults, if the override mechanism can be locked, it must be designed so that the operating mode is readily apparent to the user

For infant and child resuscitators, a device with an opening pressure of 45 cm H_2O

Optional override for infant and child resuscitators

For adults, a device with an opening pressure of 50 cm H_2O

View Answer

11. Hazards associated with use of a manual resuscitator include

Barotrauma

Inhalation of foreign substances

Delivery of low oxygen concentrations

Hyperventilation

View Answer

12. What techniques are useful to increase the tidal volume delivered from a manual resuscitator?

Two-handed technique

Slowed bag expansion

Compression against a solid surface

Using the resuscitator at low temperatures

View Answer

13. Which of the following are associated with retarding resuscitating bag expansion?

Increased minute volume

Decreased respiratory rate

Activation of the pressure limiting device may increase the inspired oxygen concentration

The nonrebreathing valve may jam

View Answer

14. Concerning spontaneous respiration through a manual resuscitator,

A wide variation in oxygen concentration may occur

Fishmouth valves are associated with a higher inspired oxygen concentration

Room air may be inspired through the exhalation port

The bag inlet valve will jam

View Answer

15. A decreased inspired oxygen concentration may be caused by

A small reservoir

Low temperature

A valve defect

Spontaneous ventilation

View Answer

Chapter 11
Humidification Equipment

General Considerations

Terminology

Humidity is a general term used to describe the amount of water vapor in a gas. It may be expressed several ways.

Absolute Humidity

Absolute humidity is the mass of water vapor present in a volume of gas. It is commonly expressed in milligrams of water per liter of gas.

Humidity at Saturation

The maximum amount of water vapor that a volume of gas can hold is the humidity at saturation. This will vary

with the temperature. The warmer the temperature, the more water vapor can be held in a gas. Table 11.1 shows the absolute humidity of saturated gas at various temperatures. At a body temperature of 37ยฐC, it is 44 mg H_2O/L.

TABLE 11.1 Water Vapor Pressure and Absolute Humidity in Moisture-saturated Gas

Temperature ยฐC	mg H_2O/L	mm Hg
0	4.84	4.58
1	5.19	4.93
2	5.56	5.29
3	5.95	5.69
4	6.36	6.10
5	6.80	6.54

6	7.26	7.01
7	7.75	7.51
8	8.27	8.05
9	8.81	8.61
10	9.40	9.21
11	10.01	9.84
12	10.66	10.52
13	11.33	11.23
14	12.07	11.99
15	12.82	12.79
16	13.62	13.63
17	14.47	14.53
18	15.35	15.48
19	16.30	16.48
20	17.28	17.54
21	18.33	18.65
22	19.41	19.83
23	20.57	21.07
24	21.76	22.38
25	23.04	23.76

26	24.35	25.21
27	25.75	26.74
28	27.19	28.35
29	28.74	30.04
30	30.32	31.82
31	32.01	33.70
32	33.79	35.66
33	35.59	37.73
34	37.54	39.90
35	39.57	42.18
36	41.53	44.56
37	43.85	47.07
38	46.16	49.69
39	48.58	52.44
40	51.03	55.32
41	53.66	58.34
42	56.40	61.50

Relative Humidity

Relative humidity, or percent saturation, is the amount of water vapor at a particular temperature expressed as a percentage of

the amount that would be held if the gas were saturated.

Water Vapor Pressure

Humidity may also be expressed as the pressure exerted by water vapor in a gas mixture. Table 11.1 shows the vapor pressure of water in saturated gas at various temperatures.

Inter-relationships

If a gas saturated with water vapor is heated, its capacity to hold moisture increases and it becomes unsaturated (has <100% relative humidity). Its absolute humidity remains unchanged. Gas that is 100% saturated at room temperature and warmed to body temperature without additional humidity will absorb water by evaporation from the surface of the respiratory tract mucosa until it becomes saturated.

If gas saturated with water vapor is cooled, it will condense (rain out) water. The absolute humidity will fall, but the relative humidity will remain at 100%.

If inspired gas is to have a relative humidity of 100% at body temperature, it must be maintained at body temperature after leaving the humidifier or heated above body temperature at the humidifier and allowed to cool as it flows to the patient. Cooling will result in condensation (rain out) in the breathing system.

The specific heat of gas is low. As a consequence, it quickly assumes the temperature of the surrounding environment. Inhaled gases quickly approach body temperature, and gases in corrugated tubes rapidly approach room temperature.

The heat of vaporization of water is relatively high. Evaporation of water, therefore, requires considerably more heat than warming of gases. Likewise, condensation of water yields more heat than cooling of gases.

Considerations for Anesthesia

Water is intentionally removed from medical gases so that gases delivered from the anesthesia machine are dry and at room temperature. As gases flow to the alveoli, inspired gas is brought to body temperature (either by heating or cooling) and 100% relative humidity (either by evaporation or condensation). In the unintubated patient, the upper respiratory tract (especially the nose) functions as the principal heat and moisture exchanger (HME). During normal nasal breathing, the temperature in the upper trachea is between 30ยฐC and 33ยฐC, with a

relative humidity of approximately 98%, providing a water content of 33 mg/L (1).

Tracheal tubes and supraglottic airway devices bypass the upper airway, modifying the pattern of heat and moisture exchange so that the tracheobronchial mucosa must assume a greater role in heating and humidifying gases.

Effects of Inhaling Dry Gases

The importance of humidification in anesthesia remains uncertain. It is of greatest benefit in pediatric patients, patients at increased risk for developing pulmonary complications, and long procedures.

Damage to the Respiratory Tract

As the respiratory mucosa dries and its temperature drops, secretions thicken, ciliary function is reduced, surfactant activity is impaired, and the mucosa becomes more susceptible to injury (2,3). If secretions are not cleared, atelectasis or airway obstruction can result. Thickened plugs may provide loci for infection. Dry gases can cause bronchoconstriction, further compromising respiratory function. Humidifying gases may decrease the incidence of respiratory complications (coughing and breath holding) associated with an inhalation induction (4,5).

There is no agreement about the minimum humidity necessary to prevent pathological changes. Recommendations have ranged from 12 to 44 mg H_2O/L absolute humidity (2,3,6,7,8,9). The duration of exposure is important. It is unlikely that a brief exposure to dry gases will damage the tracheobronchial tree. As time increases, the likelihood that significant tracheobronchial damage will become greater.

Body Heat Loss

Body temperature is lowered as the airways bring the inspired gas into thermal equilibrium and saturate it with water. The use of a humidification device can decrease the heat loss that occurs during anesthesia and may provide some heat input (10,11,12,13,14,15,16,17). Controlling inspired gas temperature and humidity is not an efficient method of maintaining body temperature. Means to increase body temperature are discussed in Chapter 31.

Absorbent Desiccation

The effects of dry absorbent on the composition of inspired

gases are discussed in Chapter 9. While HMEs preserve patient heat and humidity, they also may contribute to absorbent desiccation (18).

Tracheal Tube Obstruction

Thickened secretions in a tracheal tube increase its resistance and can result in complete obstruction (19,20,21,22,23,24).

Consequences of Excessive Humidity

An increased water load can cause ciliary degeneration and paralysis, pulmonary edema, altered alveolar-arterial oxygen gradient, decreased vital capacity and compliance, and a decrease in hematocrit and serum sodium (25).

Sources of Humidity

Carbon Dioxide Absorbent

The reaction of absorbent with carbon dioxide liberates water (Chapter 9). Water is also contained in the absorbent granules. Since the reaction is exothermic, heat is produced. If the absorbent granules desiccate, they may react with certain anesthetics and produce extreme heat. This is discussed in detail in Chapter 9.

Exhaled Gases

There is some rebreathing in the tracheal tube, the supraglottic airway device, and the connections to the breathing system. Almost half of the humidity in expired gas is preserved in this manner (26).

In systems that allow rebreathing of exhaled gases (Chapter 8), the humidity and temperature of the inspired gases depend on the relative proportions of fresh and expired gases. This will depend on the system and the fresh gas flow. As the fresh gas flow is increased, the inspired temperature and humidity are reduced. Use of the system by a previous patient will increase the humidity.

Moistening the Breathing Tubes and Reservoir Bag

Rinsing the inside of the breathing tubes and reservoir bag with water before use increases the inspired humidity (27).

Low Fresh Gas Flows

Using low fresh gas flows with a circle breathing system will conserve moisture. This is discussed in more detail in Chapter 9.

Coaxial Breathing Circuits

Coaxial circle systems, when combined with low flows, will increase the humidity more quickly than a system with two separate limbs (2), but this is not very efficient in terms of heat or humidity improvement (28).

The Bain system (see Chapter 8) is a coaxial version of the Mapleson D. It does not meet optimal

humidification requirements because of the high fresh gas flow required (26).

Heat and Moisture Exchangers

An HME conserves some exhaled water and heat and returns them to the patient in the inspired gas. Many HMEs also perform bacterial/viral filtration and prevent inhalation of small particles. The HME is also known as a condenser humidifier, Swedish nose, artificial nose, nose humidifier, passive humidifier, regenerative humidifier, moisture exchanger, and vapor condenser. When combined with a filter for bacteria and viruses, it is called a *heat and moisture exchanging filter* (HMEF).

Two international standards on HMEs have been published (29,30).

Description

HMEs are disposable devices with the exchanging medium enclosed in a plastic housing. They vary in size and shape. Typical ones are shown in Figure 11.1. Each has a 15-mm female connection port at the patient end and a 15-mm male port at the other end. The patient port may also have a concentric 22-mm male fitting (Fig.11.1C,D). There may be a port to attach the gas sampling line for a respiratory gas monitor (Fig. 11.1B,D) or an oxygen line. One type utilizes a ceramic heating element with a water input port, a membrane, and an aluminum grid that vaporizes the water (31).

The dead space of HMEs varies. Pediatric and neonatal HMEs with low dead space are available (32,33). Most modern HMEs are one of two types, as shown in Table 11.2.

Hydrophobic

Hydrophobic HMEs have a hydrophobic membrane with small

pores. The membrane is pleated to increase the surface area. A pleated hydrophobic membrane provides moderately good inspired humidity. The performance of this type of HME may be impaired by high ambient temperatures (1,21).

Hydrophobic HMEs are efficient bacterial and viral filters (34,35,36,37,38,39). A pleated hydrophobic filter will consistently prevent the hepatitis C virus from passing while a hygroscopic filter may be ineffective (40). They allow the passage of water vapor but not liquid water at usual ventilatory pressures (34,36). They are associated with small increases in resistance even when wet (12,41,42).

Hygroscopic

Hygroscopic HMEs contain a wool, foam, or paperlike material coated with moisture-retaining chemicals. The medium may be impregnated with a bactericide (43). Composite hygroscopic HMEs consist of a hygroscopic layer plus a layer of thin, nonwoven fiber membrane that has been subjected to an electrical field to increase its polarity. This improves filtration efficiency and hydrophobicity.

Most studies have shown that composite hygroscopic HMEs are more efficient at moisture and temperature conservation than hydrophobic ones (1,22,44,45,46,47,48,49,50,51,52,53). They will lose their airborne filtration efficiency if they become wet, and microorganisms held by the filter medium can be washed through the device. Their resistance can increase greatly when they become wet (42).

Indications

An HME can be used to increase inspired heat and humidity during both short- and long-term ventilation. HMEs may be especially useful when transporting intubated patients, because transport ventilators frequently have no means for humidifying inspired gases.

An HME can be used to supply supplemental oxygen to an intubated patient or patient with a supraglottic airway by connecting oxygen tubing to the gas sampling port (54,55,56).

Contraindications

Contraindications include patients with thick, copious, or bloody secretions and patients with a leak that prevents exhaled gas from traversing the passive humidifier (e.g., bronchopleuralcutaneous fistula or leaking or absent tracheal tube cuff). HMEs should be used with caution when weaning a

patient from respiratory support (57,58).

Factors Affecting Moisture Output

Heat and Moisture Exchanger Type

Composite hygroscopic HMEs have better heat and moisture exchanging properties than do hydrophobic ones.

Initial Humidity

Increasing the humidity in the gas entering the HME from the breathing system will increase the inspired humidity (59).

Inspiratory and Expiratory Flows

The faster that gas passes through the HME, the less time there is to evaporate or deposit moisture, so a large tidal volume may cause the humidity of the inspired gas to fall (45,48,59,60,61).

System Continuity

A leak around the tracheal tube will result in decreased inspired humidity (32,62).

Use

The HME selected should be of an appropriate size for the patient's tidal volume. If a small HME is used in a large patient, the HME will be inefficient (63). Connecting more than one HME in series will improve performance (64,65). Care must be taken that the units are pushed firmly together and that the increase in dead space is not

excessive for that particular patient. Added dead space is especially important in small patients.

Figure 11.1 Heat and moisture exchangers. **A,E:** Straight variety. **B:** Right angle HME with port for aspiration of respiratory gases on the breathing system side. **C:** The flexible tube attached to the HME extends the distance between the patient and the breathing system and allows the angle between the breathing system and the patient to be altered. Because this HME has significant dead space, it should be used only with high tidal volumes and controlled ventilation with monitoring of inspired and exhaled carbon dioxide. **D:** Hydrophobic HME with respiratory gas aspiration port. (Pictures C, D, and E courtesy of Gibeck Respiration, Pall Biomedical Products Corp. and ARC Medical Inc.)

An HME should be visible and accessible at all times in order to detect contamination or disconnection. The greatest inspired relative humidity occurs with the HME positioned next to the tracheal tube, mask, or supraglottic airway device. Some gas monitors (Chapter 22) are particularly sensitive to water. If the sampling line is on the machine side of the HME, the amount of moisture to which the monitor is exposed will be reduced.

An HME can be used with any breathing system. With the Mapleson systems, dead space can be reduced by

utilizing the gas sampling port as the fresh gas inlet (66). Oxygen can be administered through the gas sample port on the HME (55,56). An HME may be used for patients who have a tracheostomy (67).

TABLE 11.2 Comparison of Hygroscopic and Hydrophobic Heat and Moisture Exchangers

Type	*Hygroscopic*	*Hydrophobic*
Heat and moisture exchanging efficiency	Excellent	Good
Effect of increased tidal volume on heat and moisture exchange	Slight decrease	Significant decrease
Filtration efficiency when dry	Good	Excellent
Filtration efficiency when wet	Poor	Excellent
Resistance when dry	Low	Low
Resistance when wet	Significantly increased	Slightly increased
Effect of nebulized medications	Greatly increased resistance	Little effect

An HME may be used as the sole source of humidity or may be combined with another source such as an unheated humidifier (68) but should not be used with a heated humidifier.

If a nebulizer or metered-dose inhaler (Chapter 7) is used to deliver medication, it should be inserted between the HME and the patient or the HME removed from the circuit during aerosol treatment.

An HME should be replaced if contaminated with secretions.

Advantages

HMEs are inexpensive, easy to use, small, lightweight, reliable, simple in design, and silent in operation. They have low resistance when dry. They do not require water, an external source of energy, a temperature monitor, or alarms. There is no danger of overhydration, hyperthermia, skin or respiratory tract burns, or electrical shock. Their use may increase the correlation between esophageal and core temperatures (69). They act as a barrier to large particles, and some are efficient bacterial and viral filters, although their role in reducing nosocomial infections remains controversial. They may reduce problems caused by humidity in the breathing system such as obstruction of lines and ventilator mal-function (70).

Disadvantages

The main disadvantage of HMEs is the limited humidity that these devices can deliver. Their contribution to temperature preservation is not significant. Temperature management is discussed in Chapter 31. Active heating and humidification are more effective than an HME in retaining body heat, alleviating thick secretions, and preventing tracheal tube blockage (19,21,22,23,71,72,73,74,75). The difference is more apparent after intubation lasting for several days.

Placing an HME between the breathing system and the patient increases dead space. This may necessitate an increase in tidal volume and can lead to dangerous rebreathing (76). It also increases the work of breathing during both inspiration and exhalation (77).

Hazards

Excessive Resistance

The use of an HME increases resistance, although usually it is

not a major component of the total work of breathing (78). Resistance increases with use (9,33,35,38,58,78,79,80,81,82,83,84,85,86). Heavy viscous secretions can greatly increase resistance. An HME should not be used with a heated humidifier, as this can cause a dangerous increase in resistance. Nebulized medication increases the resistance of hygroscopic HMEs (34,38).

With a Mapleson system, increased resistance may cause diversion of fresh gas down the expiratory limb (87,88,89).

High resistance may result in sufficient back pressure to prevent the low airway pressure alarm from being activated if there is a disconnection between the patient and the HME (90,91).

If increased resistance is suspected during controlled ventilation, the peak pressure should be measured with and without the HME in place. Spontaneously breathing patients should be observed for signs of increased work of breathing.

Airway Obstruction

An HME can become obstructed by fluid, blood, secretions, a manufacturing defect, or nebulized drugs (18,92,93,94,95,96,97,98,99,100,101,102). Parts may become detached and block the breathing system (103). The HME's weight may cause the tracheal tube to kink.

If an HME is used for long-term ventilation, tracheal tube occlusion may occur (20,21,22,23,24,73).

Inefficient Filtration

Liquid can break through a hygroscopic HME, resulting in poor filtration (34,36).

Foreign Particle Aspiration

Parts of the HME may become detached (64,104,105,106,107). The parts may then be inhaled by the patient.

Rebreathing

The HME dead space may cause excessive rebreathing, especially with small tidal volumes. Special low-volume devices are available for pediatrics. Even these small devices may be too large for infants under 15 kg (108). HMEs should not be used for mask ventilation in small infants (109).

Leaks and Disconnections

Adding an HME to a breathing system increases the potential for disconnections and leaks (18,92,110,111,112).

Hypothermia

Patient warming is discussed in Chapter 31. HMEs are a means to conserve temperature, but the amount of heat preserved by this method is small (15,113,114,115).

Dry Carbon Dioxide Absorbent

HMEs will decrease the amount of humidity available to the absorbent. The extent to which HMEs will lead to absorbent desiccation is unclear. The effect of dry carbon dioxide absorbents on the production of Compound A and carbon monoxide is discussed in Chapter 9. In addition, dry absorbent will absorb some volatile agents. This can impede anesthetic induction with these agents (18).

Humidifiers

A humidifier (vaporizer or vaporizing humidifier) passes a stream of gas over water (pass-over), across wicks dipped in water (blow-by), or through water (bubble or cascade). Humidifiers may be heated or unheated.

Unheated

Most unheated humidifiers are disposable, bubble-through devices that are used to increase the humidity in oxygen supplied to patients via a face mask or nasal cannula. They cannot deliver more than about 9 mg H_2O/L.

Heated

Heated humidifiers incorporate a device to warm the water in the humidifier. Some also heat the inspiratory tube.

Description

Humidification Chamber

The humidification chamber contains the liquid water. It may be disposable or reusable. A clear chamber makes it easy to check the water level. Some humidifiers have an integral or remote reservoir that supplies liquid water to the humidification chamber (Fig. 11.2).

Heat Source

Heat may be supplied by heated rods immersed in the water or a plate at the bottom of the humidification chamber (Fig. 11.3).

Inspiratory Tube

The inspiratory tube conveys humidified gas from the humidifier outlet to the patient. If it is not heated, the gas will cool and lose some of its moisture as it travels to the patient. This water will collect in the inspiratory tubing. A water trap will be necessary to collect the condensed water.

Heating or insulating the inspiratory tube allows more precise control of the temperature and humidity delivered to the patient and avoids moisture rainout (116,117). A heated wire inside the inspiratory tubing is most often used (Fig. 11.3). It should extend as close to the patient connection as possible. Disposable wires in preassembled disposable breathing systems are available. A reusable wire must be inserted manually into the inspiratory tube by using a draw wire (118). If the gas temperature delivered to the patient is set above the temperature of the humidification chamber outlet, less than 100% relative humidity will be delivered (119,120,121,122).

Temperature Monitor(s)

Most heated humidifiers have a means to measure the gas temperature at the patient end of the breathing system. Usually, there are temperature sensors in the water reservoir or in contact with the heater plate to activate alarms and shut off heater power when necessary.

Thermostat

Servo-controlled Units

A servo-controlled unit automatically regulates power to the heating element in the humidifier in response to the temperature sensed by a probe near the patient connection or the humidifier outlet (123,124,125). These devices are equipped with alarms to warn of high temperature. Often, there are two thermostats so that if one fails, the other will cut off the power before a dangerous temperature is reached.

Nonservo-controlled Units

A nonservo-controlled unit provides power to the heating element according to the setting of a control, irrespective of the delivered temperature. It may include a servo-controlled circuit, but the

servo-controlled unit controls the heater rather than the delivered temperature (123,125).

Controls

Most humidifiers allow temperature selection at the end of the delivery tube or at the humidification chamber outlet. Some allow less than 100% relative humidity to be delivered. Some models generate saturated vapor only at a preset temperature (8).

Alarms

Alarms may warn when the temperature at the patient end of the circuit deviates from the set temperature by a fixed amount, when the temperature probe is not in place, when the heater wire is not connected, when the water level in the humidification chamber is low, or when the airway temperature probe does not sense an increase in temperature within a certain time after the humidifier is turned ON. A low temperature alarm will help to detect problems with the heater element. It

also may be the means of detecting lack of gas flow in the circuit (126).

Figure 11.2 Heated humidifier with separate water reservoir. (Picture courtesy of Hudson RCI.)

Action

Some humidifiers heat the gas to a temperature exceeding the desired patient airway temperature (superheating) so that the cooling that occurs as it flows to the patient will result in the desired temperature at the patient connection. Cooling in the tube will result in water raining out in the tube. In other humidifiers, temperature increases as it passes through the inspiratory tube so that gas with less than 100% relative humidity is delivered.

Figure 11.3 Heated humidifier. Heat is supplied from a heated plate below the humidification chamber. The heating wire at the left fits inside the delivery tube.

If the delivery tube is not heated, the temperature will drop as it flows to the patient. The magnitude of the drop depends on many factors, including ambient temperature; gas flow; and the length, diameter, and thermal mass of the breathing system. Cooling can be reduced by shortening or insulating the delivery tube or by using higher inspiratory flows. If the gas is saturated at the humidifier outlet, the temperature drop will cause water vapor condensation (rainout) to occur. A water trap will be necessary to collect the condensed water.

Standard Requirements

An international and a U.S. standard on humidifiers have been published (127,128). They contain the following provisions.

1. Humidifiers must be capable of producing an output of at least 10 mg H_2O/L. Those intended for use with patients whose supraglottic airways have been bypassed must be capable of producing an output of at least 33 mg H_2O/L.
2. The average temperature at the delivery tube outlet shall not fluctuate by more than 2ยฐC from the set temperature after a state of thermal equilibrium has been established following a change in gas flow or set temperature. If the

measured gas temperature differs from the set temperature by more than the range specified by the manufacturer, an alarm must be activated.

3. The volume of liquid exiting the humidifier shall not exceed 1 mL/minute or 20 mL/hour for humidifiers intended for use with neonates or 5 mL/minute or 20 mL/hour for all other humidifiers.
4. If the humidifier is heated, the gas temperature at the delivery tube outlet shall not exceed 41ยฐC or the gas temperature at the humidifier outlet shall be indicated continuously and the temperature-measuring device shall activate an alarm when the temperature exceeds 41ยฐC. The humidifier shall interrupt heating when the measured gas temperature exceeds 41ยฐC.
5. The accessible surface temperature of the delivery tube must not exceed 44ยฐC within 25 cm of the patient connection port.
6. When the humidifier is tilted 20ยฐ from its normal operating position, there shall be no water spilled into the breathing system.
7. All calibrated controls and indicators shall be accurate to within 5% of their full-scale values, except for temperature displays and controls. The measured gas temperature shall be accurate to ยฑ2ยฐC.
8. The direction of flow must be marked on humidifiers with flow-directionโ€“sensitive components.

Use

In the circle system, a heated humidifier is placed in the inspiratory limb downstream of the unidirectional valve by using an accessory breathing tube. A heated humidifier must not be placed in the expiratory limb (129,130). If a filter is used in the breathing system, it must be placed upstream of the humidifier to prevent it from becoming clogged.

In Mapleson systems (Chapter 8), the humidifier is usually placed in the fresh gas supply tube (131,132). Using a large-diameter tubing and placing the humidifier near the end of the tube will decrease condensation. The delivery tube temperature probe may be placed either between the fresh gas supply tube and the T-piece or between the T-piece and the patient.

The humidifier must be lower than the patient to avoid the risk of

water running down the tubing into the patient. The condensate must be drained periodically or a water trap inserted in the most dependent part of the tubing to prevent blockage or aspiration.

The heater wire in the delivery tube should not be bunched, but strung evenly along the length of the tube. The delivery tube should not rest on other surfaces or be covered with sheets, blankets, or other materials. A boom arm or tube tree may be used for support (133).

Advantages

Most heated humidifiers are capable of delivering saturated gas at body temperature or above, even with high flow rates. A heated humidifier can produce more effective humidification than an HME (74,134). Some (but not all) can be used for spontaneously breathing and tracheotomized patients (67).

Disadvantages

Humidifiers are bulky and somewhat complex. These devices involve high maintenance costs, electrical hazards, and increased work (temperature control, refilling the reservoir, draining condensate, cleaning, and sterilization). Their use is associated with higher costs than HMEs.

Compared with circulating water and forced-air warming (Chapter 31), the heated humidifier offers relatively little protection against heat loss during anesthesia (135).

Hazards

Infection

Bacterial growth can occur in water stored in a reservoir or the condensate in the delivery tube. The use of a heated circuit reduces the amount of condensate, which may reduce the infection risk.

Breathing System Problems

Reported breathing system problems include sticking valves, leaks, disconnections, incorrect connections, obstructed fresh gas line or inspiratory limb, noise, and clogged filters and HMEs (136,137,138,139,140,141).

The delivery tubing may melt, resulting in an obstruction or leak (118,142,143,144,145,146,147,148,149,150). Fires have been reported (123,151,152). A charred breathing system may result in fumes entering the patient's lungs. Overheating of breathing

circuits with melting may be caused by defects in or damage to the heated wire; bunching of the heated-wire coils within the breathing system; electrical incompatibility between the heated-wire breathing circuit and the humidifier (153); operating the device outside the specified range of flows or minute volumes; or covering the delivery tube with sheets, blankets, or other materials (133,144,147). Problems may occur if a circuit that is not from the humidifier manufacturer is used. Electrical connectors for heated-wire circuits that are physically compatible may not be electrically interchangeable (133). When ventilation is interrupted, as when cardiac bypass is begun, the humidifier should be turned OFF. Without a gas air flow, the temperature at the patient end will drop and the heating element may increase its output, causing the attached breathing circuit to melt.

Adding a humidifier may change the breathing system volume and compliance significantly (154). This can result in less accurate small tidal volume delivery. Ventilators that calculate the system compliance and gas compression must perform their checkout procedure with the humidifier in place since the humidifier can affect ventilator accuracy.

Water Aspiration

There is danger of liquid water entering the trachea and drowning the patient or causing a burn in the respiratory tract. These risks can be decreased by installing a water trap in both the inspiratory and exhalation sides in the most dependent portion of the breathing tube, draining condensate frequently, and placing the humidifier and breathing tubes below the patient.

Overhydration

A heated humidifier can produce a positive water balance and even overhydration. Although most anesthetics are of sufficiently short duration that this is not a significant problem, it can be a problem with infants.

Thermal Injury

Delivering overheated gases into the trachea can cause hyperthermia or damage to the tissues lining the tracheobronchial tree. Skin burns have been reported from administering heated oxygen nasally and when continuous positive airway pressure was delivered (125,155,156). Burns can also occur when tissue is in contact with heated breathing circuits (157,158).

Overheating inspired gas may be caused by omitting, misplacing, dislodging, or not fully inserting the airway temperature probe or by turning the humidifier ON with a low gas flow (123,155,156,159). A temporary increase in inspired gas temperature may occur following a period of interrupted flow or an increased flow rate (160).

Increased Work of Breathing

A heated humidifier increases resistance (26,161,162). Most cannot be used with spontaneously breathing patients.

Monitoring Interference

A humidifier may add enough resistance to prevent a low airway pressure alarm from being activated if the sensor is upstream of the humidifier (91). Some flow sensors are affected by condensation, producing a false positive alarm (163). Pressure and flow monitoring are discussed in Chapter 23.

High humidity can cause problems with sidestream (aspirating) respiratory gas monitors (Chapter 22).

Altered Anesthetic Agents

Halothane may be altered if it passes through a humidifier whose heating element is in direct contact with the gas at a temperature of 68ยฐC or higher (164).

Equipment Damage or Malfunction

Ventilators are sensitive to rainout caused by water condensation. Signs include increased resistance to exhalation, inaccurate pressure and volume measurements, autocycling, and ventilator shutdown (70,165). In order to prevent these problems, a water trap should be used if water is likely to condense in the breathing system. These need to be inspected regularly and emptied as needed. The humidifier needs to be lower than the patient and ventilator.

Nebulizers

Description

A nebulizer (aerosol generator, atomizer, nebulizing humidifier) emits water in the form of an aerosol mist (water vapor plus particulate water) (166). The most commonly used are the pneumatically driven (gas-driven, jet, high pressure, compressed gas) and ultrasonic nebulizers. Both can be heated. In addition to providing humidification, nebulizers may be used to deliver

drugs to the breathing system.

A pneumatic nebulizer works by pushing a jet of high-pressure gas into a liquid, inducing shearing forces and breaking the water up into fine particles. An ultrasonic nebulizer produces a fine mist by subjecting the liquid to a high-frequency, electrically driven ultrasonic resonator. The frequency of oscillation determines the size of the droplets. There is no need for a driving gas. Ultrasonic nebulizers create a denser mist than pneumatic ones (124).

Use

Because a high flow of gas must be used with a pneumatic nebulizer, it should be placed in the fresh gas line. An ultrasonic nebulizer can be used in the fresh gas line or the inspiratory limb.

Hazards

Nebulized drugs may obstruct an HME or filter in the breathing system (95,96,167). Overhydation can occur. If the droplets are not warmed, hypothermia may result. Infection can be transmitted because microorganisms can be suspended in the water droplets.

There are reported cases where a nebulizer was connected directly to a tracheal tube without provision for exhalation (168). In one case, this resulted in a pneumothorax.

Advantages

Nebulizers can deliver gases saturated with water without heat and, if desired, can produce gases carrying more water.

Disadvantages

Nebulizers are somewhat costly. Pneumatic nebulizers require high gas flows. Ultrasonic nebulizers require a source of electricity and may present electrical hazards. There may be considerable water deposition in the tubings, requiring frequent draining, water traps in both the inspiratory and exhalation tubes, and posing the dangers of water draining into the patient or blocking the tubing.

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Questions

For the following questions, select the correct answer.

1. Which is not an effect of inhaling dry gases?

- Drying of the mucosa
- Decreased compliance
- Development of loci for infection
- Impairment of surfactant activity
- Decreased alveolar-arterial oxygen difference

View Answer

2. Where should a heated humidifier be located in the circle system?

- Between the exhalation tubing and the carbon dioxide absorber
- Between the Y-piece and tracheal tube
- Between the inspiratory tubing and the Y-piece
- Between the absorber and the inspiratory tubing
- Between the Y-piece and the mask

View Answer

3. If a bacterial filter is used in a circle system that has a heated humidifier, where should the filter be placed?

- Between the Y-piece and the tracheal tube
- Between the Y-piece and the inhalational tubing
- Between the inhalational tubing and the humidifier
- Between the inhalational unidirectional valve and the humidifier

Between the Y-piece and the exhalation tubing

View Answer

4. Which is the definition of *absolute humidity*?

The pressure exerted by water vapor in a gas mixture

The amount of water vapor at a particular temperature as a percentage of the amount that would be held if the gas were saturated

The maximum amount of water vapor that a volume of gas can hold

The mass of water vapor present in a volume of gas.

The humidity of gases at body temperature

View Answer

5. What will cause water to rain out in the breathing hose?

Using coaxial tubes in the breathing system

Heated humidified gas that cools in the breathing tube

Warming cooled humidified gases in the breathing tube

Maintaining the temperature of heated gas in the breathing tubes

Using an extra-long breathing tube

View Answer

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

6. Which of the following statements about humidity and ambient conditions are true?

If a gas saturated with water is heated, it can hold more water

Gas that is 100% saturated at room temperature and warmed to body temperature will be about 60% saturated

If a gas saturated with water is heated, the absolute humidity remains the same

If a gas saturated with water is heated, the relative humidity increases

View Answer

7. A result of the low specific heat of gases is

Inhaled gas will quickly assume body temperature

Water will condense in the exhalation side of a circle system

Gas in breathing tubes will quickly assume room temperature

Gas has a tendency to change temperature slowly

View Answer

8. Heat and moisture are normally lost during anesthesia because

Dry gases are supplied from the anesthesia machine

Gases are heated by the body

Tracheal intubation bypasses normal humidification mechanisms

The tracheal tube does not act to conserve heat or moisture

View Answer

9. Sources of humidity in the breathing system include

Carbon dioxide absorbent

Exhaled water from a previous patient

Rebreathing of previously exhaled gases

Fresh gas

View Answer

10. Advantages of a hydrophobic HME over a composite hygroscopic HME include

Better filtration

Less resistance when wet

Nebulized drugs have little effect on resistance

Better humidification

View Answer

11. Using a heated breathing tube with a heated humidifier will result in

Rainout in the delivery tube

A higher temperature at the Y-piece

Drying of secretions

A delivered relative humidity of 100%

View Answer

12. Hazards of heated humidifiers include

Sticking valves

Overhydration

Alteration of anesthetic agents

Obstruction of sidestream gas monitors

View Answer

13. Advantages of HMEs include

Fluctuating temperature and humidity

Decrease in dead space

Low compliance

Decreased resistance to breathing

View Answer

14. Contraindications to use of an HME include

Bloody secretions

Patient temperature of less than 35ยฐC

Bronchopleurocutaneous fistula

Uncuffed tracheal tube

View Answer

15. When using an HME, the inspired humidity can be increased by

Use of an uncuffed tube

Increasing the minute volume

Lowering the humidity of gas entering the HME

Use of a hygroscopic rather than a hydrophobic HME

View Answer

16. Which patients or conditions derive the greatest benefit from humidification of inspired gases?

Long anesthetics

Patients who are likely to develop pulmonary complications

Pediatric patients

Elderly patients

View Answer

17. Which of the following are respiratory complications of dry respiratory mucosa?

Bronchoconstriction

Airway obstruction

Infection

Atelectasis

View Answer

18. Consequences of excessive humidity include which of the following?

Pulmonary edema

An increased serum sodium

Ciliary degeneration

Increased pulmonary compliance

View Answer

19. Hazards associated with using a nebulizer include

Overhydration

Filter obstruction

Bacteria infection

Hypothermia

View Answer

Chapter 12
Anesthesia Ventilators

A ventilator (breathing machine) is an automatic device designed to provide or augment patient ventilation. Newer anesthesia ventilators are an integral part of the anesthesia workstation. They are designed with more features and ventilatory modes than earlier models and have the ability to ventilate more difficult patients and to allow ventilation to be tailored to the patient's needs.

Traditional anesthesia ventilators could not provide as high inspiratory pressures or flows as their intensive care unit (ICU) counterparts (1,2,3,4). As a result, some ICU ventilators needed to be adapted for use during surgery in order to care for patients who were difficult to ventilate. If positive end-expiratory pressure (PEEP) were needed, often the anesthesia provider had to add a PEEP valve to the anesthesia breathing system. Some of these valves were imprecise, not variable, and could be misconnected (Chapter 7). On some older ventilators, the user had to manually enable the low pressure alarm when the ventilator was turned ON. Also, it may have been necessary to close the adjustable pressure limiting (APL) valve and/or turn the bag/ventilator switch when turning on the ventilator. Another drawback of older ventilators was that separate models or different bellows assemblies were required for adult and pediatric patients. The delivered tidal volume was affected by fresh gas flow and breathing system compliance. Finally, older ventilators offered only volume control ventilation.

The demand for performance equivalent to ICU ventilators has led to a number of improvements in anesthesia ventilators. High inspiratory pressures and flows can be delivered. Newer anesthesia ventilators have an integral PEEP valve, and many have several ventilatory modes. Another improvement is improved flexibility so that the ventilator can deliver volumes for a wide range of patients from the smallest child to the largest adult. The new ventilators are designed to overcome the effects of fresh gas, breathing system compliance and gas compression on tidal volume. Turning the ventilator ON involves fewer steps

and automatically enables the low airway pressure alarm.

Ventilators used in anesthesia are covered by international and U.S. standards (5,6,7).

This chapter will cover a number of ventilators available at the time of this writing. It is impossible to provide all of the details that need to be mastered to safely use a particular ventilator. Software updates and upgrades occur frequently. It is important that the user manual be studied before using a ventilator that is unfamiliar to the anesthesia provider.

Definitions

1. *Barotrauma*: Injury resulting from high airway pressure.

2. *Compliance*: Ratio of a change in volume to a change in pressure. It is a measure of distensibility and is usually expressed in milliliters per centimeter of water (L or mL/cm H_2O). Most commonly, compliance is used in reference to the lungs and chest wall. Breathing system components, especially breathing tubes and the reservoir bag, also have compliance.
3. *Continuous Positive Airway Pressure* (CPAP): Airway pressure maintained above ambient. This term is commonly used in reference to spontaneous ventilation.
4. *Exhaust Valve*: Valve in a ventilator with a bellows that when open allows driving gas to exit the bellows housing.
5. *Expiratory Flow Time*: Time between the beginning and end of expiratory flow.
6. *Expiratory Pause Time*: Time from the end of expiratory flow to the start of inspiratory flow.
7. *Expiratory Phase Time*: Time between the start of expiratory flow and the start of inspiratory flow. It is the sum of the expiratory flow and expiratory pause times.
8. *Fresh Gas Compensation*: A means to prevent the fresh gas flow from affecting the tidal volume by measuring the actual tidal volume and using this information to change the volume of gas delivered by the ventilator.

9. *Fresh Gas Decoupling*: A means to prevent the fresh gas flow from affecting the tidal volume by isolating the fresh gas flow so that it doesn't enter the breathing system during inspiration.
10. *Inspiratory Flow Time*: Period between the beginning and end of inspiratory flow.
11. *Inspiratory Pause Time*: That portion of the inspiratory phase time during which the lungs are held inflated at a fixed pressure or volume (i.e., the time during which the inspiratory phase has zero flow). It is also called the *inspiratory hold*, *inflation hold*, and *inspiratory plateau*. The inspiratory pause time may be expressed as a percentage of the inspiratory phase time.
12. *Inspiratory Phase Time*: Time between the start of inspiratory flow and the beginning of expiratory flow. It is the sum of the inspiratory flow and inspiratory pause times.
13. *Inspiratory: Expiratory Phase Time Ratio* (I:E ratio): Ratio of the inspiratory phase time to the expiratory phase time.
14. *Inspiratory Flow Rate*: Rate at which gas flows to the patient expressed as volume per unit of time.
15. *Inverse Ratio Ventilation*: Ventilation in which the inspiratory phase time is longer than the expiratory phase time.
16. *Minute Volume*: Sum of all tidal volumes within one minute.
17. *Peak Pressure*: Maximum pressure during the inspiratory phase time.
18. *Plateau Pressure*: Resting pressure during the inspiratory pause. Airway pressure usually falls when there is an inspiratory pause. This lower pressure is called the *plateau pressure*.
19. *Positive End-expiratory Pressure* (PEEP): Airway pressure above ambient at the end of exhalation. This term is commonly used in reference to controlled ventilation.
20. *Resistance*: Ratio of the change in driving pressure to the change in flow rate. It is commonly expressed as centimeters of water per liter per second (cm H_2O/L/second).

21. *Sigh*: Deliberate increase in tidal volume for one or more breaths.
22. *Solenoid*: A component that controls pneumatic flow by means of an electronic signal.
23. *Spill Valve*: The valve in an anesthesia ventilator that allows excess gases in the breathing system to be sent to the scavenging system after the bellows or piston has become fully filled during exhalation.
24. *Tidal Volume*: Volume of gas entering or leaving the patient during the inspiratory or expiratory phase time.
25. *Ventilatory (Respiratory) Rate or Frequency*: Number of respiratory cycles per minute.
26. *Volutrauma*: Injury due to overdistention of the lungs.
27. *Work of Breathing*: Energy expended by the patient and/or ventilator to move gas in and out of the lungs. It is expressed as the ratio of work to volume moved, commonly as joules per liter. It includes the work needed to overcome the elastic and flow-resistive forces of the both the respiratory system and apparatus.

Relationship of the Ventilator to the Breathing System

A ventilator replaces the reservoir bag in the breathing system. It may be connected to the breathing system by a bag/ventilator selector valve (Chapter 9). On some newer workstations, turning the bag/ventilator selector switch to the ventilator position or a mode selection switch turns ON the ventilator. On other ventilators, there is an ON-OFF switch.

Most anesthesia ventilators have a bellows in a box (bag in a bottle, double circuit) design (Fig. 12.1). The bellows is housed in a pressure chamber, and the inside of the bellows is connected to the breathing system. The bellows acts as an interface between the breathing system and the ventilator driving gas, just as the reservoir bag acts as an interface between the breathing system and the anesthesia provider's hand. It separates

breathing system gas from driving gas. The pressure of the anesthesia provider's hand is replaced by the driving gas pressure that compresses the bellows.

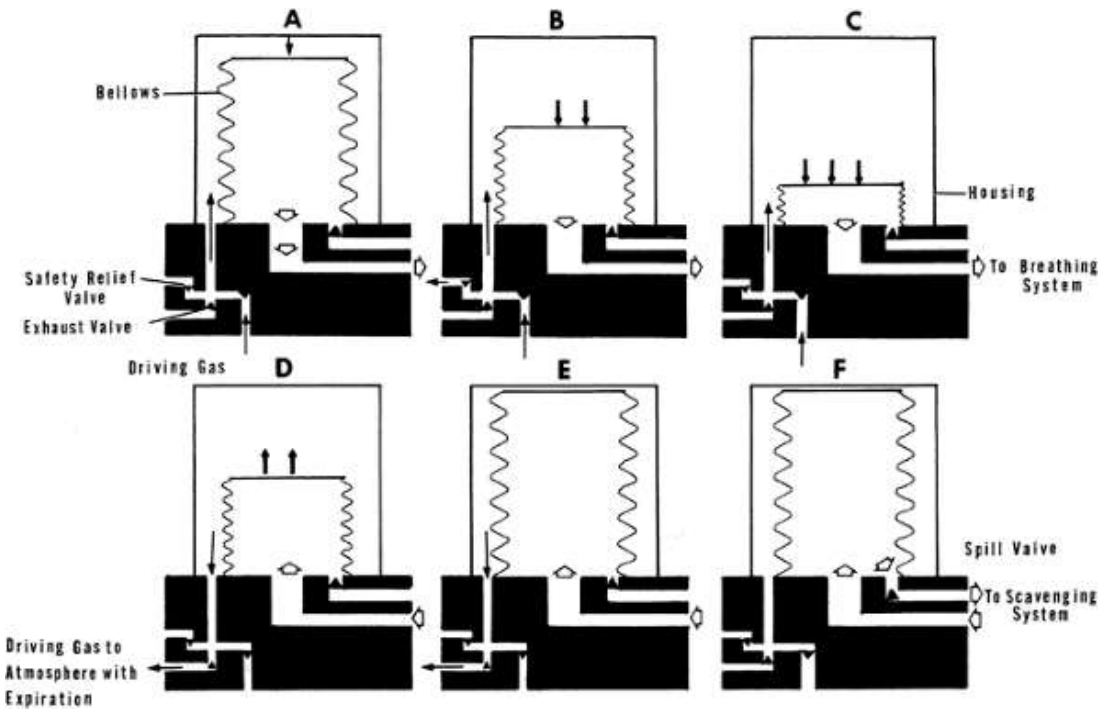


Figure 12.1. Functioning of the bellows-in-box ventilator. **A:** Beginning of inspiration. Driving gas begins to be delivered into the space between the bellows and its housing. The exhaust valve (which connects the driving gas pathway with atmosphere) is closed. The spill valve (which vents excess breathing system gases to the scavenging system) is also closed. **B:** Middle of inspiration. As driving gas continues to flow into the space around the bellows, its pressure increases, exerting a force that causes the bellows to be compressed. This pushes the gas inside the bellows toward the breathing system. The exhaust and spill valves remain closed. If the pressure of the driving gas exceeds the opening pressure of the safety relief valve, the valve will open and vent driving gas to atmosphere. **C:** End of inspiration. The bellows is fully compressed. The exhaust and spill valves remain closed. **D:** Beginning of expiration. Breathing system (exhaled and fresh) gases flow into the bellows, which begins to expand. The expanding bellows displaces driving gas from the interior of the housing. The exhaust valve opens, and driving gas flows through it to atmosphere. The spill valve remains closed. **E:** Middle of expiration. The bellows is nearly fully expanded. Driving gas continues to flow to atmosphere. The spill valve remains closed. **F:** End of expiration. Continued flow of gas into the bellows after it is fully expanded creates a

positive pressure that causes the spill valve at the base of the bellows to open. Breathing system gases are vented through the spill valve into the scavenging system.

During inspiration, driving gas is delivered into the space between the bellows and its housing. This causes the bellows to be compressed so that gas flows into the breathing system. At the same time, the spill valve (which vents excess gases to the scavenging system) and exhaust valve (which vents driving gas) are closed.

During exhalation, the bellows re-expands as breathing system gases and fresh gas flow into it. Driving gas is vented to atmosphere through the exhaust valve. After the bellows is fully expanded, excess gas from the breathing system is vented to the scavenging system through the spill valve.

Instead of a bellows in a box, some ventilators have an electrically driven piston. By eliminating the need for a drive gas circuit (an additional source of compressible volume), a stable flow delivery can be provided. In piston ventilator systems that are presently available, the reservoir bag is not isolated from the breathing system during the exhalation phase of automatic ventilation and acts to modulate pressure increases in the system. During inspiration, when the piston forces gases into the breathing system, the bag is isolated from the breathing system and collects the fresh gas flow entering the breathing system. On some ventilators, the bag can be seen to expand and contract with respiration even though the piston is actually ventilating the patient. A problem with piston ventilators may be air entrainment with a disconnection

(8,9). In this case, the machine may not alarm and the patient will continued to be ventilated, but air will be entrained, resulting in lower concentrations of oxygen and anesthetic agents.

Factors That Affect the Delivered Tidal Volume

Fresh Gas Flow

With older ventilators, the delivered tidal and minute volumes changed when the fresh gas flow, I:E ratio, or respiratory rate

was altered despite the bellows excursion remaining unchanged. If the fresh gas flow increased, the tidal and minute volumes increased (10,11,12,13). If the fresh gas flow decreased, the tidal and minute volumes decreased. Since fresh gas was added to the inspired tidal volume only during inspiration, ventilator settings that prolonged the inspiratory time (and thereby increased the I:E ratio) would cause an increased tidal volume. Lower I:E ratios decrease the tidal volume. As respiratory rate increased, the increase in tidal volume from fresh gas flow was less, although the effect on minute volume remained the same. Slowing the respiratory rate had the opposite effect.

Manufacturers have re-engineered their ventilators to eliminate the fresh gas effect on the inspired volume. One method is to measure the inspired fresh gas flow and compensate for it by altering the bellows excursion (fresh gas compensation). Another method is to prevent the fresh gas from entering the breathing system during inspiration by using a valve that diverts the fresh gas into a reservoir bag during inspiration (fresh gas decoupling).

Compliance and Compression Volumes

Decreases in compliance in the breathing system can be accompanied by decreases in tidal volume as more of the inspiratory flow is expended by expanding the components. Gas compression losses depend on the volume of the breathing system and the pressure during inspiration. Advanced technology now allows the ventilator to compensate for changes in breathing system compliance by altering the volume delivered. Breathing system compliance is determined during the checkout procedure before use. For accurate compliance compensation, the breathing system must be in the configuration that is to be used when the checkout procedure is performed. Changes in the circuit configuration (such as lengthening the breathing tubes or adding components) will cause the compensation to be inaccurate (14).

Other ventilators measure inspired volumes at the patient connection and adjust the ventilator excursions accordingly.

Leaks

A leak around the tracheal tube or supraglottic device will cause

a decrease in tidal volume that is not taken into account by the ventilator. Sidestream gas monitors may decrease the volume delivered to the patient.

Components

Driving Gas Supply

Most currently available anesthesia ventilators are pneumatically powered but electrically controlled. The driving (drive, power) gas is either oxygen, air, or a mixture of air and oxygen. It is usually less expensive to power the ventilator with air. Some ventilators can switch between driving gases so that if there is a loss of pressure in the primary driving gas supply, the other gas can be used.

Some ventilators use a device called an *injector* (Venturi mechanism) to increase the driving gas flow. An injector is shown in Figure 12.2. As the gas flow meets a restriction, its lateral pressure drops (Bernoulli principle). When the lateral pressure drops below atmospheric, air will be entrained. The result is an increase in the total gas flow leaving the injector, and a decreased consumption of driving gas.

A significant flow of gas is necessary to drive a bellows (15,16,17). The amount will vary, depending on the ventilator and the settings. The use of a gas cylinder to power a ventilator may quickly deplete the gas supply.

Controls

The ventilator controls regulate the flow, volume, timing, and pressure of the bellows compression or piston movement.

Alarms

The ventilator and workstation standards (6,7) group alarms into three categories: high, medium, and low priority, depending on whether the condition requires

immediate action, prompt action, or operator awareness but not necessarily action (Chapter 26).

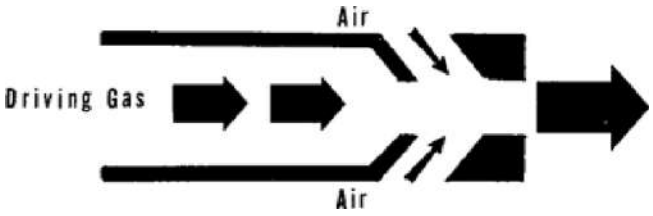


Figure 12.2. Injector (Venturi). Gas flows through the constricted area at a high velocity. The pressure around it drops below atmospheric, and air is entrained. The net result is an increase in total gas flow leaving the outlet of the injector.

The ventilator standard (6) mandates an alarm that indicates that the pressure in the breathing system has exceeded a set limit (high-pressure alarm). On modern ventilators, this threshold is adjustable by the user, usually with a default around 50 cm H_2O.

There must be an alarm to indicate that the pressure in the breathing system has not reached a minimum value within a certain time period (low airway pressure alarm).

Pressure-limiting Mechanism

A pressure-limiting mechanism (pressure-limiting valve, maximum limited pressure mechanism, driving gas pressure relief valve, pressure limitation mechanism, maximum working pressure control, pressure limit controller, inspiratory pressure limit, adjustable pressure relief valve, high pressure safety relief valve, overpressure release) is designed to limit the inspiratory pressure. The anesthesia workstation standard (7) mandates that this be adjustable. An adjustable mechanism carries the hazard of operator error. If set too low, insufficient pressure for ventilation may be generated; if set too high, excessive airway pressure may occur. Setting the pressure limit 10 cm H_2O above the peak pressure achieved with the desired tidal volume and flow rate will avoid most barotrauma (18).

Pressure-limiting devices work in one of two ways. When the maximum pressure is reached, one type holds the pressure at that level until the start of exhalation, at which time the pressure decreases. The other type terminates inspiration when the pressure limit is reached so that the pressure drops immediately.

Bellows Assembly

Bellows

The bellows is an accordionlike device that is attached at either the top or bottom of the bellows assembly. Latex-free bellows are available. There are two types of bellows, distinguished by their motion during exhalation: ascending (standing, upright, floating) and descending (hanging, inverted). Ventilators with descending bellows were common until the mid 1980s. After that, most new ventilators had ascending bellows, but descending bellows are used by a number of more recent ventilators.

With an ascending bellows (Figs. 12.36, 12.44), the bellows is attached at the base of the assembly, and the bellows is compressed downward during inspiration. During exhalation, the bellows expands upward. These ventilators impose a slight resistance at the end of exhalation, at which time the pressure in the bellows rises enough (2 to 4 cm H_2O) to open the spill valve.

The tidal volume may be set directly by adjusting the inspiratory time and flow or by a plate that limits upward excursion of the bellows. With a disconnection or leak in the breathing system, the bellows will collapse to the bottom or fail to expand fully. The ventilator may continue to deliver small tidal volumes (19).

To deliver the entire tidal volume, the bellows must descend to the proper level or, depending on the ventilator, be fully compressed at the end of the inspiratory phase. If the inspiratory flow is insufficient to fully compress the bellows or achieve the desired tidal volume, a lower tidal volume will be delivered.

With a descending bellows (Fig. 12.50), the bellows is attached at its top and is compressed upward during inspiration. There is usually a weight in the dependent portion of the bellows that facilitates downward re-expansion during exhalation. As the weight descends, it can cause a small negative pressure in the bellows and breathing system. With a leak or disconnection in the breathing system, the weight in the bellows will cause the

bellows to expand, and room air will enter the breathing system. All or part of the next inspiration will then be lost into the room. Newer ventilators with hanging bellows employ sophisticated software to detect disconnections or leaks (20,21). The software analyzes sensor outputs and triggers appropriate alarms. A negative pressure relief valve prevents the patient from being exposed to negative pressure.

Housing

The bellows is surrounded by a clear plastic cylinder (canister, bellows chamber or cylinder, pressure dome) that allows the bellows movement to be observed. A scale on the side of the housing provides a rough approximation of the tidal volume being delivered. The housing for piston ventilators usually has a scale that can be observed.

Exhaust Valve

The exhaust valve (exhalation valve, ventilator relief valve, compressed gas exhaust, bellows control valve) communicates with the inside of the bellows housing on pneumatically powered ventilators. It is closed during inspiration. During exhalation, it opens to allow driving gas inside the housing to be exhausted to atmosphere. With a piston ventilator, there is no need for an exhaust valve.

Spill Valve

Because the APL valve is isolated from the breathing system during ventilator operation, a spill valve (vent valve, dump valve, overflow valve, expired gas outlet, expiratory valve or port, safety dump valve, pop-off valve, relief valve, flapper valve, pressure relief valve, overspill

valve, gas evacuation outlet valve, exhaust gas valve, gas evacuation or evacuator valve, expiratory pressure relief valve) is used to direct excess respired gases into the scavenging system. This valve is closed during inspiration. During exhalation, it remains closed until the bellows or piston is fully expanded, then opens to vent excess breathing system gases. The scavenging transfer tubing connects the exhalation port of the spill valve to the scavenging system interface (Chapter 13).

With an ascending bellows, the spill valve has a minimum opening pressure of 2 to 4 cm H_2O (22). This enables the bellows to fill during exhalation. This amount of PEEP is applied to the breathing system. It is not applied with a piston or a hanging bellows ventilator.

With a piston ventilator, excess gas is vented through a spill valve, which may not in the ventilator, or through an electronically controlled APL valve, which acts as a spill valve.

Ventilator Hose Connection

The ventilator standard (6) requires that the fitting on the tubing connecting the ventilator to the breathing system be a standard 22-mm male conical fitting. A filter may be used on the tubing to lessen transmission of pathogens and particles. In most newer ventilators, a separate hose is not present, and the connections between the ventilator and the breathing system are internal. This reduces the likelihood of misconnections, disconnections, or kinked hoses (23).

Positive End-expiratory Pressure Valve

PEEP valves are discussed in Chapter 7. Modern ventilators have integral electrically operated PEEP valves. Some ventilators apply PEEP to the entire system, while others apply it only to the expiratory hose (23).

A standing causes a small amount (2 to 4 cm H_2O) of PEEP. There is no unset PEEP with hanging bellows or piston-driven ventilators.

Ventilation Modes

Anesthesia ventilators offer one or more ventilation modes (18). Many offer dual modes to gain the advantages of both. Ventilator settings must be carefully individualized in each mode to avoid hypoventilation, hyperventilation, volutrauma, or barotrauma. It is important when switching from one mode to another to ensure that the tidal volume, peak pressure, and alarm settings are appropriate.

A ventilator can deliver gas by generating flow or pressure. With flow generators, the flow pattern can be constant (square wave) or nonconstant (accelerative or decelerative). Pressure

generators produce a constant or nonconstant pressure. Inspiratory flow rate varies according to the preset pressure and the patient's resistance and compliance.

The characteristics of inspiration and exhalation related to the ventilator settings, compliance, and resistance are reflected in the pressure and flow-volume loops. These are discussed in detail in Chapter 23.

Features of some commonly used ventilatory modes are shown in Table 12.1. The terminology used to describe the way a ventilator operates has not been universally agreed on, and some manufacturers have coined new terms for their ventilators.

Volume Control

The most commonly used mode in the operating room is volume control (volume-controlled or volume) ventilation, in which a preset tidal volume is delivered. The tidal or minute volume and respiratory rate are set by the anesthesia provider and delivered by the ventilator, independent of patient effort. It is time initiated, volume limited, and cycled by volume or time.

Flow rate is fixed at a constant value during inspiration. If the inspiratory flow is too low to provide the set tidal volume, the bellows or piston will not complete its excursion. If the flow is set at a faster rate than is needed to provide the tidal volume, there will be an

inspiratory pause. An excessively high peak inspiratory pressure may result from setting the inspiratory flow rate too high (24). The inspiratory phase may be terminated before the tidal volume has been delivered if the peak airway pressure reaches the set pressure limit.

TABLE 12.1 Ventilatory Modes

Mode	*Initiation*	*Limit*	*Cycle*
Volume control ventilation	Time	Volume	Volume/Time
Pressure control	Time	Pressure	Time

ventilation			
Intermittent mandatory ventilation	Time	Volume	Volume/Time
Synchronized intermittent mandatory ventilation	Time/Pressure	Volume	Volume/Time
Pressure support ventilation	Pressure/Flow	Pressure	Flow/Time

Typically, a volume control waveform shows steadily increasing pressure during inspiration. Changes in compliance or resistance are reflected in changes in peak inspiratory pressure and the difference between peak and plateau pressure (25). For a given set tidal volume, the pressure in the breathing system is determined by the resistance and compliance of the breathing system and the patient. Plateau pressure is a reflection of compliance. Peak pressure is also influenced by resistance. The pressure-volume and flow-volume loops associated with volume control ventilation are seen in Figures 23.22 and 23.23.

Adding PEEP decreases the tidal volume delivered, with the effect greater with small tidal volumes (26,27). On newer ventilators with integral PEEP, ventilation may be better maintained (4).

If closed system suctioning is performed during volume control ventilation, there will be a significant rise in airway pressure when the catheter is inserted and low airway pressure during suctioning (28,29,30).

Pressure Control

Pressure control (pressure-limited, pressure-controlled, pressure-preset control, lung protective, or pressure) ventilation is available on many anesthesia ventilators (2,31,32,33). With this mode, the operator sets the inspiratory pressure at a level

above PEEP. The ventilator quickly increases the pressure to the set level at the start of inspiration and maintains this pressure until exhalation begins.

Inspiratory gas flow is highest at the beginning of inspiration, then decreases. Increased resistance may change the shape of the flow-versus-time waveform to a flatter, more square-shaped pattern as tidal volume delivery shifts into the latter part of the inspiration (25). This allows the ventilator to preserve tidal volume with increased resistance until resistance becomes severe. The pressure-volume and flow-volume loops show special characteristics seen with pressure-controlled ventilation (Figs. 23.29, 23.30).

When pressure control ventilation is used, tidal volume is determined by the rise time and set pressure. Tidal volume is not set or constant but fluctuates with changes in resistance and compliance and with patient-ventilator asynchrony (25). If resistance increases or compliance decreases, the tidal volume will decrease. It has been postulated that a decrease in tidal volume with pressure control ventilation would detect a partially occluded tracheal tube, but it was found that tidal volume was not decreased until the occlusion was nearly complete (25).

Unlike most ICU ventilators, an anesthesia ventilator in the pressure control mode operates with a preset I:E ratio, so increasing the respiratory rate shortens inspiratory time and lowers tidal volume (2). An increase in PEEP causes a reduction in tidal volume. Tidal volume is not affected by fresh gas flow because excess gas is vented through the spill valve.

On some ventilators, the inspiratory flow is adjustable (Fig. 12.48). There may also be a setting that controls the inspiratory rise time. For patients with good compliance, inspiratory flow should be high to ensure that the inspiratory pressure is rapidly attained. Limiting the maximum inspiratory flow is useful to avoid overshooting the target pressure, especially when compliance is low.

In patients with lung injury or during single-lung ventilation, pressure control ventilation may improve oxygenation and produce greater tidal volumes than volume control ventilation because of the decelerating flow pattern that delivers gas to the alveoli early during inspiration (31). It is often used with supraglottic devices and patients with narrow or partially

obstructed tracheal tubes to provide ventilation at relatively low pressures (34,35). It may be useful if there is an airway leak (e.g., uncuffed tube, supraglottic airway device, bronchopleural fistula). However, if there is a large leak, the cycling pressure limit may not be reached, causing a prolonged inspiration (18).

During closed system suctioning (Chapter 3), pressure control ventilation results in less intrinsic PEEP during catheter insertion and less subatmospheric pressure during suctioning than during volume control ventilation (28,29).

Intermittent Mandatory

With intermittent mandatory ventilation (IMV), the ventilator delivers mechanical (mandatory, automatic) breaths at a preset rate and permits spontaneous, unassisted breaths of a controllable inspiratory gas mixture between mechanical breaths. The ventilator has a secondary source of gas flow for spontaneous breaths. This utilizes either continuous gas flow within the circuit or a demand valve that opens to allow gas to flow from a reservoir. Continuous gas flow at a rate greater than peak inspiratory flow involves no additional work of breathing but requires a large volume of fresh gas. The demand valve system, although more efficient in fresh gas use, can impose significant work of breathing on the patient.

This mode is often used for weaning patients from mechanical ventilation. The IMV rate is gradually

reduced, allowing increased time for the patient's spontaneous breaths.

Synchronized Intermittent Mandatory

Synchronized intermittent mandatory ventilation (SIMV) synchronizes ventilator-delivered breaths with the patient's spontaneous breaths. If patient inspiratory activity is detected, the ventilator synchronizes its mandatory breaths so that the set respiratory frequency is achieved. Positive pressure (mandatory) breaths may occur at irregular intervals.

The time between the end of each mandatory breath and the beginning of the next is subdivided into a spontaneous breathing time and a trigger time. During the trigger time, the ventilator checks whether the airway pressure has dropped a minimum

amount below the pressure measured at the end of the expiratory phase. If a drop is not sensed, the ventilator delivers a breath. The trigger window may be adjustable (Fig. 12.49).

A mandatory tidal volume and a minimum mechanical ventilation rate must be selected. This determines the minimum minute ventilation. When setting the ventilator rate, the patient's spontaneous rate must be considered. If the SIMV rate is set too high, the patient may become apneic. Setting an I:E ratio is not required in SIMV. The I:E ratio will change as the patient's respiratory rate and rhythm changes.

SIMV is used to facilitate emergence from anesthesia as the patient transitions from controlled to spontaneous ventilation. It ensures a minimal amount of ventilation while freeing the anesthesia provider from periodically ventilating the patient by hand. It reduces the incidence of patient-ventilator disharmony where the patient tries to fight the ventilator and the need for sedation or narcosis for the patient to tolerate mechanical ventilation. During anesthesia, SIMV may be used to provide backup mechanical ventilation for spontaneously breathing patients. SIMV can be combined with pressure support ventilation (PSV).

Mandatory Minute

Mandatory minute ventilation (MMV) is a method of mechanical ventilation in which the amount of ventilatory support is automatically adjusted to fluctuations in spontaneous ventilation so that a preset minute ventilation is delivered. The ventilator circuitry monitors spontaneous expired volume and, if it falls below a predetermined level, provides the difference between the selected and actual minute volume.

Pressure Support

PSV (pressure-assisted or assisted spontaneous ventilation) has been a feature of ICU ventilators for years and is now on many anesthesia ventilators (36,37,38,39). It is designed to augment the patient's spontaneous breathing by applying positive pressure to the airway in response to patient-initiated breaths. A disadvantage of this mode of ventilation is that if the patient fails to make any respiratory effort, no pressure-supported breaths will be initiated. To avoid this potentially disastrous situation,

most ventilators have a backup or ‍€apneic‍€ SIMV rate in case that the patient's spontaneous respiration ceases (assist/control ventilation).

A supported breath may be pressure or flow initiated. Flow triggering imposes less inspiratory workload than pressure triggering and is used more frequently (40).

When the user-selected flow or sub-baseline pressure caused by a spontaneous breath is reached, flow from the ventilator begins and the set pressure is quickly reached. The ventilator then modulates the flow to maintain that pressure. The flow decreases until it falls below a predetermined fraction of the initial rate (usually 5% or 25%) or a fixed flow (usually 5 L/minute) or after a specific duration as a backup (41). At this point, flow is terminated and exhalation begins. Because the PSV level is reached early in inspiration and is maintained throughout the inspiratory phase, the pressure waveform has a square, flat-topped shape. PEEP may be added if needed.

The anesthesia provider must set the trigger sensitivity and the inspiratory pressure (usually from 5 to 10 cm H_2O). The triggering sensitivity should be set so that it will respond to inspiratory effort without auto-cycling in response to artifactual changes in airway pressures. The initial inspiratory flow is usually nonadjustable but can be changed on some ventilators by adjusting the inspiratory rise time (Fig. 12.48). The optimal initial inspiratory flow is highest in patients with low compliance, high resistance, and most active ventilatory drive. On some ventilators, the trigger window can be changed (Fig. 12.49).

Tidal volume is determined by the pressure support level, lung characteristics, and patient effort. The desired tidal volume should be calculated and the pressure support level adjusted so that the desired volume is delivered. If the exhaled volume is inadequate, the inspiratory pressure should be increased or inspiratory rise time decreased (if adjustable). PEEP may cause an increase in tidal volume (42). Very high inspiratory flow (due to a high set pressure) may decrease tidal volume by prematurely terminating inspiration (37). As the patient's effort increases, the level of inspiratory pressure can be reduced. Undesired hyperventilation can be treated by adjusting the trigger sensitivity, pressure level, or trigger window or, if these seem adequate, additional sedation.

PSV can be used to reduce the patient's work of spontaneous breathing (38,43,44). In addition, it can increase the functional residual capacity. It may be useful for preoxygenating obese patients by improving the efficiency

of spontaneous ventilation and during weaning from mechanical ventilation. It can be useful with a supraglottic airway device to keep the airway pressure lower than the supraglottic device leak pressure (38,42,45). If there is a leak around the device, PSV will be able to compensate for the leak to some extent, as the airway pressure is maintained irrespective of the volume.

An advantage of PSV is the synchrony between the patient and the ventilator. The patient controls rate, volume, and inspiratory time. This may increase patient comfort. Breath stacking and ‘€fighting the ventilator‘€ are decreased. Even patients who are initially tachy-pneic may be successfully managed in this mode, as the pressure support can be set sufficiently high to augment tidal volume and hence reduce the respiratory rate. Peak and mean airway pressures are lower than with volume control ventilation, reducing the risk of barotrauma (42).

Too high an inspiratory flow may cause patient discomfort (33). PSV will deliver a variable minute volume in a patient with a changing respiratory drive. Inappropriate ventilator triggering can occur with PSV (40,46,47). This may be caused by a leak or a decrease in airway pressure caused by cardiac contractions.

With closed system suctioning, PSV results in a lower airway pressure during catheter insertion and higher end-expiratory pressure during suctioning than either volume control or pressure control ventilation (28,48).

Specific Ventilators

Drager AV2+

The AV2+ is the successor to the AVE and AV2 ven-tilators.

Description

The AV2+ is shown in Figures 12.3 and 12.4. It has an ascending bellows. Tidal volume is adjusted by using the knob above the bellows assembly, which raises or lowers a plate at

the top of the bellows. A scale on the bellows housing provides a rough indication of the tidal volume delivered.

Most ventilator controls are located across the top of the ventilator. To the left of the tidal volume control and above the bellows is the inspiratory pressure limit control. On the left above the pressure limit and tidal volume controls is the frequency control with a digital

readout to the left. To the right of the frequency control are the control and display for the I:E ratio. In order to set an inverse ratio, an extended range button below the display and control must be depressed.

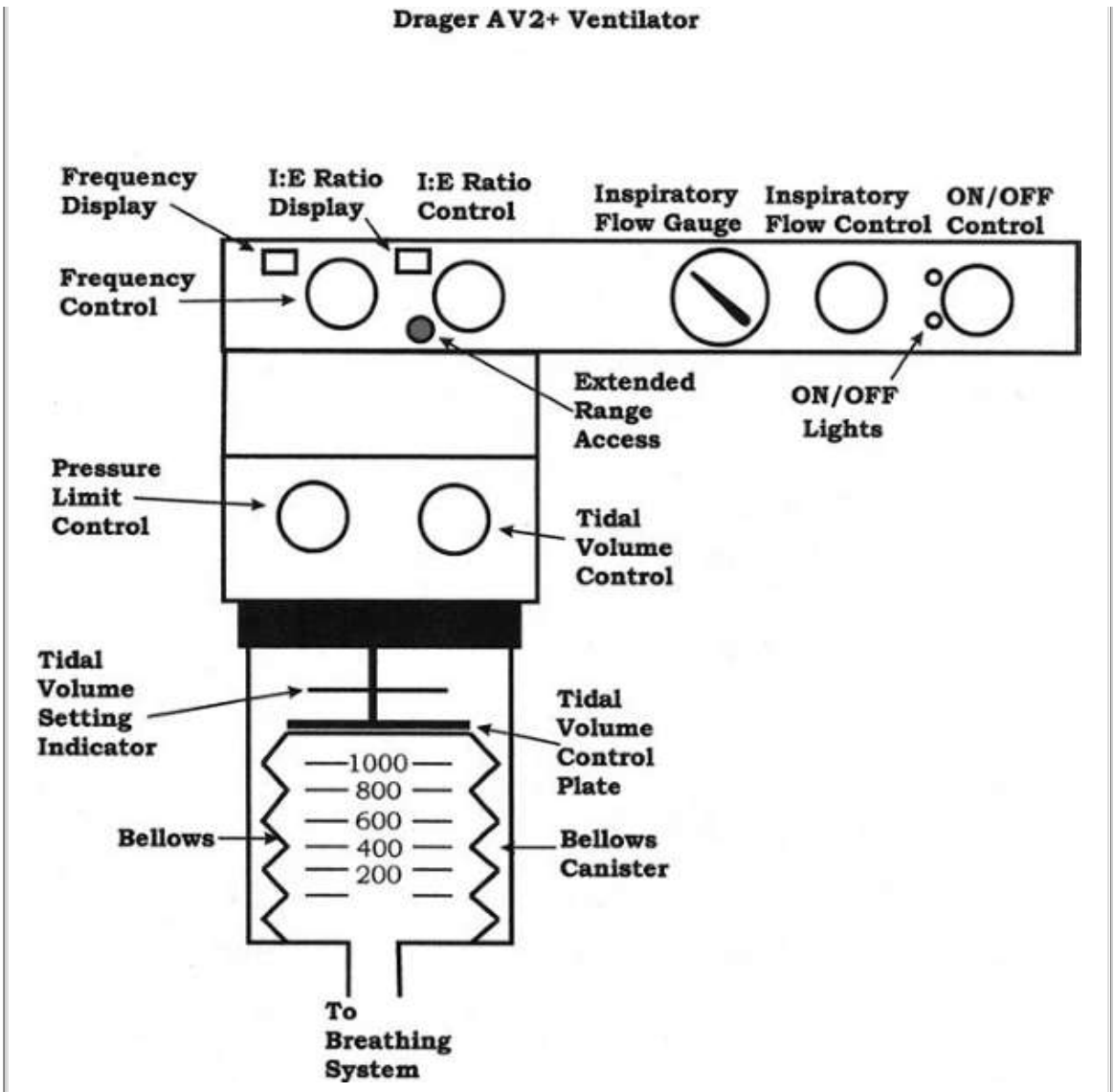


Figure 12.3. Drager AV2+ ventilator. I:E, inspiratory:expiratory.

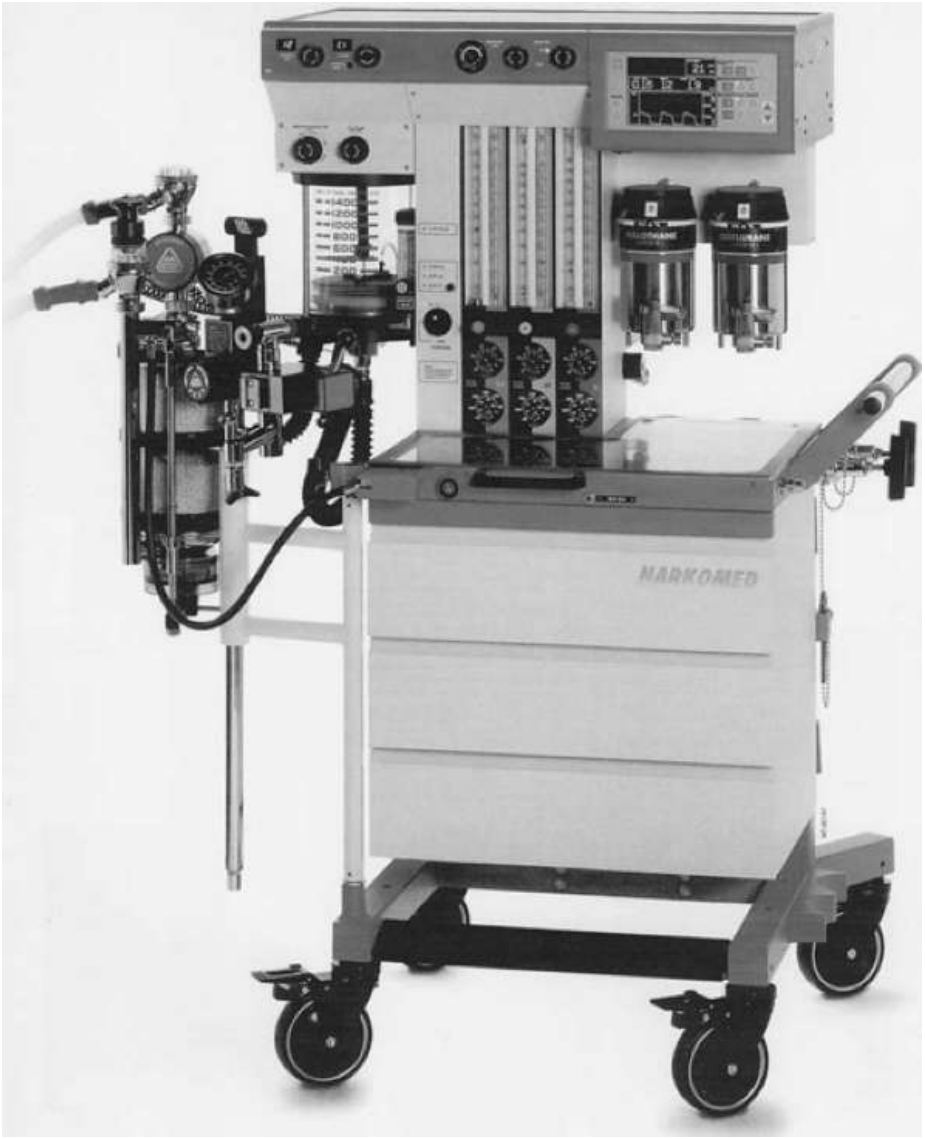


Figure 12.4. Drager AV2+ ventilator. (Courtesy of Drager Medical.)

To the right of the I:E ratio control are the inspiratory flow control and gauge. The scale on the gauge is divided into low, medium, and high flow.

To the right is the ventilator ON/OFF switch. A green light next to the switch indicates that the ventilator is turned ON. The ventilator may be turned ON at this switch or by turning the Manual/Automatic switch on the absorber to the automatic

position. The ventilator control switch can only be turned ON with the Manual/Automatic switch in the Automatic position. If the ON/OFF switch is turned ON with the bag/vent selector switch in the bag position, a fault light to the left of the ON/OFF switch will be illuminated.

The spill valve (Fig. 12.5) is at the base of the bellows assembly. A pilot line from the canister connects through the top of the spill valve to a balloon diaphragm. Pressure in the canister causes the balloon diaphragm to be inflated, closing the opening to the scavenging system. The ball in the spill valve ensures that a certain pressure must be present to allow gas flow through the spill valve, even if the balloon diaphragm is deflated. This results in approximately 2 cm H_2O PEEP in the breathing system.

The internal construction is shown in Figures 12.6 to 12.9. The inspiratory pressure regulator reduces the gas from approximately 50 psig to the value indicated on the inspiratory flow gauge. A solenoid in the oxygen line links the pneumatic and electronic portions of the ventilator. When the solenoid is energized, it allows gas to flow through the control valve in the oxygen line to the Venturi mechanism.

A small-diameter tube carries oxygen from the inspiratory flow regulator to the top of the auto-ranging valve, which controls the amount of ambient air entrained at any given inspiratory setting. The auto-ranging valve contains a diaphragm that is depressed when pressure is applied. The plunger moves downward, controlling the opening through which ambient air is entrained during inspiration.

Figure 12.5. Spill valve on Drager AV2+ ventilator. (Courtesy of Drager Medical.)

The control valve allows gas to flow through it when pressure is applied. The Venturi receives oxygen from the control valve and air from the auto-ranging valve and combines them to form the drive gas that pushes the bellows downward during inspiration.

The pilot actuator, which controls the opening of the exhaust valve, operates in response to oxygen pressure that enters at the top. When sufficient pressure is applied, the valve moves downward against the spring, which closes the valve when no pressure is applied. During inspiration, the pressure of the driving gas inside the bellows housing pushes the bellows

downward. When no pressure is applied to the pilot actuator, the exhaust valve opens, and the driving gas flows to atmosphere through the exhaust valve.

Controls

The ventilator can deliver tidal volumes from 20 to 1500 mL. Respiratory rate can be set from 1 to 99 breaths per minute (bpm). Inspiratory flow can be set between 10 and 100 L/minute. The I:E ratio can be set from 1:4.5 to 4:1. The inspiratory pressure limit range is 15 to 120 cm H_2O.

Alarms

The AV2+ alarms are associated with the anesthesia machine and are not part of the ventilator. Alarm messages are displayed on the anesthesia machine monitoring screen. Warnings are accompanied by a three-pulse pattern that is initially repeated every few seconds in a series of descending volume and then constantly at full volume until the alarm condition is resolved. Cautions are accompanied by a three-pulse tone pattern that is repeated every 30 seconds. Advisories utilize a single tone or no sound, depending on the advisory. The highest priority currently active alarm condition is annunciated. Audio signals for lower-priority alarm conditions are temporarily suppressed to minimize confusion caused by simultaneous alarms.

Ventilation Modes

Volume control is the only ventilatory mode on this ventilator. The ventilator is time cycled and volume preset.

Inspiration

During inspiration (Fig. 12.6), the controller energizes the solenoid and pressurizes the control valve, causing it to open. This allows oxygen from the pressure regulator to flow to the bellows assembly. A small portion of the oxygen is diverted to the pilot actuator. This causes the pilot actuator to move downward, sealing the exhaust valve and preventing drive gas from escaping to atmosphere. A small portion of the regulated oxygen also flows to the auto-ranging valve and opens it in proportion to the setting on the inspiratory flow regulator.

Oxygen flows through the Venturi, entraining room air. The drive

gas, consisting of oxygen and entrained air, then pressurizes the space between the bellows and the canister. This causes the bellows to be compressed and gases inside the bellows flow to the breathing system.

The spill valve prevents gases from entering the scavenging system during inspiration. Drive gas flows through the pilot line and inflates a balloon diaphragm that blocks the outlet between the inside of the bellows and the scavenging system. This valve remains closed until the bellows has reached its limit of expansion during exhalation.

Inspiratory Pause

During the inspiratory pause (Fig. 12.7), the controller continues to energize the solenoid. As long as oxygen flows to the bellows assembly, pressure on the pilot actuator is maintained, and the exhaust valve remains closed. Since the bellows is completely compressed, no additional gas can enter the bellows housing, and no more air is entrained by the Venturi. Excess oxygen is vented to atmosphere through the air entrainment port. The pilot line and the balloon diaphragm

in the spill valve remain pressurized, so gas flow to the scavenging system remains blocked.

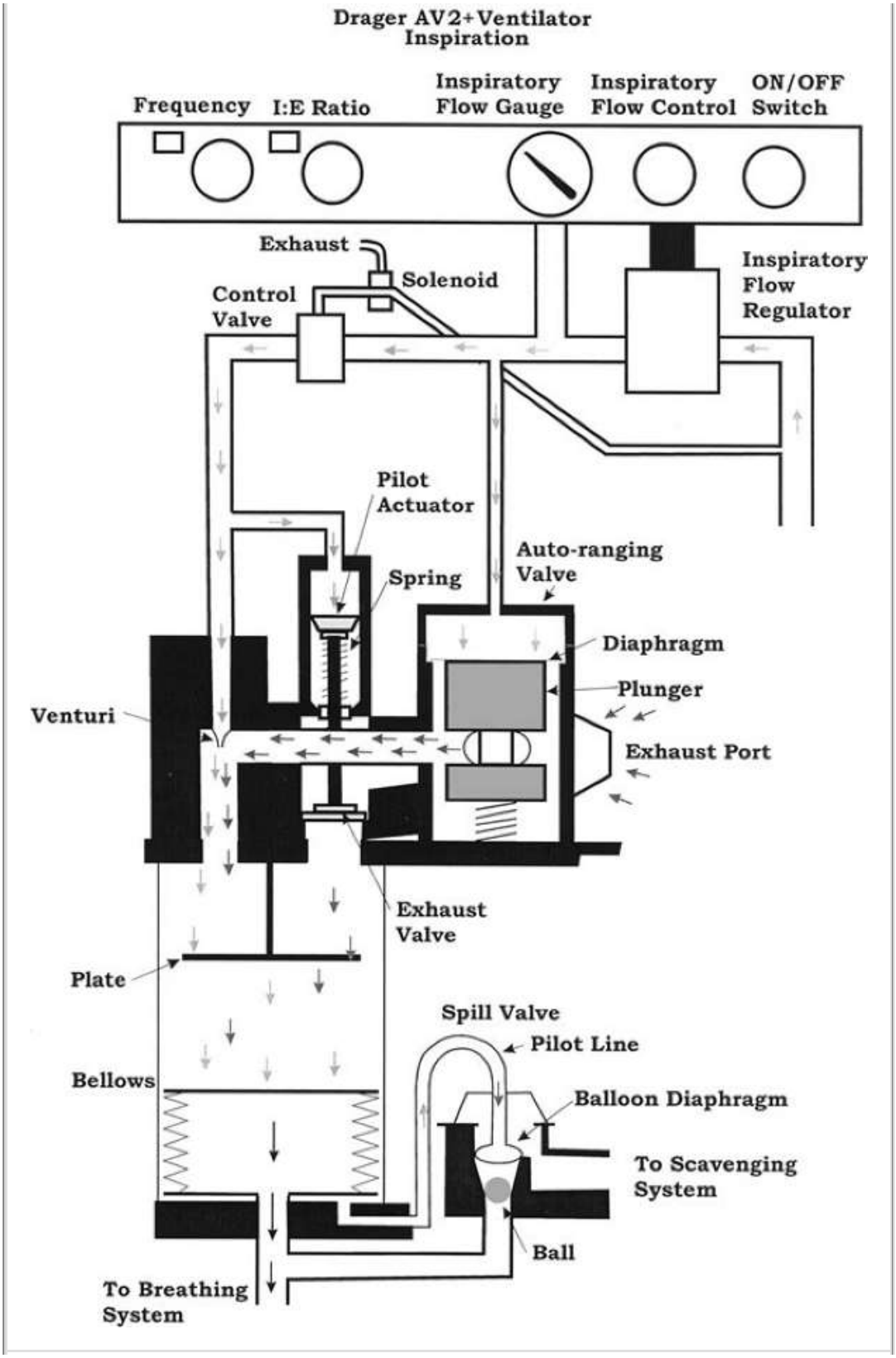

Drager AV2+Ventilator
Inspiration
Frequency
I:E Ratio
Inspiratory Flow Gauge
Inspiratory Flow Control
ON/OFF Switch
Exhaust
Solenoid
Control Valve
Inspiratory Flow Regulator
Pilot Actuator
Spring
Auto-ranging Valve
Diaphragm
Plunger
Venturi
Exhaust Port
Exhaust Valve
Plate
Spill Valve
Pilot Line
Bellows
Balloon Diaphragm
To Scavenging System
Ball
To Breathing System

Figure 12.6 Drager AV2+ ventilator. Inspiration. I:E, inspiratory:expiratory. (Redrawn courtesy of Drager Medical.)

Exhalation

During exhalation (Fig. 12.8), the controller de-energizes the solenoid, which stops the flow of oxygen through it. The oxygen in the tubing between the solenoid and the supply valve is vented to atmosphere via a small exhaust tube at the top of the solenoid. Once this oxygen is vented, the control valve closes and stops the flow of oxygen to the Venturi. This also allows the pilot actuator to depressurize. With the pilot actuator depressurized, the spring forces the plunger upward, opening the exhaust port. Exhaled gases push the bellows upward. Drive gas vents to atmosphere through the exhaust port. As the pressure in the canister decreases, the pressure within the pilot line for the spill valve also decreases, and the balloon diaphragm deflates. The ball check valve below the balloon diaphragm presents more resistance to the flow of exhaled gas than does the bellows, so exhaled gases

continue to fill the bellows. Expiratory flow ends when the bellows reaches the plate at the top.

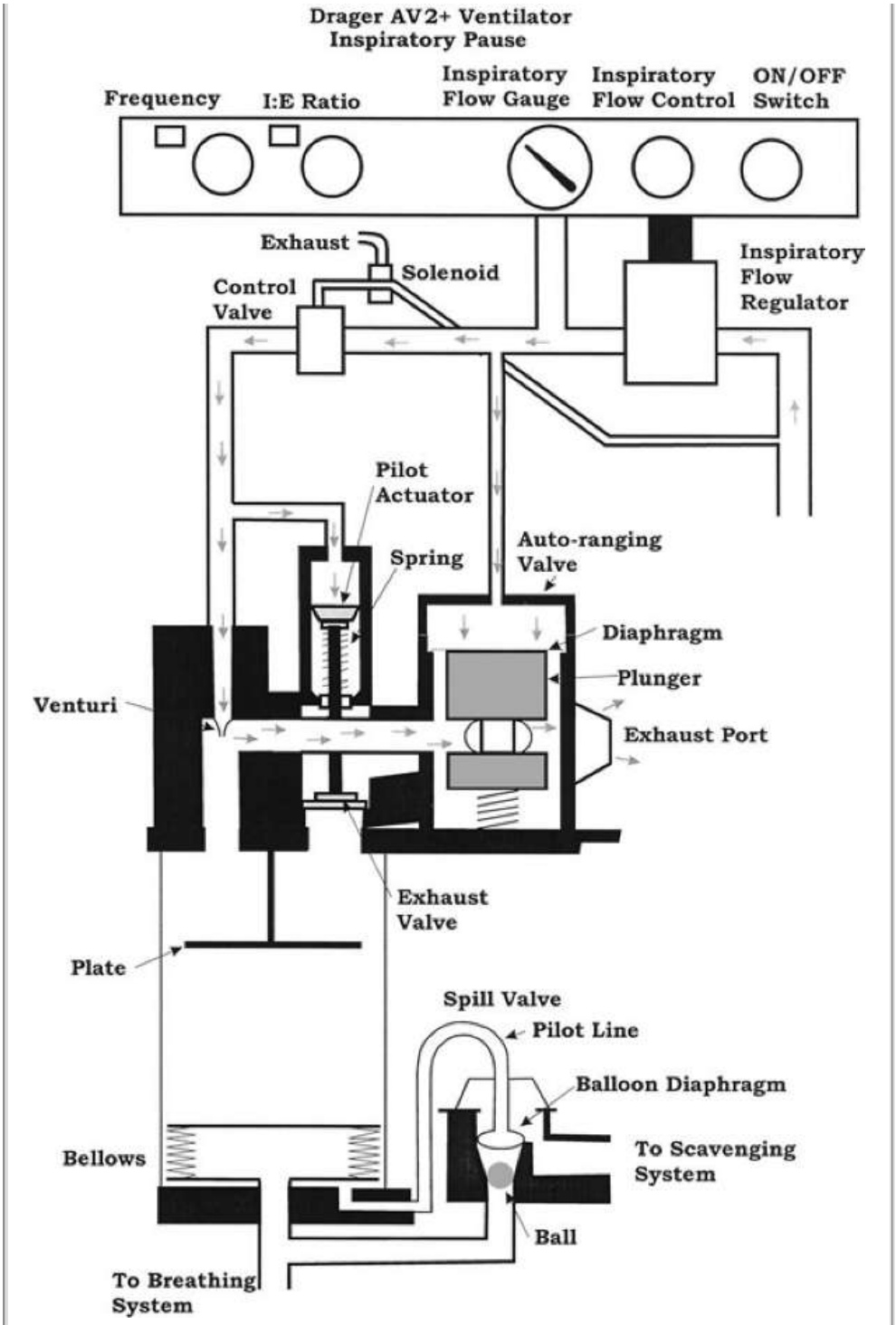


Figure 12.7. Drager AV2+ ventilator. Inspiratory pause. I : E, inspiratory : expiratory. (Redrawn courtesy of Drager Medical.)

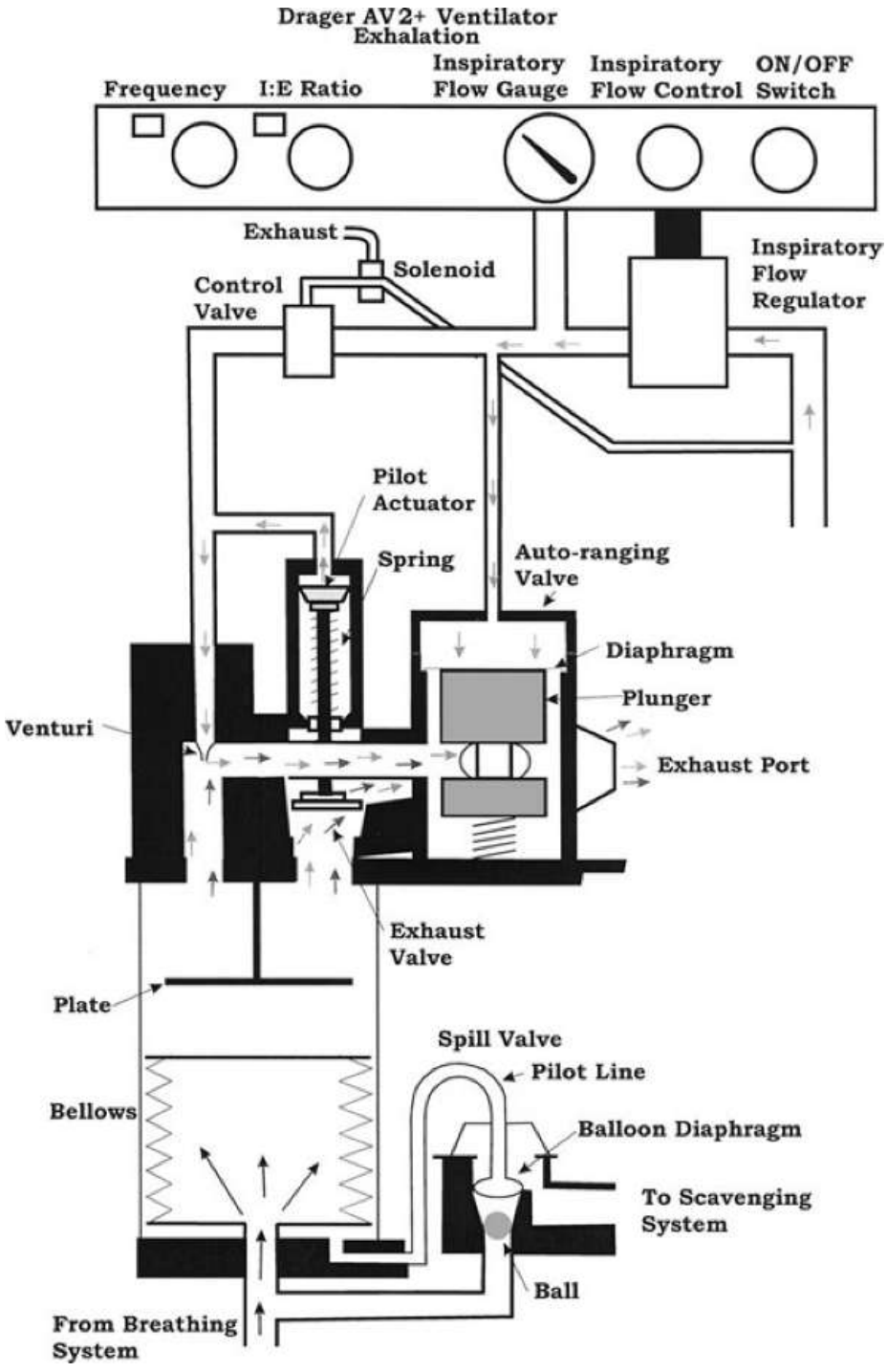


Figure 12.8. Drager AV2+ ventilator. Exhalation. I:E,

inspiratory:expiratory. (Redrawn courtesy of Drager Medical.)

Expiratory Pause

After the bellows has reached maximum expansion (Fig. 12.9), the expiratory pause time begins. The solenoid and the supply valve remain closed. The pressure in the pilot line to the spill valve decreases to atmospheric, and the balloon diaphragm deflates. When pressure from gas in the bellows exceeds the resistance created by the weight of the ball in the spill valve, the ball is lifted, and gases can flow into the scavenging system.

Special Features

A safety relief valve vents drive gas to atmosphere if the drive gas pressure exceeds 120 cm H_2O.

In the event of mains power failure, a fully charged battery will power the ventilator for approximately 20 minutes. There are yellow indicators to signify that there is alternating current (AC) power failure and that the battery power is low. If the machine has switched to

battery power, a three-pulse tone sounds every 30 seconds. A battery test button is present on the machine. A green battery test indicator signifies that the battery power is satisfactory. Battery messages are displayed on the monitor screen.

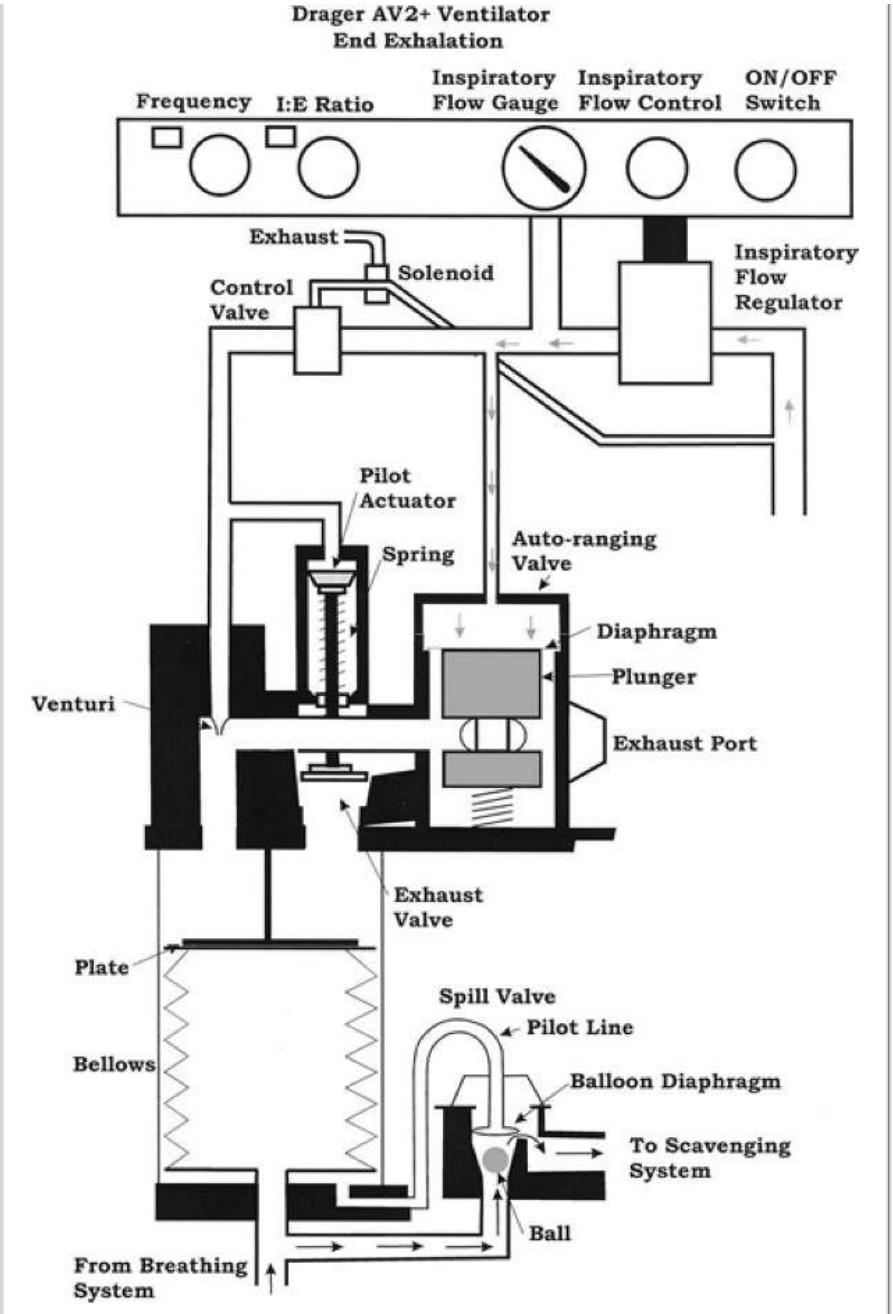


Figure 12.9. Drager AV2+ ventilator. End exhalation. I:E, inspiratory:expiratory. (Redrawn courtesy of Drager Medical.)

Hazards

The problems discussed below were reported with the predecessor AV-E ventilator. Since the two ventilators are similar in construction, there is a possibility that similar problems could occur with the AV2+ ventilator.

A case has been reported in which the muffler placed over the driving gas exhaust became saturated with water and obstructed the flow from the bellows chamber (49). This resulted in high airway pressures as gas continued to flow into the ventilator.

In another reported case, the control valve malfunctioned, resulting in continuous driving gas flow to the bellows (50). High airway pressures resulted.

Prolongation of the inspiratory phase owing to insufficient parts lubrication has been reported (51).

Ventilatory irregularities resulting from improper seating between the bellows and its mount have been reported (52).

There has been a report of the spill valve becoming incompetent, resulting in hypoventilation (53). In other reported cases, the pilot line connecting the bellows chamber to the spill valve became kinked so that it was occluded (54,55). If the pilot line becomes occluded during inspiration, hypoventilation will result because the spill valve will be open. If the occlusion occurs during exhalation, gas will be unable to exit the circuit, and the pressure inside the circuit will increase.

PEEP can result under certain circumstances. This was reported when some hoses were draped over the spill valve, partially obstructing the pilot line (56,57).

Cleaning and Sterilization

Cleaning and disinfection or sterilization are complicated matters beyond the scope of this text. They are explained in detail in the operator's manual.

Drager Divan

The Divan ventilator (digital ventilator for anesthesia) is a component of the North American Drager 6000 series machines.

Description

The ventilator control panel (Fig. 12.10) is situated at the front of the anesthesia machine below the desktop. To alter a function, the key for that function is pressed. Changes are made by using the rotary knob at the right of the control panel and the change confirmed by pressing the knob. If the altered value or mode is not confirmed within 10 seconds, the ventilator returns to the previous value.

At the left side of the control panel is a Manual/ Spontaneous key. After pressing this key and confirming the setting, the patient can breathe spontaneously or be ventilated manually by adjusting the APL valve.

Below the Manual/Spontaneous key is the Volume Mode key. When it is pressed and its function confirmed, the ventilator goes into the volume control mode. Below the volume mode key is the SIMV key. To the right of this key is the key for pressure control ventilation (Pres Mode).

To the right of the Manual/Spontaneous key is a window with a bar graph that indicates piston movement and displays the percent of the set tidal volume (0% represents full exhalation, while 100% indicates inspiration to the set tidal volume).

Below the bar graph window is a numeric display window that displays the values for the keys below it. At the left is the setting for maximum allowable pressure (Pmax) in the volume and SIMV modes or preset airway pressure (Pset) in the pressure control mode. In the middle is the setting for tidal volume in the SIMV and volume control modes. At the right is the respiratory rate setting. To alter a parameter, the key under it is pressed and the rotary knob rotated to increase or decrease the setting. The new value is displayed in the window above the key. When the proper

value is displayed, it is confirmed by pushing the rotary knob.

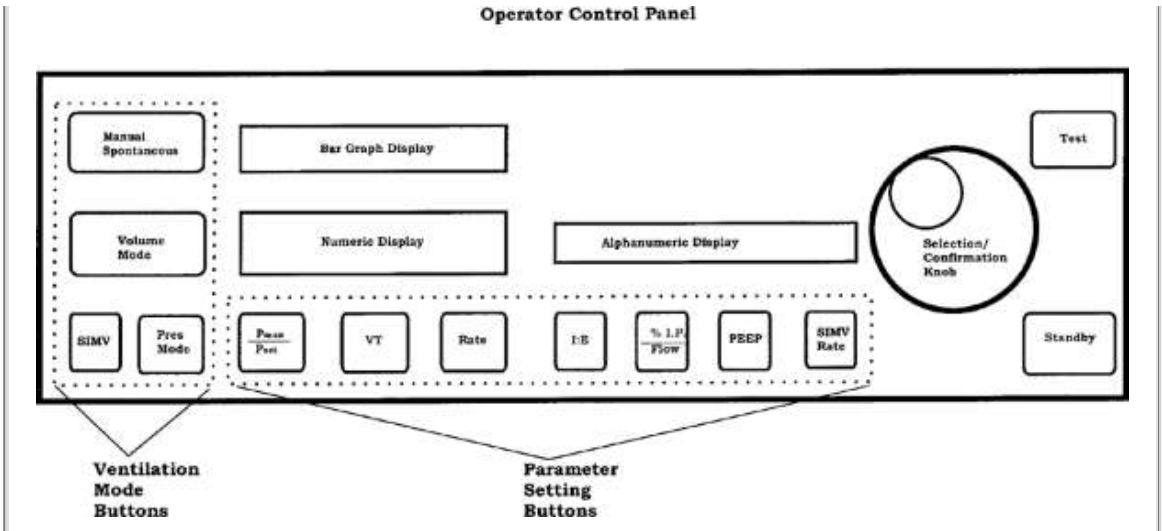


Figure 12.10. Control panel of Divan ventilator. (Redrawn courtesy of Drager Medical.)

To the right of the numeric display is an alphanumeric display. This prompts the operator to take certain actions during the checkout procedure and updates the progress of the checkout. After a change in ventilatory mode or parameter is made, there will be a prompt to confirm the change. Other messages reporting status and faults are displayed here.

Under the alphanumeric display are additional keys. The I:E key sets the I:E ratio. The % I.P./Flow key sets the ratio of inspiratory pause time to inspiration phase time in the volume control and SIMV modes and the inspiratory flow rate in the pressure control mode. The PEEP key is used to set the PEEP in all modes. The SIMV Rate key sets the minimum ventilatory rate in the SIMV mode.

At the right side of the control panel is a standby key. In this mode, drive gas use is minimized, and inspection or repairs can be performed.

Above the standby key is a test key. This causes the ventilator to measure system compliance and leakage. This can only be initiated when the ventilator is in the standby mode.

Below the tabletop is an electrically powered piston (Fig. 12.11). The manufacturer offers an optional top cover with a transparent

window that allows the user to see piston movement. If there is inadequate gas in the breathing system to allow the piston to retract fully, the piston will stop and alert the anesthesia provider. This will prevent a negative pressure from being exerted (23).

A heater is incorporated into the absorber head to minimize moisture condensation.

The internal construction of the ventilator and breathing system is shown in Figures 12.12 to 12.17. V1 is the fresh gas decoupling valve. V2 is the surplus gas valve. V3 is the valve that controls gas flow to the APL and gas relief valves. Gas is aspirated from near the patient port, analyzed, and returned to the circuit downstream of the expiratory unidirectional valve. An ultrasonic flow sensor (Chapter 23) and PEEP valve are located in the expiratory limb.

Controls

The ventilator cannot be set to values resulting in an inspiratory flow greater than 75 L/minute, a minute volume greater than 25 L/minute, or an expiratory time of less than 400 ms.

PEEP can be set from 0 to 20 (default 0) cm H_2O. PEEP is not available in the Man/Spont or SIMV modes.

The peak airway pressure (Pmax/Pset) can be set from 10 to 80 (default 25) cm H_2O in the volume control and SIMV modes and 10 to 70 (default 10) cm H_2O in the pressure control mode.

When the maximum allowable pressure is reached, flow is adjusted so that the pressure remains constant through the end of inspiration. In this situation, the full tidal volume may not be delivered.

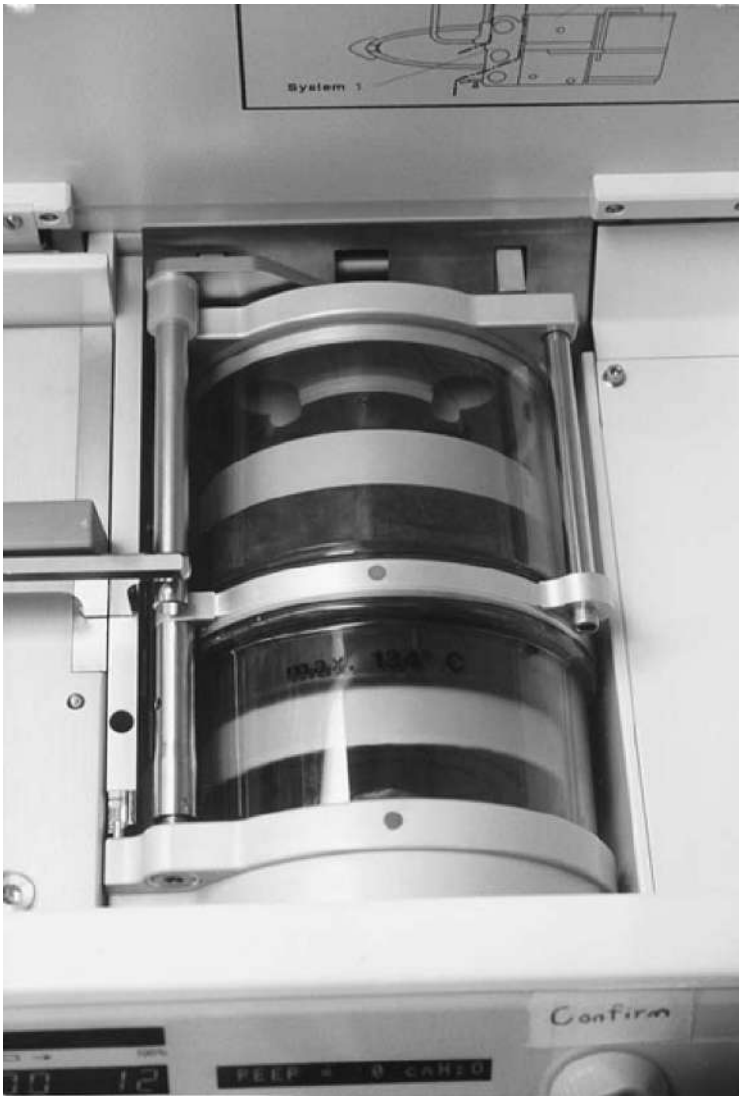


Figure 12.11. Piston ventilator of Divan ventilator. (Courtesy of Drager Medical.)

The minimum difference between Pmax and PEEP is 5 cm H_2O. If the pressure increases by more than 5 cm H_2O above Pmax, inspiration is immediately stopped and expiration begins.

The % inspiratory pause/flow (% I.P./Flow) sets the length of the inspiratory pause in the volume control and SIMV modes or the inspiratory flow in the pressure control mode. The pause range is 0% to 60% (default 10%). During pressure control ventilation, the

inspiratory flow rate can be set from 5 to 75 (default 50) L/minute.

The available tidal volumes are 10 to 19 mL, 20 to 100 mL, and 110 to 1400 (default 600) mL.

The respiratory rate range is 6 to 80 (default 12) bpm in the volume and pressure control modes and 3 to 80 (default 12) bpm in the SIMV mode.

The range of available I:E ratios is 1:3 to 2:1 (default 1:2). If an inverse I:E ratio is set and confirmed, a message is displayed.

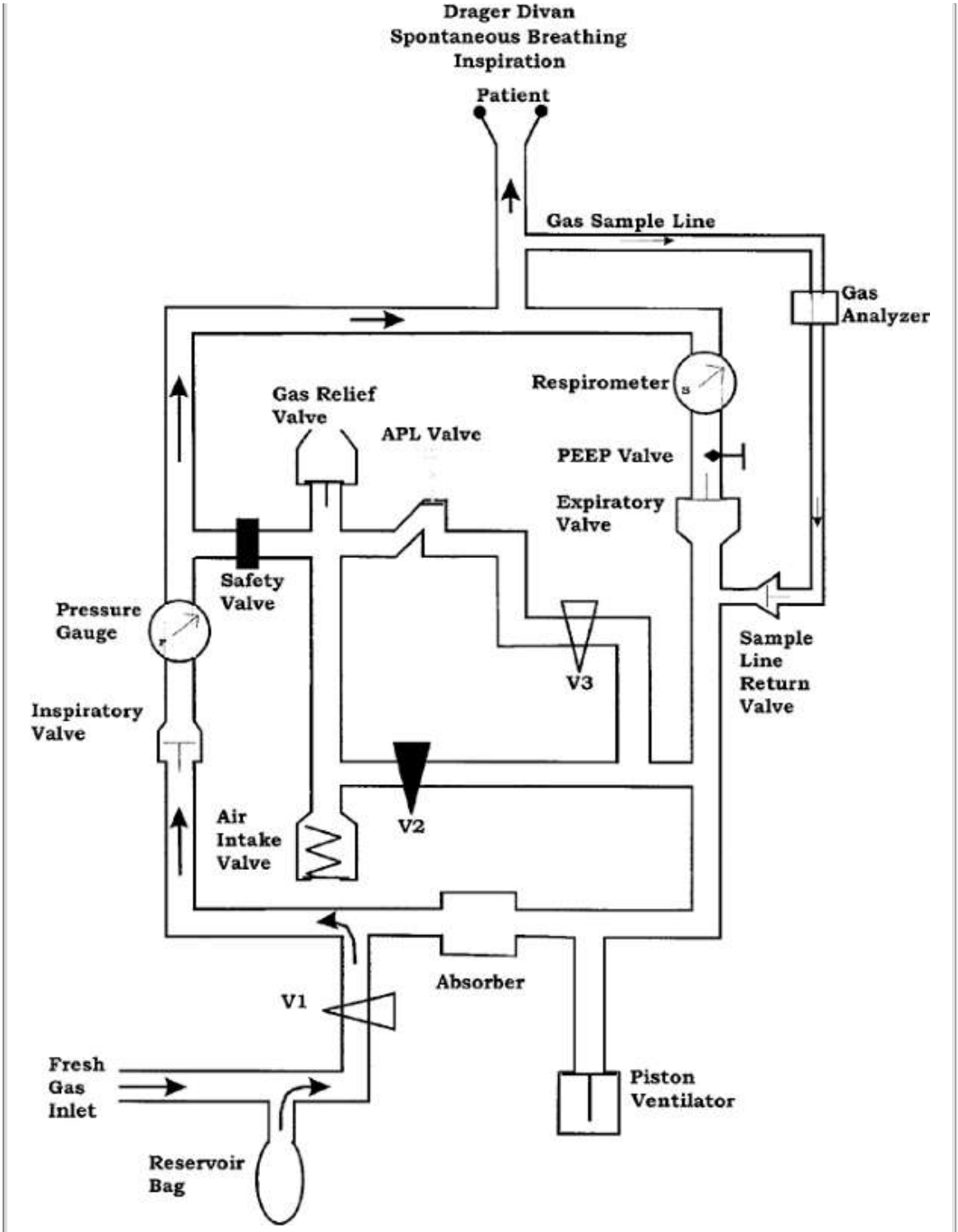


Figure 12.12. Divan ventilator. Spontaneous inspiration. APL, adjustable pressure limiting; PEEP, positive end-expiratory pressure. (Redrawn

courtesy of Drager Medical.)

Alarms

Alarm limits, which depend on the ventilatory mode and the patient, are presented in an alarm window on the machine monitor screen. If an alarm limit is exceeded or not reached, the alarm limits menu is displayed, and the value is highlighted. Related alarms are combined. A message that indicates the computer analysis of the problem will appear.

The alarm silence key in the alarm window allows the alarms to be audio paused (silenced) for 60 seconds if pressed once and for 120 seconds if pressed twice. Alarms can be suspended by pressing a key on the bottom of the screen.

Warnings are announced by a three-tone sequence of high, high, low. The tones are also in a sequence of different volumes with the first and fourth sequence being at full volume. Alarm messages are displayed on a flashing red background with white text. The flashing stops when the alarm silence button is depressed. Flashing resumes when the audio pause (silence) period has ended.

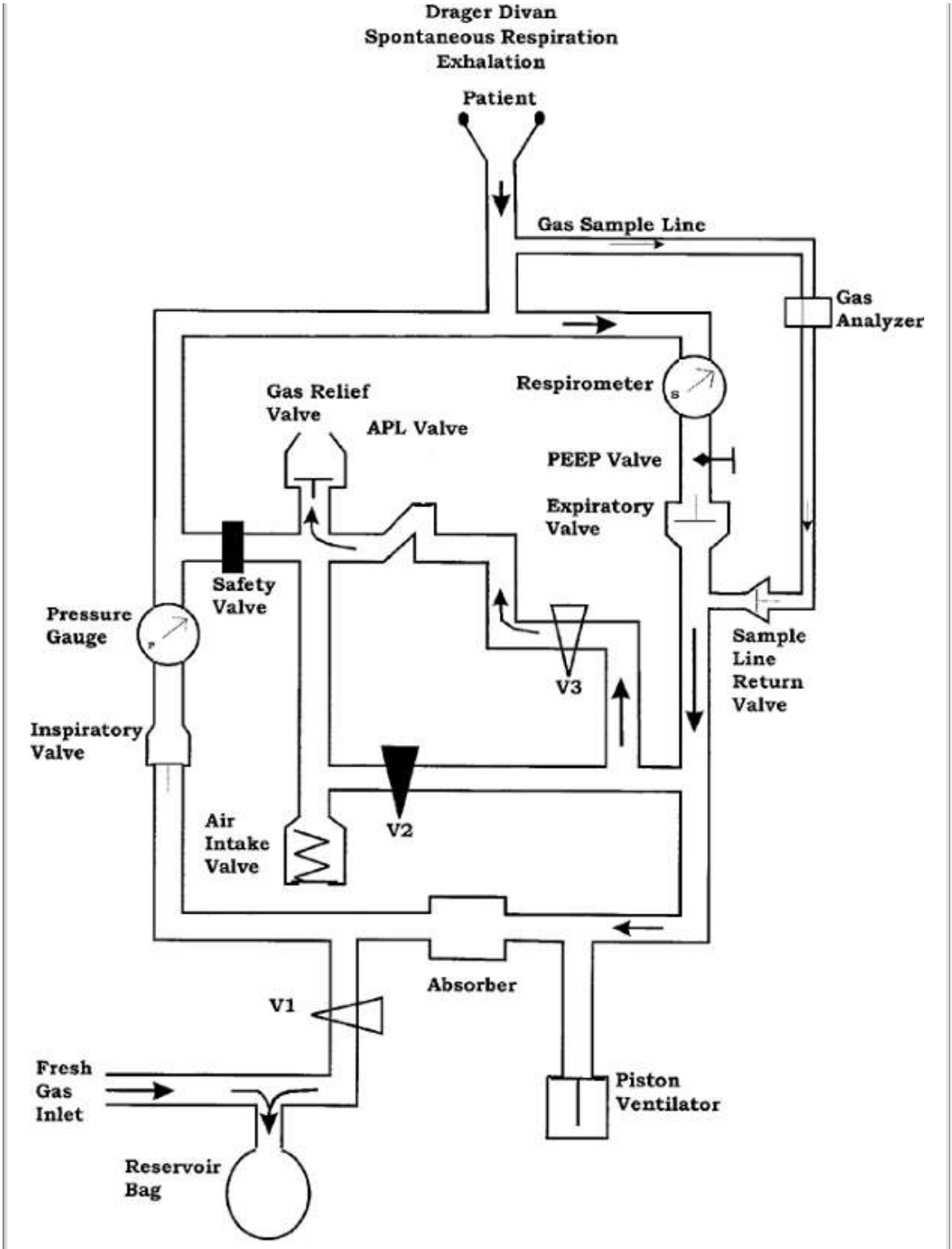


Figure 12.13. Divan ventilator. Spontaneous exhalation. APL, adjustable

pressure limiting; PEEP, positive end-expiratory pressure. (Redrawn courtesy of Drager Medical.)

Cautions are displayed on a flashing yellow background in black text. The messages are announced by a three-tone burst of low, low, high. Announcements occur every 30 seconds.

Advisories are displayed on a white background with black text that does not flash. A single tone may sound.

An alarm log can be accessed. It will allow the clinician to observe all alarm events that have occurred during the case. It can store up to 500 events.

Ventilation Modes

The desired mode (Volume or Pressure Control or SIMV) is selected by pushing the key for that mode and confirming that choice.

In the pressure control mode, inspiratory flow rate can be set independent of airway pressure (Pset). However, Pset may not be achieved if the inspiratory flow rate is too low. In this case, an alarm message will be displayed.

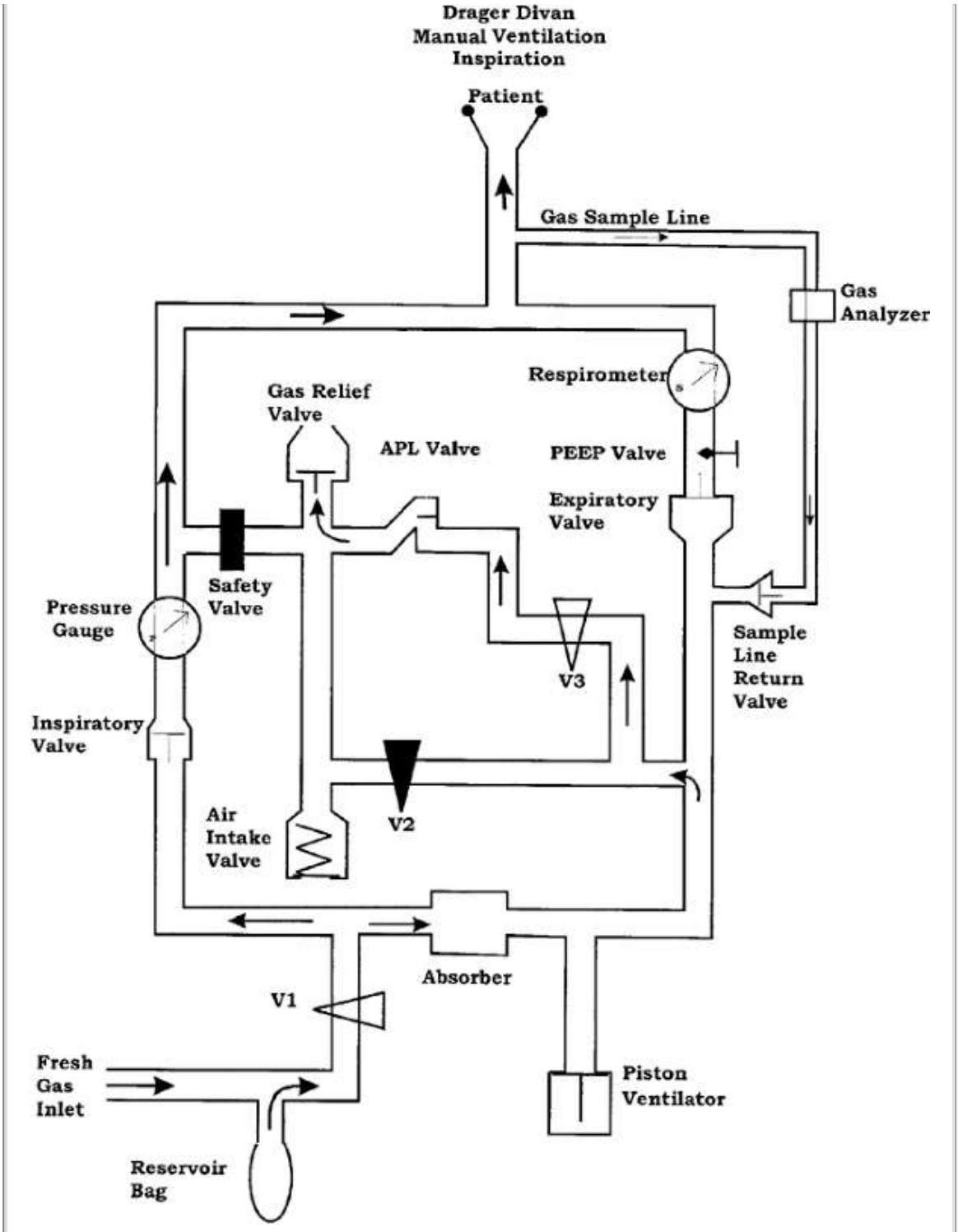


Figure 12.14. Divan ventilator. Inspiration during manual ventilation. APL, adjustable pressure limiting; PEEP, positive end-expiratory

pressure. (Redrawn courtesy of Drager Medical.)

During SIMV, the time between each mandatory respiration and the beginning of the next is subdivided into a spontaneous breathing time (Tspont) and a trigger time (Ttrigger). During the trigger time, the system checks whether the airway pressure has dropped at least 0.5 cm H_2O below the pressure measured at the end of expiration. If this has not occurred, the ventilator delivers a breath.

Spontaneous Breathing

To allow spontaneous breathing, the MANUAL/SPONTANEOUS key is pressed and the APL valve set to SPONT. Valves V1 and V3 are open, while V2 is closed. When the patient inspires (Fig. 12.12), the inspiratory valve opens, and gas flows from the reservoir bag. During exhalation (Fig. 12.13), the expiratory valve opens, and exhaled gases pass through the absorber and into the bag. During late exhalation, the pressure rises,

and excess gas flows through V3 and the gas relief valve to the scavenging system.

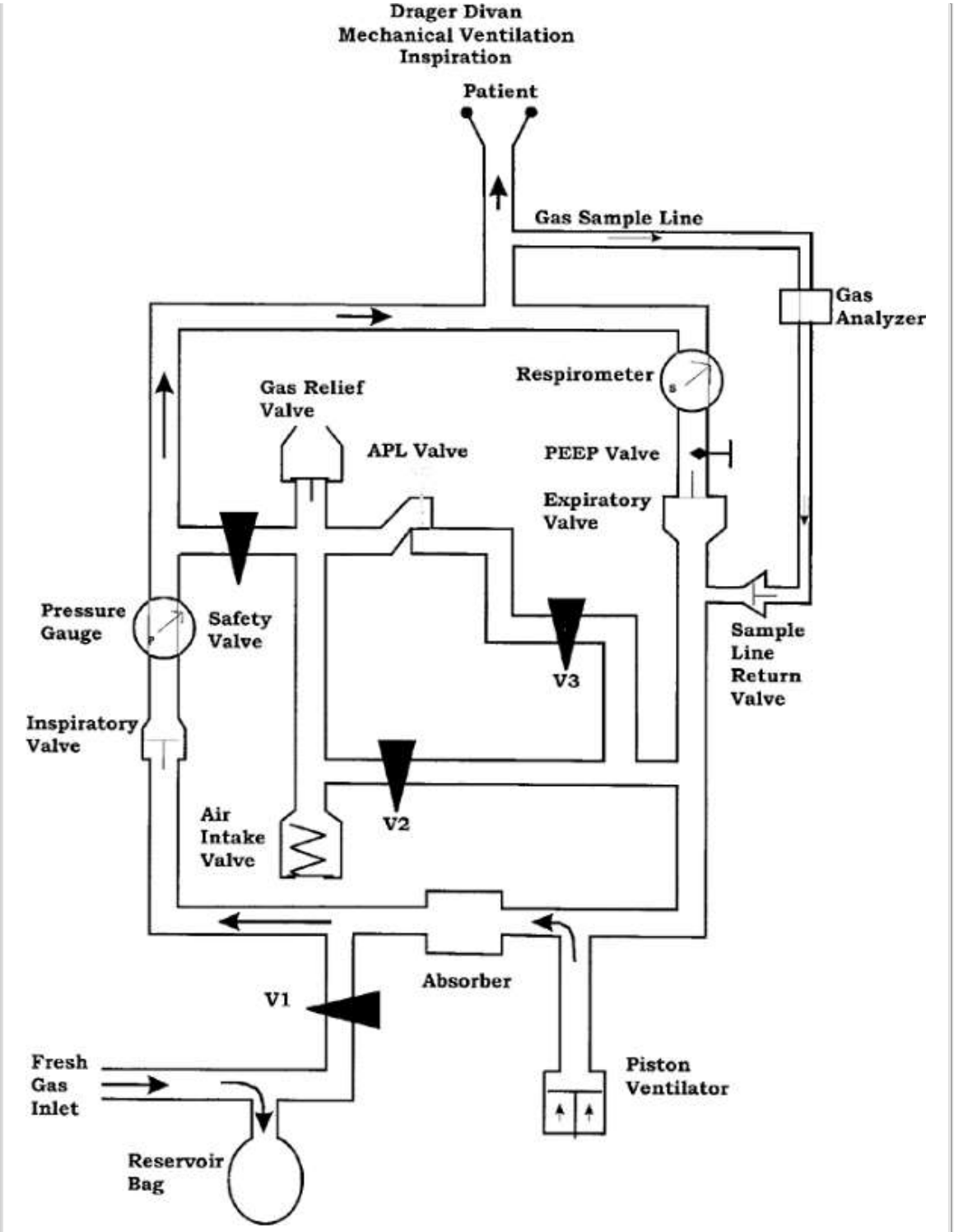


Figure 12.15. Divan ventilator. Inspiration during mechanical ventilation. APL, adjustable pressure limiting; PEEP, positive end-expiratory

pressure. (Redrawn courtesy of Drager Medical.)

Manual

For manual ventilation, the Manual/Spontaneous key is pressed, and the APL valve is set to MAN. The pressure during inspiration will be limited by the APL valve setting. When the pressure limit is reached, excess gas will flow through V3 and the APL valve to the scavenging system through the gas relief valve (Fig. 12.14). During exhalation, exhaled gases flow through the absorber into the reservoir bag.

Mechanical

When mechanical ventilation is selected, the APL valve is closed. The bag functions as a reservoir for fresh gas.

During inspiration (Fig. 12.15), valves V1, V2, and V3 are closed. Piston movement produces gas flow through the inspiratory valve to the patient port. Fresh gas

continues to enter the reservoir bag but does not affect the tidal volume, because valve V1 is closed (fresh gas decoupling).

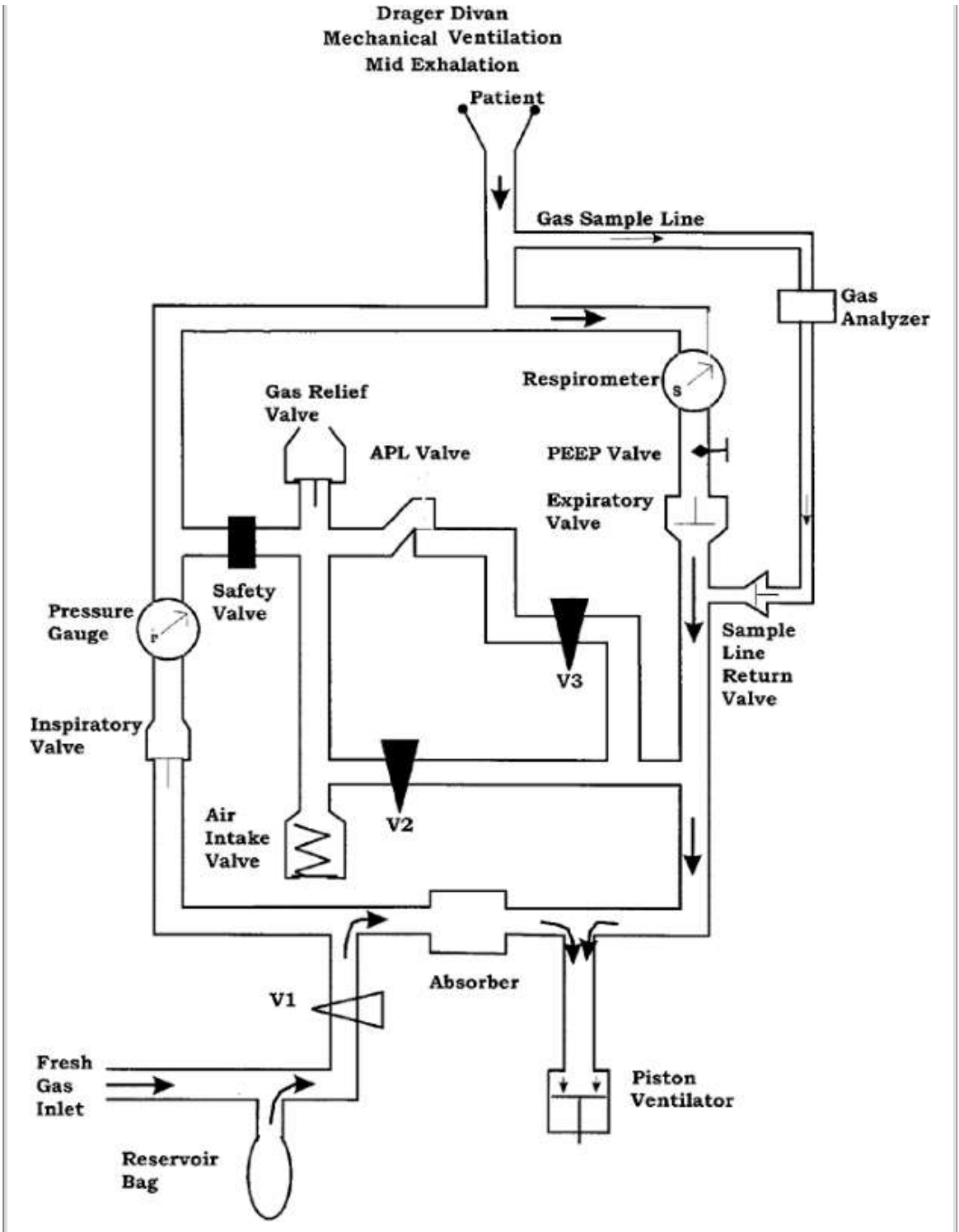


Figure 12.16. Divan ventilator. Mid exhalation during mechanical ventilation. APL, adjustable pressure limiting; PEEP, positive end-

expiratory pressure. (Redrawn courtesy of Drager Medical.)

When exhalation begins, the expiratory valve opens, allowing exhaled gases to flow through the absorber and into the retracting piston and to the reservoir bag through V1, which opens. Valves V2 and V3 remain closed. Fresh gas flowing into the system mixes with some of the exhaled gases in the piston ventilator. Mid exhalation is depicted in Figure 12.16. The piston retracts, allowing the cylinder to fill with gas from the reservoir bag and fresh gas. During the later part of exhalation (Fig. 12.17), V2 opens, and gases are vented to the scavenging system through the gas relief (spill) valve.

Special Features

The Divan ventilator decouples fresh gas flow from tidal volume. Fresh gas entering the circuit during inspiration

is isolated from the patient circuit and accumulates in the reservoir bag. If the oxygen flush is activated during inspiration, the gas will not be added to the tidal volume but will enter the reservoir bag (23). The reservoir bag will inflate and deflate during mechanical ventilation.

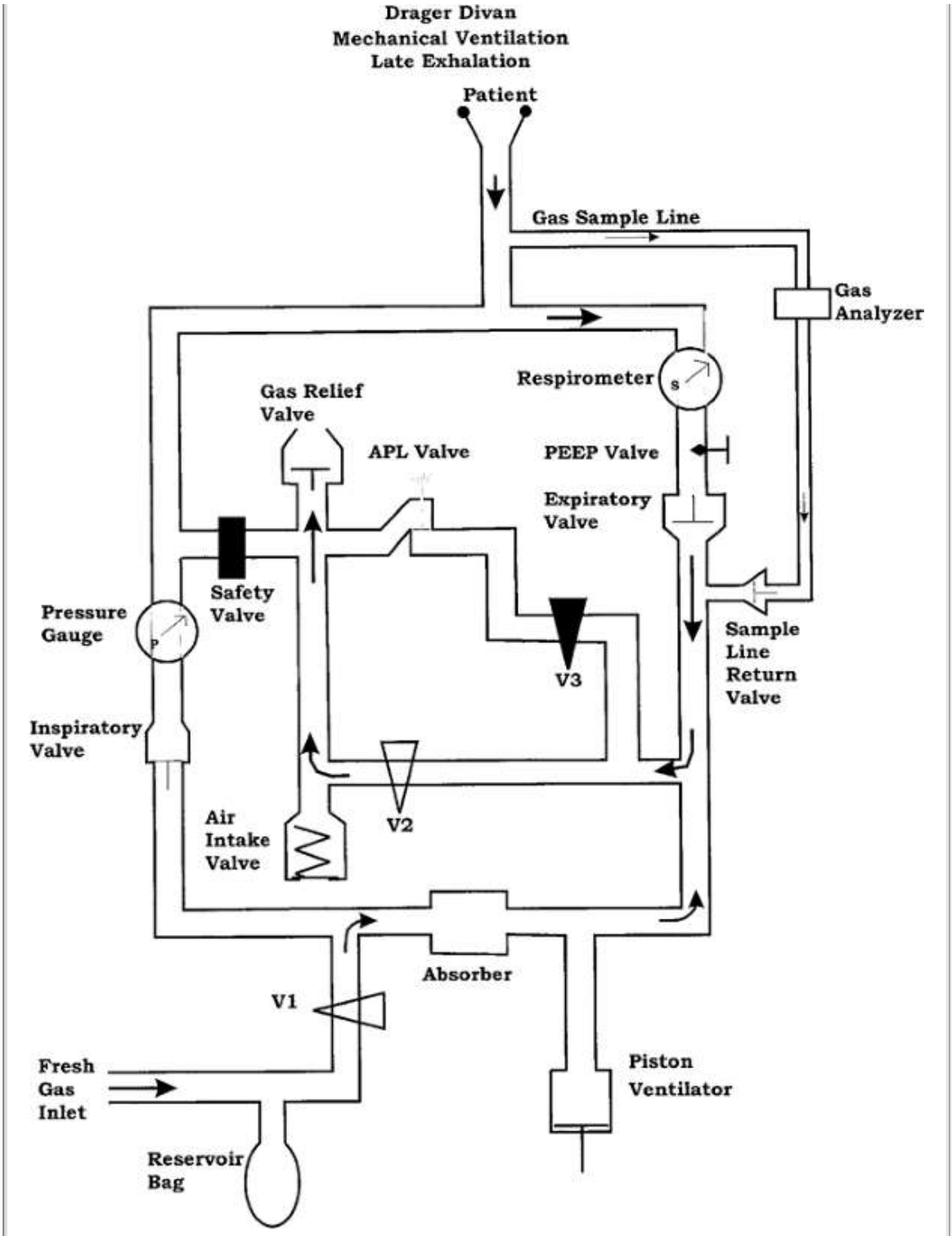


Figure 12.17. Divan ventilator. Late exhalation during mechanical ventilation. APL, adjustable pressure limiting; PEEP, positive end-

expiratory pressure. (Redrawn courtesy of Drager Medical.)

This ventilator compensates for breathing system compliance and gas compression so that the patient receives the set tidal volume. Information that makes tidal volume compensation possible is gathered during the automated checkout. The Y-piece must be occluded and fresh gas flow set at a minimum to perform these measurements.

Small-diameter breathing tubes are recommended for pediatric patients where tidal volumes are less than 200 mL. After switching to the pediatric tubes, the leak and compliance test should be performed before the patient is connected to the ventilator. If a low-compliance circuit such as a pediatric circuit were added without

conducting a compliance test, the ventilator could deliver excessive volumes. To prevent this from occurring when a tidal volume of less than 200 mL is selected, the ventilator will use the measured circuit compliance only if it is 0.8 mL/cm H_2O or less (58). If the measured circuit compliance is higher, a default value of 0.6 mL/cm H_2O is used.

The breathing system and piston assembly are designed to minimize circuit volume and the time that it takes the system to respond to changes in fresh gas composition. A low-flow wizard helps the clinician to assess the fresh gas surplus. It provides graphical information of fresh gas surplus, a message report, and a help key. The message area gives recommendations for use with low flows, including bag size and ventilator settings.

When the anesthesia machine is turned ON, an automated checkout process that requires about 5 minutes is set in motion. Other than a few prompts reminding the anesthesia provider to set a pressure at the APL valve and to occlude the Y-piece on the breathing system, this checkout is fully automatic. The checkout allows the computer to determine information about gas compression, leaks, and compliance of the breathing system.

If the ventilator detects an internal fault that might affect patient safety during mechanical ventilation, it initiates a safe state in which ventilation can be continued in the Manual/Spontaneous

mode. When the ventilator enters the safe state, the clinician is alerted by a display reading ‾€Equipment Fault,‾€ and an audible tone sounds. The ventilator now performs as if it were in the manual/spontaneous mode.

The ventilator override button is on the machine near the absorber head. It is provided in the event there is an unforeseen condition that the software does not recognize. Activating this override removes power from the ventilator and allows manual or spontaneous ventilation.

The Narkomed 6000 has battery backup that will power the machine and ventilator for at least 30 minutes. An alarm indicates when the battery has only another 10 minutes. After the batteries are exhausted, the machine can continue to be used with manual ventilation or spontaneous breathing.

Respitone is an option on the 6400 anesthesia machine. It is a ventilation sound composed of two distinct tones. One tone annunciates when the pressure waveform crosses the apnea threshold during inhalation. Another tone annunciates on the rising edge of a carbon dioxide waveform corresponding to exhalation.

Evaluation

A comparison between a Divan and an AV2+ ventilator was made during simulated ventilation of pediatric patients (59). The Divan offered advantages in the low tidal volume range during volume control ventilation.

The Divan and an ICU ventilator were compared by using both an infant lung model and infants with congenital heart disease (60,61). Both ventilators provided adequate ventilation in the volume control mode.

In comparison with an ICU ventilator and an anesthesia ventilator with a gas-powered bellows during pressure control ventilation, the Divan maintained tidal volume with increasing respiratory rates better than the other anesthesia ventilator but not as well as the ICU ventilator (2).

Hazards

A high negative pressure applied to the airway can exceed the ability of the ventilator's negative pressure relief valve, causing

the piston to lock (62,63). The problem can be remedied by opening the ventilator cover and removing the piston to break the negative seal.

The ventilator override button is in a rather inconspicuous place (64).

A case of power supply failure that interrupted ventilation has been reported (64,65). The linkage to the backup batteries prevented them from kicking in.

Cleaning and Disinfection

Most of the ventilator parts, including those exposed to breathing gases, can be steam autoclaved. See the operation manual for specific disassembly and sterilizing instructions.

Drager Fabius GS

Description

On the Fabius machine, the ventilatory module, which includes a piston, is located behind a door on the left side of the machine (Fig. 12.18). The piston is inside a metal case that will swing out when the door is opened (Fig. 12.19). A window allows the operator to view piston movement.

The piston assembly is shown in Figures 12.20 and 12.21. Electrical power is used to raise and lower the piston. The motor is near the bottom of the cylinder that holds the piston. There are two rolling diaphragms that seal the piston and prevent mixing of ambient and respired gases. The upper diaphragm is attached at the top and fits over the upper end of the piston. The lower part of upper diaphragm rolls upward and downward as the piston moves upward and downward (Fig. 12.20). The lower diaphragm is connected between the piston wall and the inside of the cylinder. As the piston moves downward, the space above the upper diaphragm increases, allowing exhaled gases to enter that space. There are high pressure and negative pressure relief valves on the top of the piston, connecting with the space for respired gases.

Figure 12.18. Drager Fabius GS ventilator. A window allows the operator to view piston movement.

P.335

The display screen is shown in Figure 12.22 (see page 338). At the left side are keys that determine the ventilatory mode (volume control, pressure control, manual/spontaneous). A rotary mouse is at the bottom right of the screen. Once a parameter is selected, the value is altered by turning the rotary mouse and is confirmed by depressing it. The Standby key is to the right of the rotary mouse. To the right of the rotary mouse and above the Standby key is the Mains Power light-emitting diode (LED), which, when lit, confirms that the machine is connected to a functioning electrical system.

To the right of the screen are three keys. The bottom one is the Home key. It causes the main screen to be displayed. The Setup key is above the Home key. When pressed, the displayed window enables the operator to view and change ventilation and to review settings.

P.336

Above the Setup key is the Alarms key. When pressed, alarm limits are shown on the right side of the screen. To the right of the Alarms key is the Alarm Silence key. Pushing this causes

active alarms to be audio paused for 2 minutes.

Figure 12.19. Drager Fabius GS ventilator. When the door is opened, the piston ventilator, which is inside a metal case, will swing out.

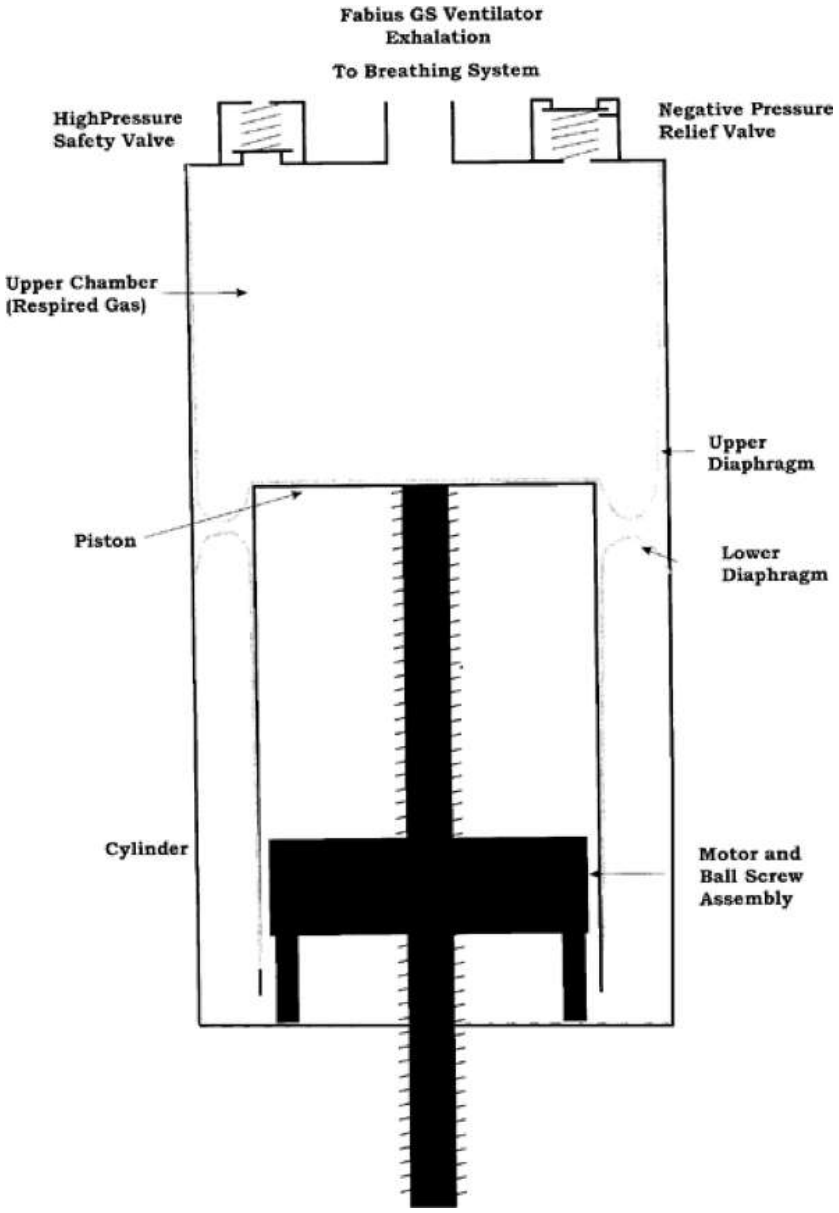


Figure 12.20. Piston assembly. As the piston moves downward, the upper diaphragm moves downward with it, creating a space for respired gases.

To the right of the Alarms key are two LED lamps that indicate the urgency of the alarm message. A status bar near the top of the screen displays the ventilatory mode being used. It also displays alarm silence status, battery power level, and the time.

To the left side of the screen are virtual flowmeters for air, oxygen, and nitrous oxide. To the right of the flowmeters in the upper third of the screen is an alarm window. This displays up to four of the highest priority

alarms. To the right of this window, the inspired oxygen concentration and alarm limits for oxygen concentration are displayed. The respiratory volume monitor window is the middle window to the right of the flowmeter window. It displays respiratory rate and tidal and minute volumes. Below the respiratory volume window is the breathing pressure monitor window. It displays PEEP values and peak and mean inspiratory pressures. Below the flowmeters and the breathing pressure window is the breathing pressure waveform window. Below this are six windows associated with ventilator parameters. Below these windows are keys for the associated parameters.

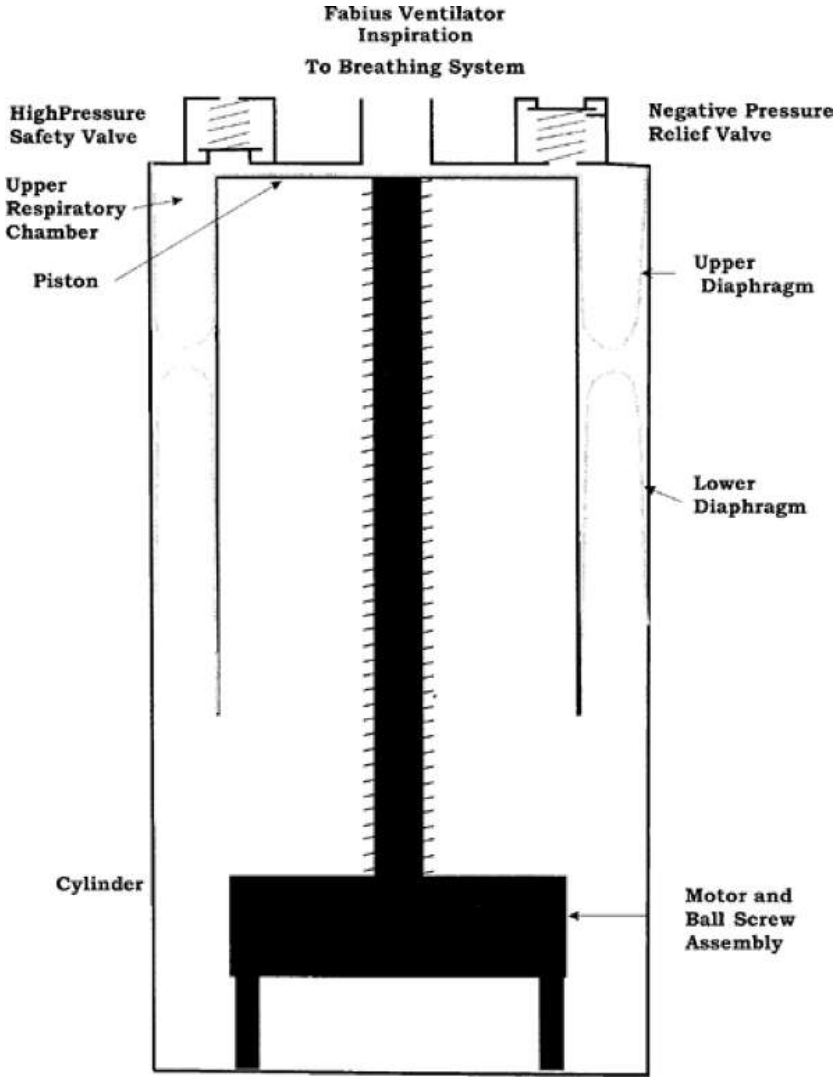


Figure 12.21. As the piston moves upward, gases are forced out of the space at the top.

Controls

The range for the maximum ventilation pressure (P_{MAX}) is 10 to 70 (default 40) cm H_2O. Other controls are discussed under the individual ventilation modes.

With volume control ventilation frequency can be set from 4 to 60 (default 12) bpm. The time ratio between the inspiratory and expiratory time phases (Ti:Te) range is 4:1 to 1:4 (default 1:2).

The inspiratory pause can be set from 0% to 50% (default 10%). PEEP can be set from 0 to 20 (default 0) cm H_2O. The range for tidal volume is 20 to 1400 (default 600) mL.

In the pressure control mode, the inspiratory pressure (P_{INSP}) can be set from 5 to 60 (default 15) cm H_2O,

and the inspiratory flow can be set from 10 to 75 (default 30) L/minute. PEEP can be set from 2 to 20 (default 0) cm H_2O. Ventilation frequency can be set from 4 to 60 (default 12) bpm.

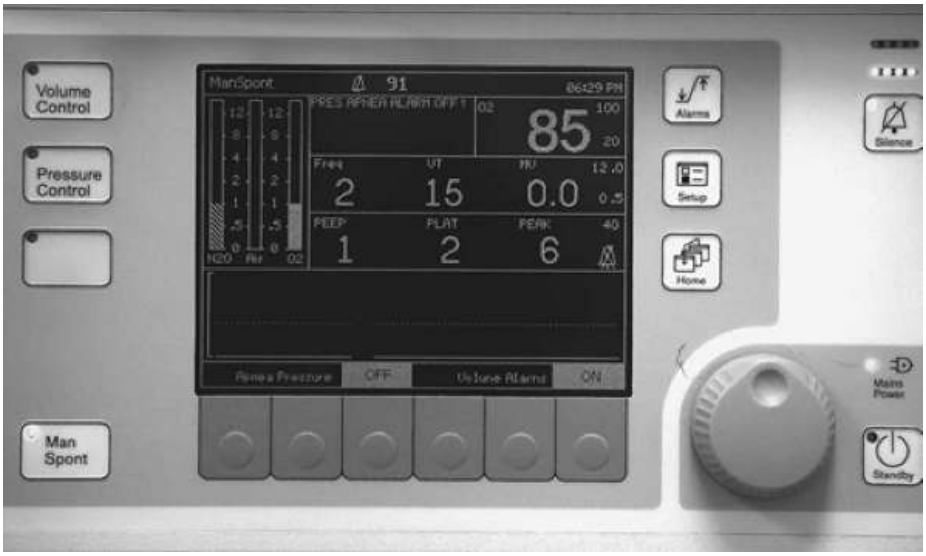


Figure 12.22. Display screen for the Drager Fabius GS ventilator.

Alarms

Alarms are automatically enabled when the ventilator is switched to a ventilation mode. Alarm messages are displayed in the alarm box in the center of the top of the data screen. The text displays are followed by exclamation marks (!). There are three marks (!!!) for warnings, two (!!) for caution, and one (!) for advisories. The LEDs to the right of the alarm silence key indicate the urgency of the alarm condition. A warning is signaled by a blinking red LED. A caution is expressed by a

blinking yellow LED. An advisory is indicated by a continuous yellow LED. Warning tones are continuous. Caution tones enunciate every 30 seconds. An advisory has a single or no tone.

Ventilation Modes

The Fabius offers volume control and pressure control ventilation. PSV can be added. When the ventilation mode is changed, the function is displayed across the bottom of the data screen and above the appropriate key.

Standby

In the Standby mode, the ventilator stops, and the monitoring and alarms are turned OFF. If gas flow is detected, a ĺ€Gas Still Flowingĺ€ message appears in the alarm window. If the machine is in the Standby mode for 5 minutes and there is no user input, the machine goes into the Sleep mode, and a screen saver appears.

Manual/Spontaneous

In Man/Spon mode, the piston in the ventilator is moved to its topmost position to minimize system compliance. The APL bypass valve is closed, directing excess gas through the APL valve.

For spontaneous ventilation, the APL valve is put in the SPONT position, in which it is fully open. During inspiration (Fig. 12.23), gas from the bag flows through the fresh gas decoupling valve and the inspiratory unidirectional valve to the Y-piece.

During exhalation (Fig. 12.24), exhaled gases flow through the expiratory unidirectional valve and the absorber. The reservoir bag fills with a combination of fresh gas and gas that has passed through the absorber. Excess gas exits through the APL valve.

During manual ventilation, the APL valve is set to the MAN position. The opening pressure can be adjusted from 5 to 70 cm H_2O. As the bag is compressed (Fig. 12.25, see page 341), the gas in the bag flows through the fresh gas decoupling valve, the inspiratory unidirectional valve, and the Y-piece. Some gas flows retrograde through the absorber and the APL valve, which is adjusted to provide the proper pressure. During exhalation,

exhaled gases flow through the expiratory unidirectional valve and the absorber. The reservoir bag fills with a combination of fresh gas and gas that has passed through the absorber.

Mechanical

When the Fabius is in automatic mode, the APL bypass valve is held open. Fresh gas decoupling is accomplished by using a decoupling valve between the fresh gas inlet and the breathing system. The reservoir bag will inflate and deflate during mechanical ventilation. If the oxygen flush is activated during inspiration, the gas will not be added to the tidal volume but will enter the reservoir bag (23).

During inspiration (Fig. 12.26, see page 342), the pressure generated by the piston closes the fresh gas decoupling valve. Fresh gas flows retrograde through the

absorber and enters the reservoir bag. The piston pushes gas through the inspiratory unidirectional valve and the inspiratory hose to the Y-piece. If the pressure exceeds the pressure limit, the Pmax valve opens.

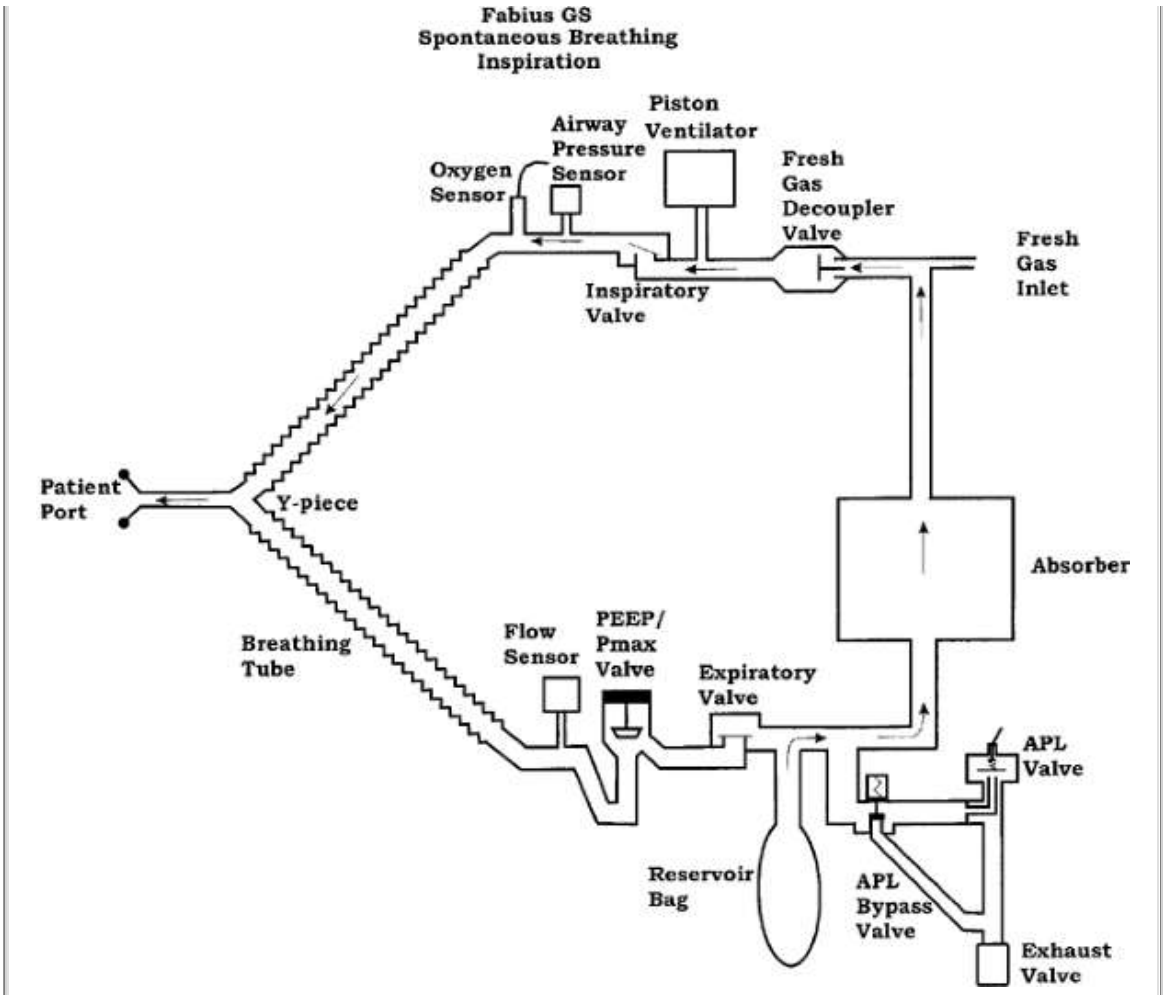


Figure 12.23. Drager Fabius GS ventilator. Inspiration during spontaneous breathing. PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

During exhalation (Fig. 12.27, see page 343), exhaled gas flows through the expiratory unidirectional valve and into the reservoir bag, where fresh gas has been collecting during inspiration. The piston retracts, drawing in gas. Excess gas flows through the APL bypass valve and the exhaust valve to the scavenging system.

Special Features

A high pressure and a negative pressure relief valve are located at the top of the ventilator piston (Figs. 12.20, 12.21). The high

pressure relief valve opens at 75 ยฑ5 cm H_2O. The negative pressure safety relief valve lets in air at -2 to -5 cm H_2O.

If a fault in the ventilator is not corrected and the anesthesia provider cannot switch to manual ventilation by using the Man/Spont mode, manual ventilation is still possible. To do this, the ON/OFF system power switch on the rear panel is switched OFF, then ON.

The Fabius GS has battery backup that will power the machine and ventilator for at least 45 minutes if the batteries are fully charged. If the power fails, the mains LED will go out, a message will appear, and a battery symbol will appear in the status bar. After the battery is exhausted, the patient can be ventilated in the manual/spontaneous mode.

Breathing system compliance is determined during the checkout procedure. For accurate compliance compensation, the breathing system must be in the configuration in which it is to be used for the patient when the checkout procedure is performed.

The Fabius GS is equipped with fresh gas decoupling. During mechanical inspiration, the fresh gas decoupling valve closes. This directs the fresh gas to the reservoir bag, thereby stopping it from being added to the inspired tidal volume. During exhalation, the decoupling valve

opens, allowing exhaled gas and the accumulated fresh gas to fill the piston.

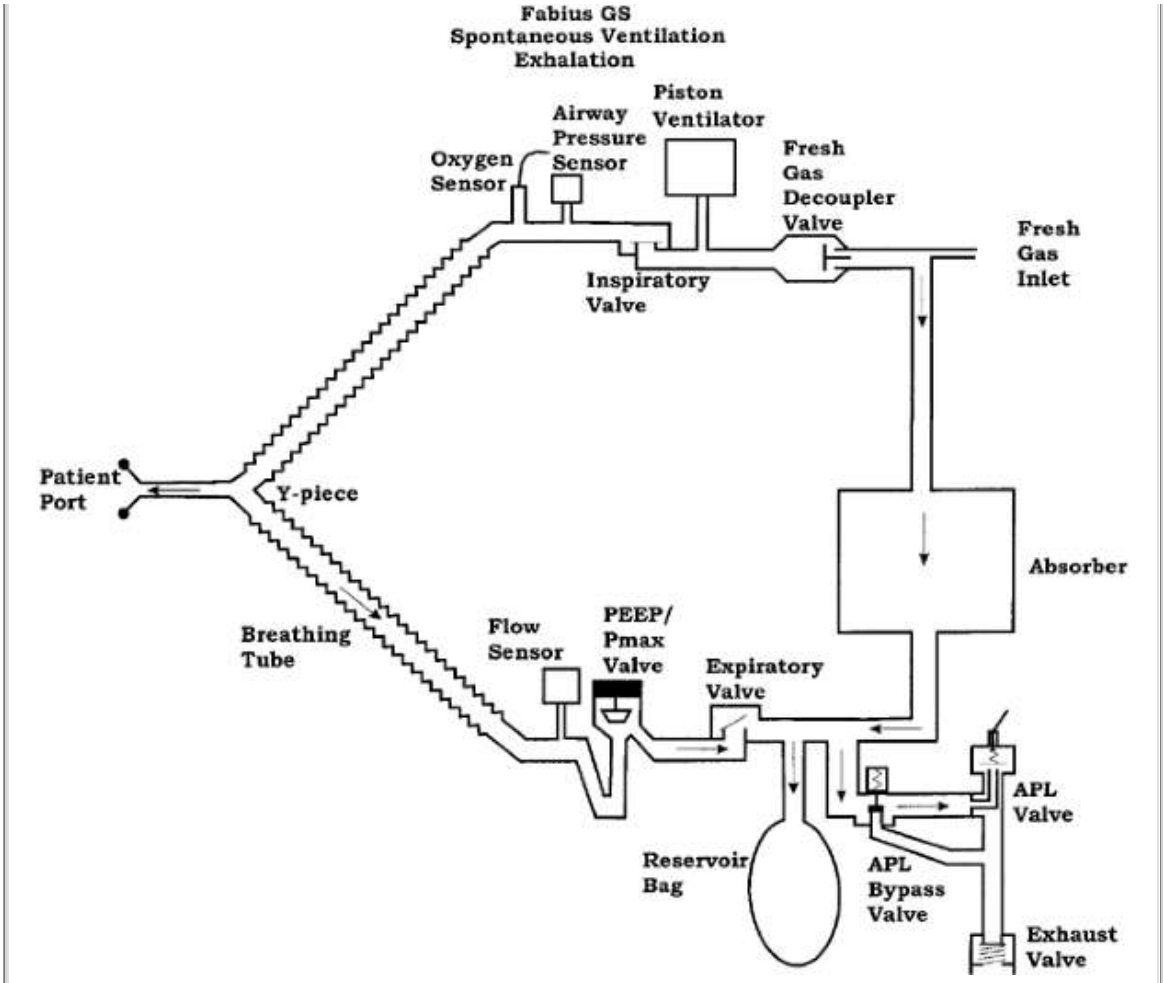


Figure 12.24. Drager Fabius GS ventilator. Exhalation during spontaneous breathing. PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

Hazards

Air can be entrained during mechanical ventilation if there is a disconnection or leak or the fresh gas flow is directed to the wrong circuit (9,66,67). This could lead to patient awareness and hypoxia. Such a problem should be discovered during the checkout procedure but could occur later.

Ventilator failure resulting from worn parts of the motor that drives the bellows has been reported (68,69). A ventilator failure warning was posted and manual ventilation was possible after

the ventilator was placed in the standby mode.

Cleaning and Sterilization

External parts of the ventilator may be cleaned with detergents and disinfectants. The parts that are exposed to respiratory gases can be removed from the ventilator. The ventilator diaphragm, cover, and hoses can be steam autoclaved.

Drager Apollo

Description

The main screen of the Drager Apollo machine is shown in Figure 12.28 (see page 344). At the left on the bottom are virtual flowmeters. Above this is gas-monitoring information. To the right of this is the carbon dioxide waveform and pressure- and flow-volume loops. Below the pressure-volume loop are bar graphs for tidal volume and airway pressure. To the right of the carbon dioxide waveform and flow-volume loop are the values for ventilatory parameters. Below this are the pipeline and cylinder pressures. At the right are soft keys for various other functions.

Ventilatory functions are controlled by using two sets of keys below the bottom of the screen (Fig. 12.29, see page 345). The keys in the bottom row are used to

set the ventilatory mode (manual/spontaneous, volume mode, pressure mode, or pressure support). To select a mode, the key is pressed, and the knob to the right is pressed to confirm the change. The right key is used to select the auxiliary common gas outlet, which is an optional feature.

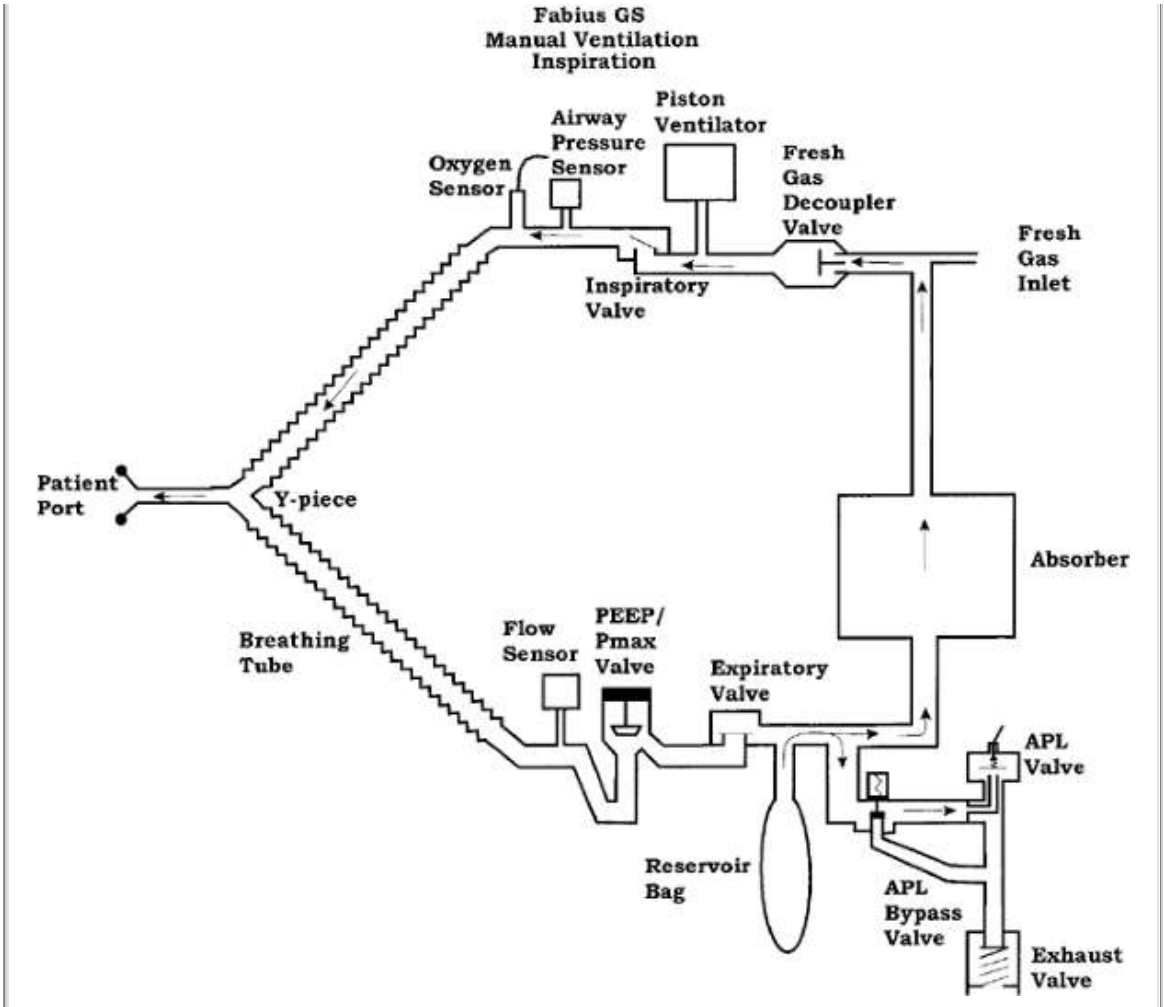


Figure 12.25. Drager Fabius GS ventilator. Inspiration during manual ventilation. PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

Above this row of keys is another row that is used to set the ventilation parameters. To alter the setting, the key is pressed, and the knob is rotated to increase or decrease the value shown above the soft key until the desired value is reached. Then, the knob is pressed to confirm that setting.

To the right of the knob (not shown in Fig. 12.29) is the standby key, which is used to switch between operating and standby modes.

The internal construction of the Apollo ventilator is shown in

Figures 12.30 to 12.35 (see pages 345,346,347,348,349,350,351). Fresh gas enters the breathing system and passes through the fresh gas decoupler valve. The ventilator, which has an electrically driven piston, is connected to the inspiratory side of the circuit downstream of the fresh gas decoupler valve. A flow sensor just downstream of the unidirectional valve monitors the inspiratory flow.

On the exhalation side of the circuit another flow sensor, a pressure gauge and a PEEP valve are located upstream of the expiratory unidirectional valve. The reservoir bag and APL valve as well as an APL bypass valve leading to the exhaust valve from the ventilator are between the expiratory unidirectional valve and the absorber.

Controls

The range for pressure limitation (P_{MAX}) is 10 to 70 (default 40) cm H_2O, with a minimum of PEEP +10 cm H_2O. The range for tidal volume is 20 to 1400 (default 600) mL. With PSV, the tidal volume range is 10 to 1400 mL. Respiratory frequency can be set from 3 to 80 (default 12) bpm in volume control and pressure control ventilation. During PSV, the frequency is Off or 3 to 20 (default 3) bpm. Inspiratory time (T_{INSP}) can be set from 0.2 to 6.7 (default

1.7) seconds. Inspiratory pause time can be set from 0% to 60% (default 10%) of inspiratory time. PEEP can be set from 0 to 20 (default 0) cm H_2O, with a maximum of Pmax -10 cm H_2O. Trigger sensitivity can be set from 0.3 to 15 (default 3) L/minute in pressure support mode. Rise time (T_{SLOPE}) can be set from 0.0 to 2.0 (default 0.0) seconds. The pressure support range (ฮ”Pps) is 3 to 50 (default 5) cm H_2O. The inspiratory pressure in the pressure mode is PEEP +5 cm H_2O, up to 70 cm H_2O. Patient age can be set from <1 to 120 (default 40) years.

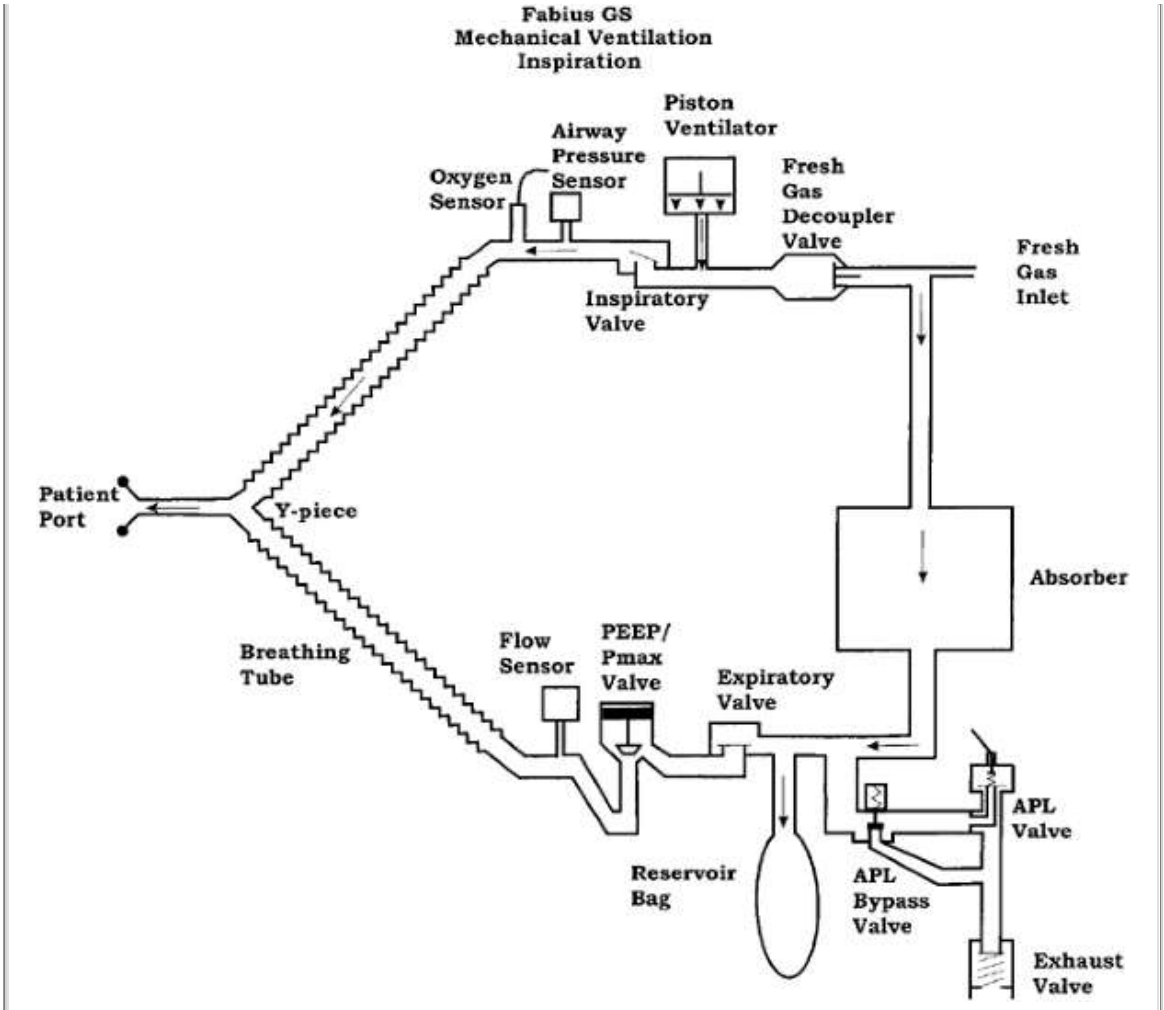


Figure 12.26. Drager Fabius GS ventilator. Inspiration during mechanical ventilation. PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

Alarms

Alarms are indicated on the status field at the top of the screen (Fig. 12.28). Warning messages flash ON and OFF on a red background, and a continuous tone sounds. Caution messages flash ON and OFF on a yellow background, and an intermittent tone sounds every 30 seconds. Advisory messages appear on a white background, and depending on the advisory, a single tone may sound.

Ventilation Modes

Volume control (with or without synchronization and optional pressure support) and pressure control (with or without synchronization and optional pressure support) ventilation are standard features. There is a 15-second timeout period for making ventilation mode changes, with an audible tone after the first 10 seconds. If the new setting is not confirmed within this time, the previous ventilatory mode remains in effect.

Manual/Spontaneous

To use the manual/spontaneous ventilation mode, the user must first set the APL valve to the appropriate mode (manual or spontaneous), then select the mode on the front display panel. The fresh gas decoupler valve stays open.

During spontaneous respiration (Fig. 12.30), the patient inhales gas from the reservoir bag and fresh gas. During exhalation (Fig. 12.31), gas flows into the reservoir

bag. Excess gas will exit via the APL valve, which should be fully open.

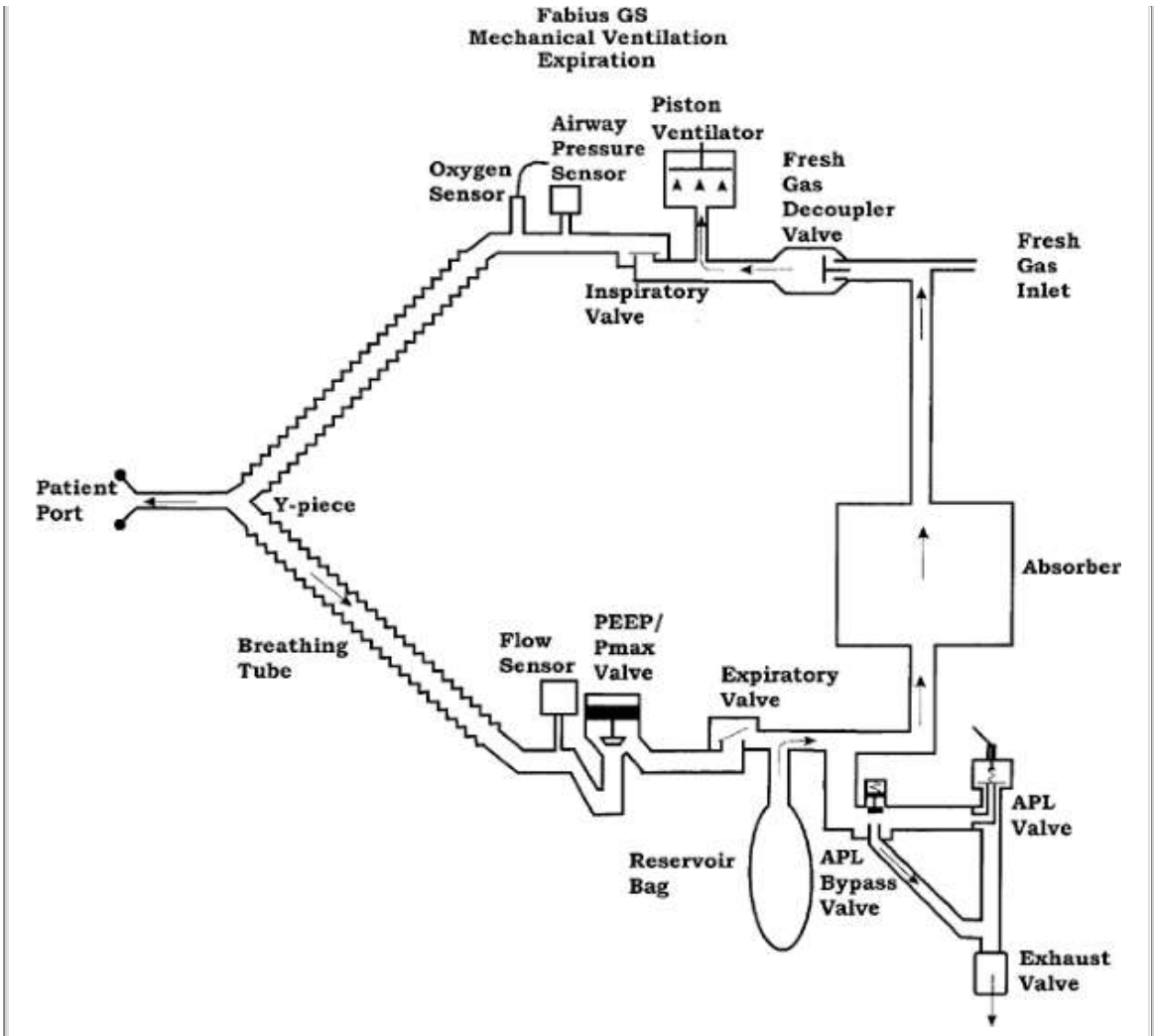


Figure 12.27. Drager Fabius GS ventilator. Exhalation during mechanical ventilation. PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

During manual inspiration (Fig. 12.32), the APL valve is turned to the desired pressure. When the bag is squeezed, gas flows through the absorber and past the fresh gas inlet. The pressure will be limited to that set on the APL valve. Pulling up on the APL valve knob will temporarily relieve excessive pressure. During exhalation, the reservoir bag fills with exhaled gas and fresh gas flowing retrograde through the absorber.

Mechanical

During mechanical ventilation, the fresh gas decoupler valve closes during inspiration (Fig. 12.33). This causes fresh gas to flow retrograde through the absorber.

During early exhalation (Fig. 12.34), exhaled gas flows through the absorber and into the retracting piston ventilator. Fresh gas also flows into the ventilator. After the piston has fully retracted (Fig. 12.35), excess gas flows through the exhaust valve to the scavenger system. Some fresh gas will flow retrograde through the absorber.

Volume Control

The parameters for volume-controlled respiration can be preset before the volume mode is activated. Compliance compensation is applied during volume-controlled ventilation. Compliance is determined during the leak test performed in the standby mode. For compliance compensation to work accurately, it is important that the hoses used during the test match those used during the procedure.

Activating synchronization is optional. It is activated by entering a value for trigger sensitivity. A breath triggered by the patient is represented by a vertical black line on the pressure and flow curves. The active window for a breath triggered by the patient is the last 25% of the expiratory time. In order to maintain a constant frequency, a breath triggered prematurely is compensated for in the next cycle.

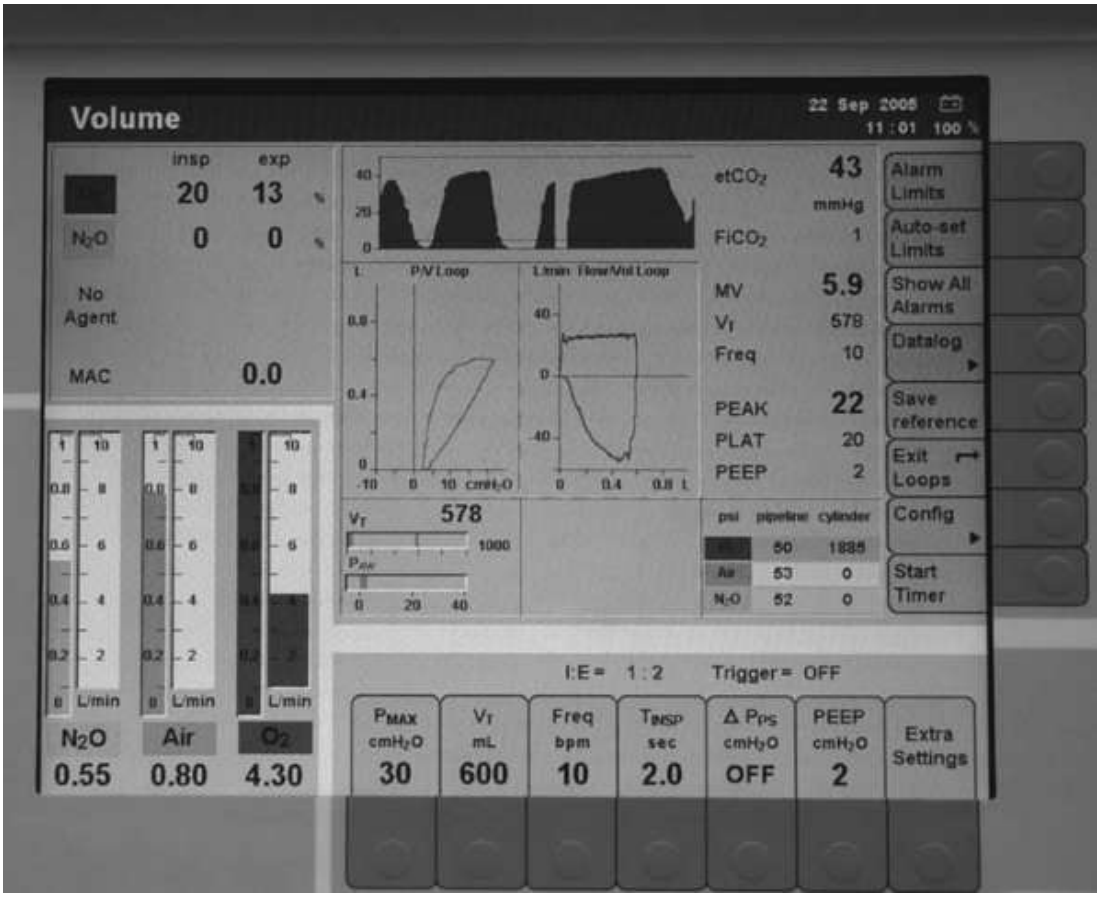


Figure 12.28. Main screen of the Apollo anesthesia machine.

Pressure Control

Pressure control ventilation is a standard feature on the Apollo ventilator. The rate at which the pressure rises is set via the rise time (T_{SLOPE}). The maximum time for controlled ventilation is set via the frequency. In the pressure control mode, the maximum inspiratory flow is 150 L/minute. The ventilator can be configured so that the inspiratory pressure will be automatically changed when PEEP is changed in the pressure control mode.

Synchronization with spontaneous breathing can be activated in this mode by entering a value for trigger sensitivity. A ventilation stroke triggered by the patient is represented by a vertical black line in the pressure and flow curves (trigger indicator). The

window for

triggering by the patient is the last 25% of the expiratory phase time. In order to maintain a constant frequency, a breath triggered prematurely is compensated for in the next cycle.

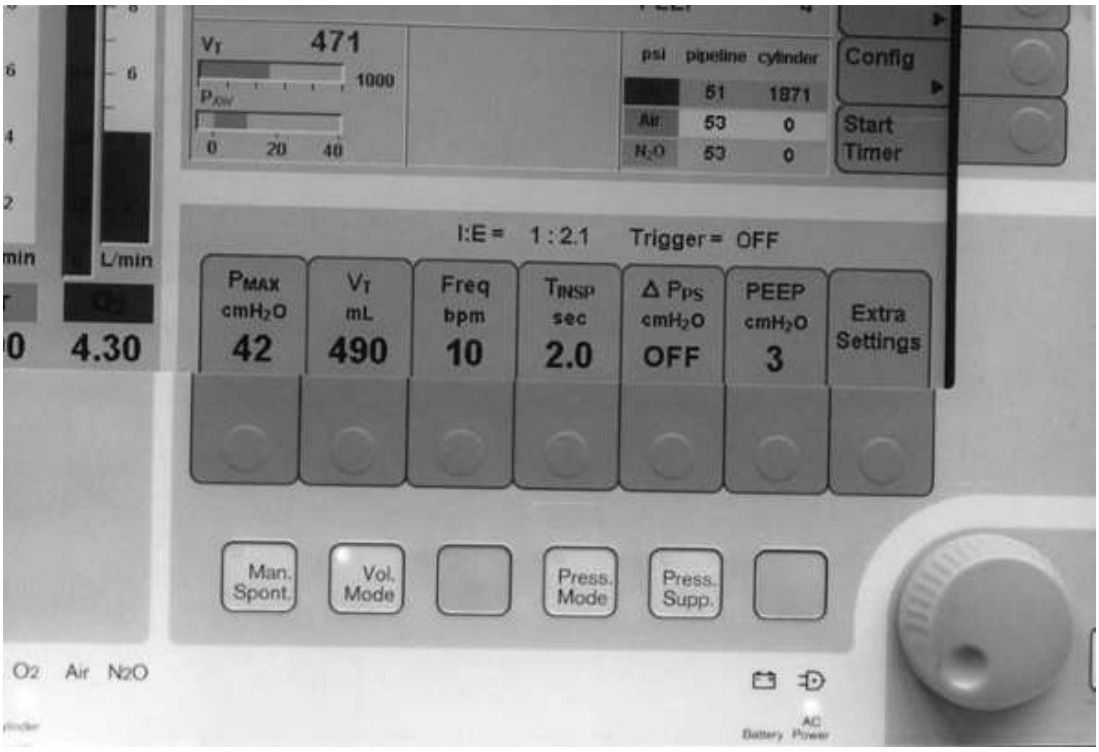


Figure 12.29. Two sets of keys below the screen are used to set ventilatory mode and parameters. The control knob is at the right, and to its right is the edge of the Standby key.

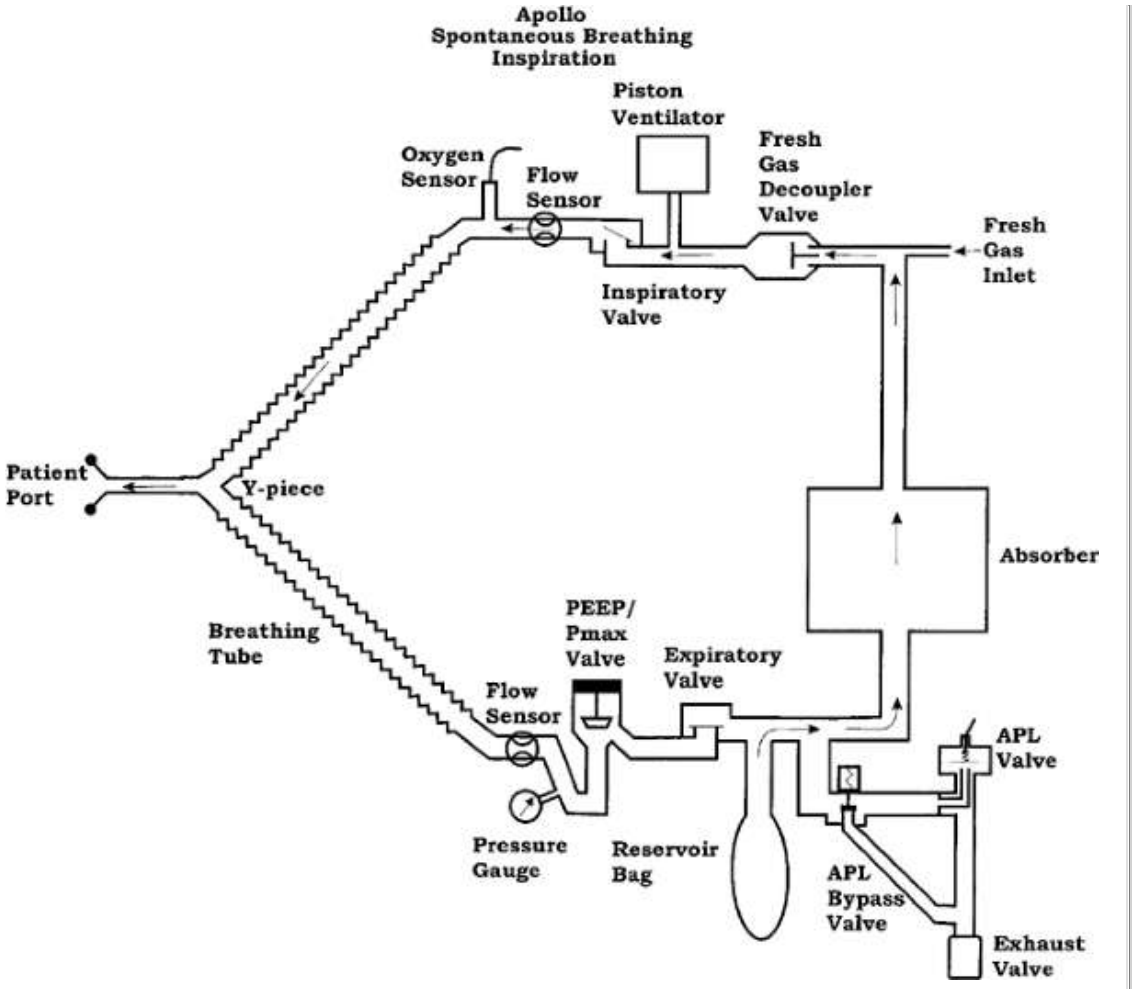


Figure 12.30. Apollo ventilator. Inspiration during spontaneous breathing. PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting. (Redrawn courtesy of Drager Medical.)

Pressure Support

Pressure-assisted spontaneous breathing, if present, is optional in the pressure control and volume control modes. It can be used as a separate mode. It is activated by entering a value for the level of support (ฮ”Pps). If the patient is being ventilated without synchronization when pressure support is turned ON, synchronization will be automatically activated. Synchronization will be maintained when pressure support is deactivated.

The rate at which the pressure rises is set by using the rise time

(T_{SLOPE}). The manufacturer recommends that the rise time be set so that the plateau pressure is reached within one third of the inspiratory time. Inspiration ends as soon as the inspiratory flow drops below 25% of the inspiratory peak flow.

The inspiratory time for spontaneous breathing cannot be greater than 1.5 seconds in patients under 4 years of age or more than 4 seconds in patients over that age.

Special Features

The machine has an automated checkout procedure that includes a compliance measurement.

Entering the patient's body weight and age causes the ventilator to produce default settings based on the given information. These settings need to be confirmed.

The inspiratory pressure can be automatically changed when PEEP is altered in the pressure control mode. This feature can be disabled. The inspiratory time can be automatically altered in the volume-controlled or pressure-controlled ventilation modes without synchronization so that the resultant I:E ratio remains constant.

If this setting is disabled, the inspiratory time will be independent of the change in frequency, and the I:E ratio will change accordingly.

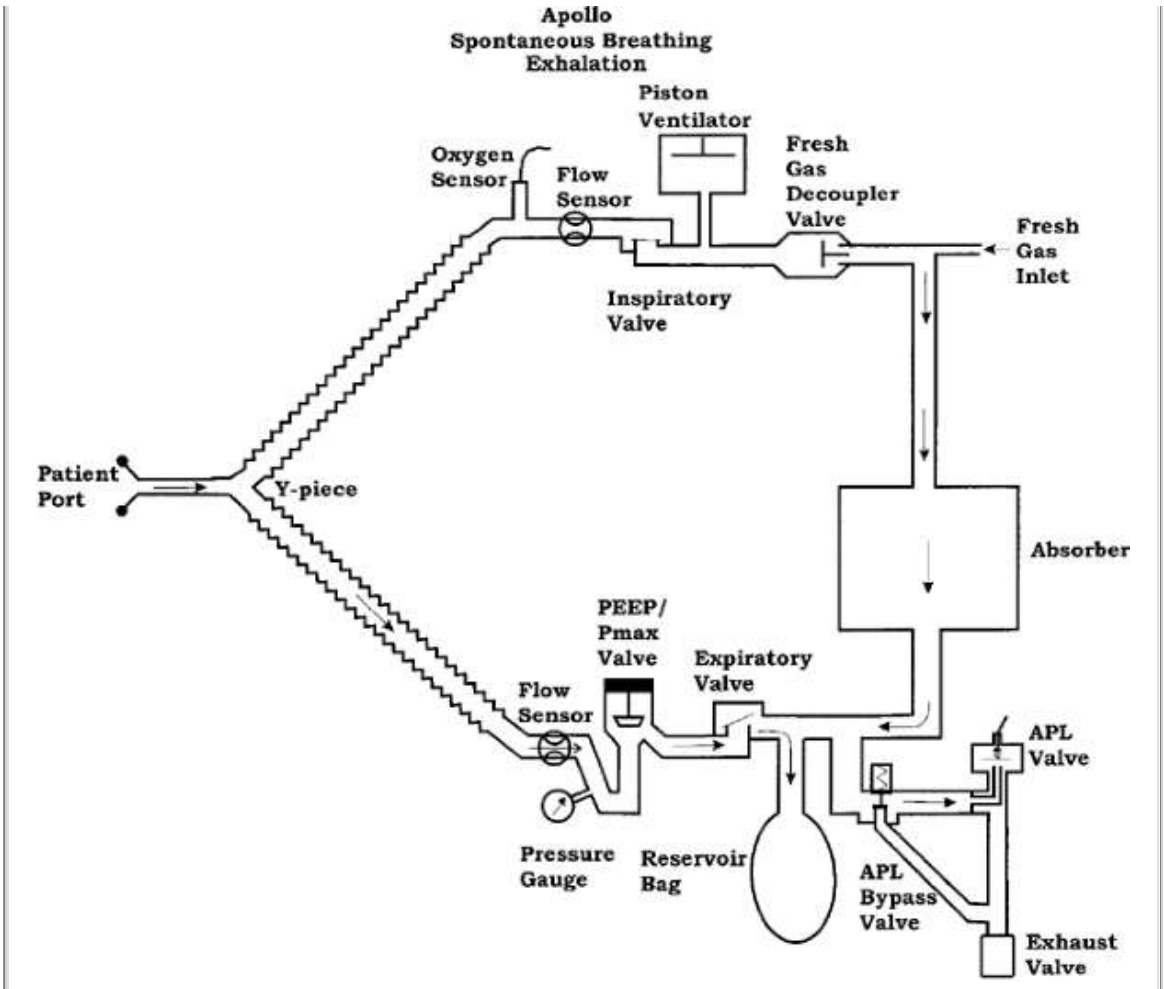


Figure 12.31. Apollo ventilator. Exhalation during spontaneous breathing. PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting. (Redrawn courtesy of Drager Medical.)

The Apollo has fresh gas decoupling. During inspiration with mechanical ventilation, the fresh gas decoupler valve closes. This directs the fresh gas that enters the system to the reservoir bag, thereby stopping it from being added to the inspired tidal volume. During exhalation, the fresh gas decoupler valve opens, allowing exhaled gas and the accumulated fresh gas to fill the ventilator.

Cleaning and Sterilization

The breathing system and ventilator may be disassembled for

cleaning and sterilization. All parts of the breathing system except the Spirolog flow sensor can be thermally disinfected in an automatic cleaning and disinfecting machine at 93ยฐC for 10 minutes. Only neutral cleaning agents and fully demineralized water may be used. Chemical disinfectants should not be added for thermal disinfection, as they may cause corrosion. The internal parts of the ventilator can be steam sterilized at 134ยฐC for 8 minutes. The Spirolog sensor also can be immersed in 70% alcohol for approximately 1 hour and allowed to dry for 30 minutes.

General Electric Datex-Ohmeda 7900 Series

Description

The 7900 (SmartVent) ventilator is an integral part of a number of Datex-Ohmeda anesthesia machines (4,12). There are a variety of software versions in use, and a particular ventilator may have added features such as additional ventilatory modes. Since there are so many variations in use, it is not possible to discuss each variation. The instructions for the version that the user has should be consulted.

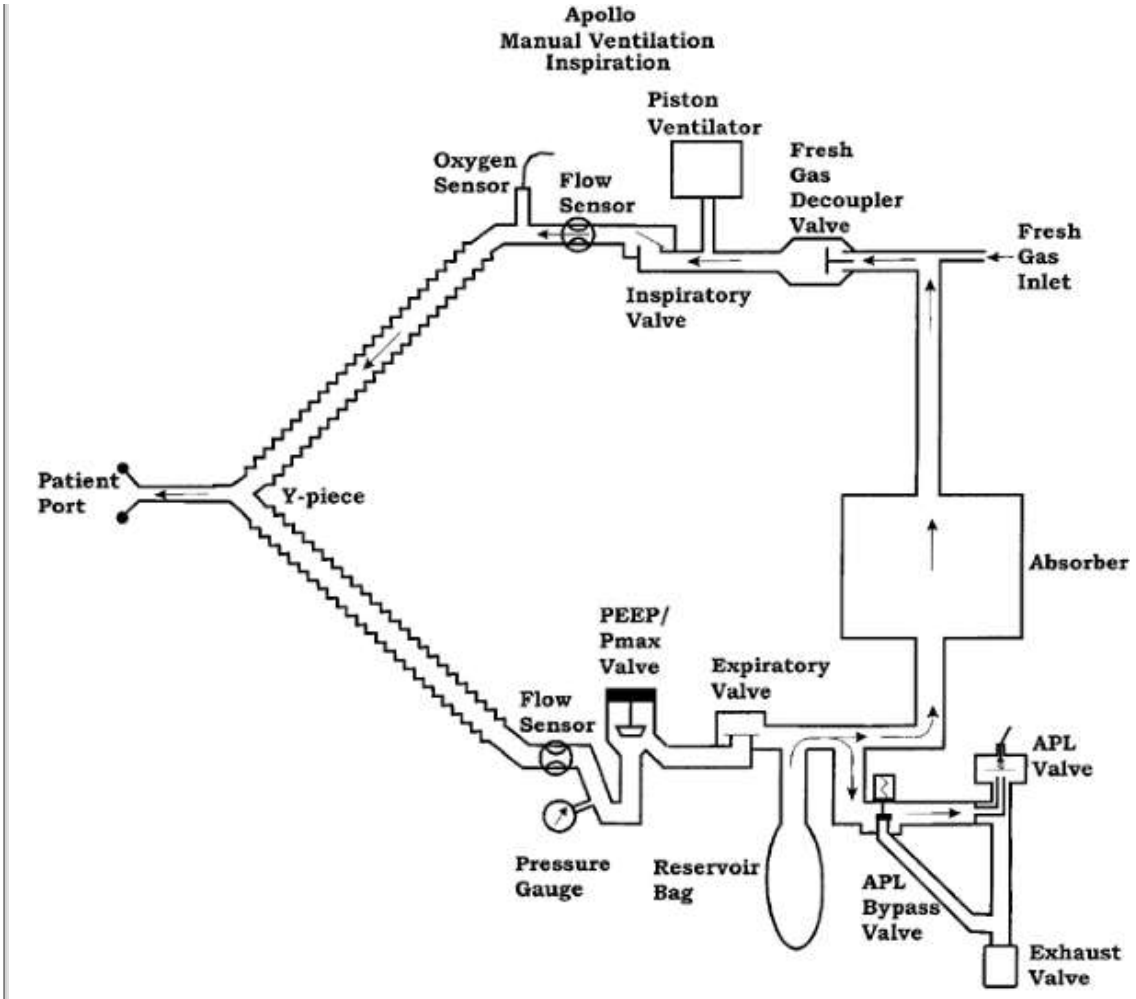


Figure 12.32. Apollo ventilator. Inspiration during manual ventilation. PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting. (Redrawn courtesy of Drager Medical.)

The bellows assembly (Fig. 12.36, see page 351), which has an ascending bellows, is separate from the control portion. On newer machines, the Bag/Vent selector switch on the top of the carbon dioxide absorber serves as the ON-OFF control for the ventilator. Placing the switch in the Vent position turns the ventilator ON. Older models have an ON-OFF switch on the ventilator (Fig. 12.37, see page 352).

The ventilator can be powered by air or oxygen and has a peak

inspiratory flow of 70 L/minute. Inspired and exhaled volumes are measured using variable orifice flow sensors at the outlet and inlet on the absorber (Chapter 23). Information from the inspiratory sensor is used to regulate the bellows compression during inspiration. Several breaths are needed to allow equilibration so that the ventilator delivers the set tidal volume. The ventilator can compensate for fresh gas flows from 15 to 200 mL/minute and moderate breathing system leaks. This eliminates the effect of fresh gas flow on the delivered tidal volume but does not protect completely from added volume if the oxygen flush is activated during inspiration (23). The flow sensor in the expiratory limb measures exhaled volume, which is then displayed on the screen. Because the flow sensors are at the absorber, changes in tidal volume resulting from gas compression and circuit compliance cannot be compensated for.

The front panel on older models (Fig. 12.37) has the controls for the ventilator functions and a display screen. The ON-OFF key, which has a bellows icon, is to the left of the screen. On some machines, this key is replaced by an End Case key that puts the apnea and volume alarms into standby and causes user selections to be returned to default settings. Above the ON-OFF key is a key to audio pause (silence) alarms. On the right is a key to disable/enable the apnea and volume alarms. Below this is the menu access key. Below the menu key is a rotary mouse (ComWheel) that is used to select menus and change settings.

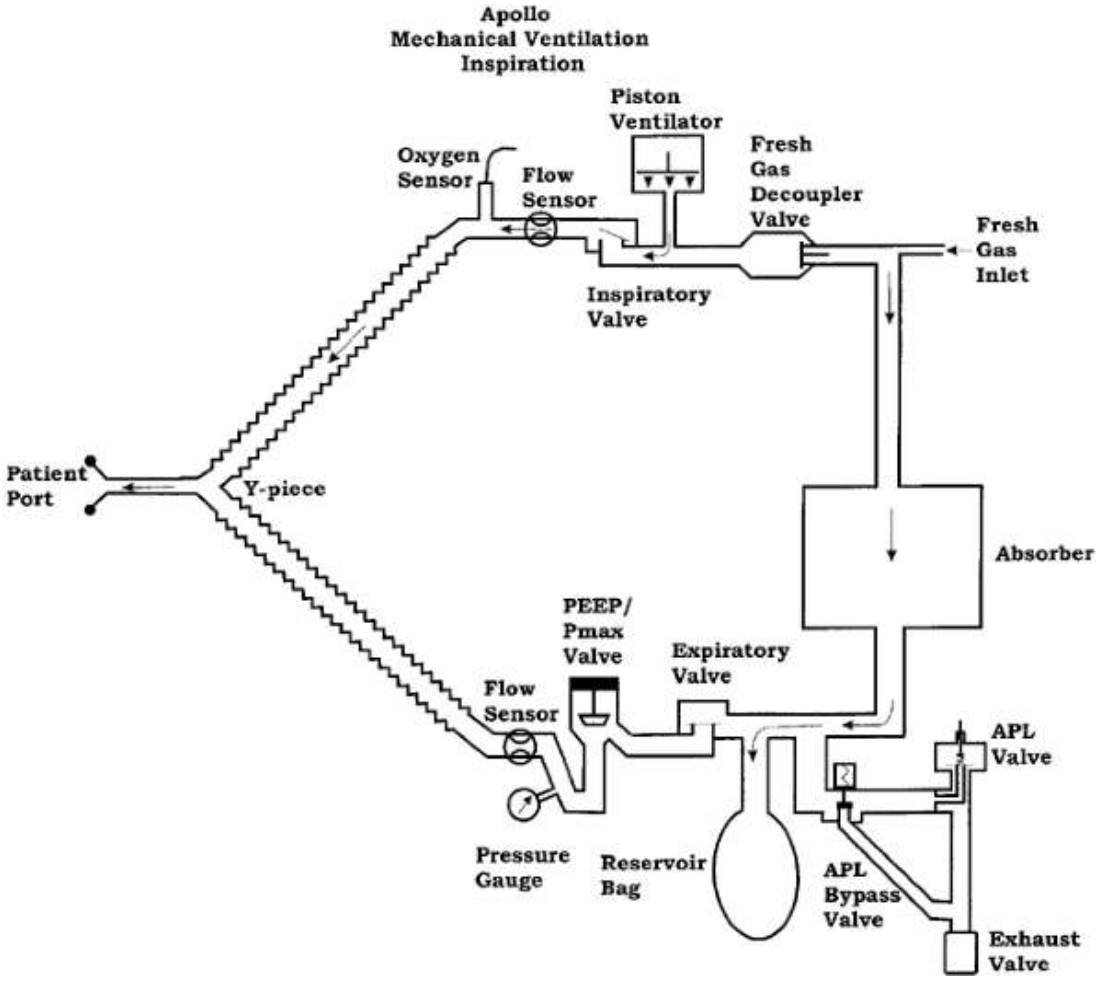


Figure 12.33. Apollo ventilator. Inspiration during mechanical ventilation. PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting. (Redrawn courtesy of Drager Medical.)

The screen displays alarm messages, alarm status, ventilatory modes, ventilatory control values, various measured values, and waveforms. Above the waveform, the status of the apnea alarm and volume monitor are displayed. Inspired oxygen concentration; exhaled tidal and minute volumes; respiratory rate; and peak, mean, and plateau airway pressures are shown on the left side of the screen. Alarm limits can be displayed to the right of some values. Alarm messages are displayed above this area (Fig. 12.38, see page 352).

Below the screen are selection keys. When a key is pressed, the box around the display window above that key flashes. The setting can be adjusted by turning the rotary mouse. Pressing the key or the rotary mouse confirms the selected value. If the setting is not confirmed in 8 seconds, the setting remains unchanged. Once a change in a parameter is confirmed, it usually takes several breaths for the ventilator to adjust to the new setting.

Menus (Fig. 12.39, see page 353) are accessed by pressing the button above the rotary mouse. These are used for settings that are changed less frequently. The content of the menus depends on the software in place.

The control panel for a newer model is shown in Figure 12.40 (see page 353). On the left are controls for the timer. On the right at the top is the Silence Alarms (audio pause) key. Below this is the key for the alarm setup, which when pressed will bring up an alarm menu. Below this is a Help key. Below that is a key for Trends. The next key is for the Main Menu. Below this is the Checkout key. Below this is the Start/End Case key.

At the bottom left is the Gas Setup key. Above this are three keys that control the parameters in the boxes above them (O_2%, total flow, and vaporizer setting). To the right of this is the Ventilator Setup key. Above this are three keys that control parameters relating to the selected ventilation mode. To the right is the Spirometry key. To the right is a key to

bring up the Normal Screen. To its right is the rotary mouse.

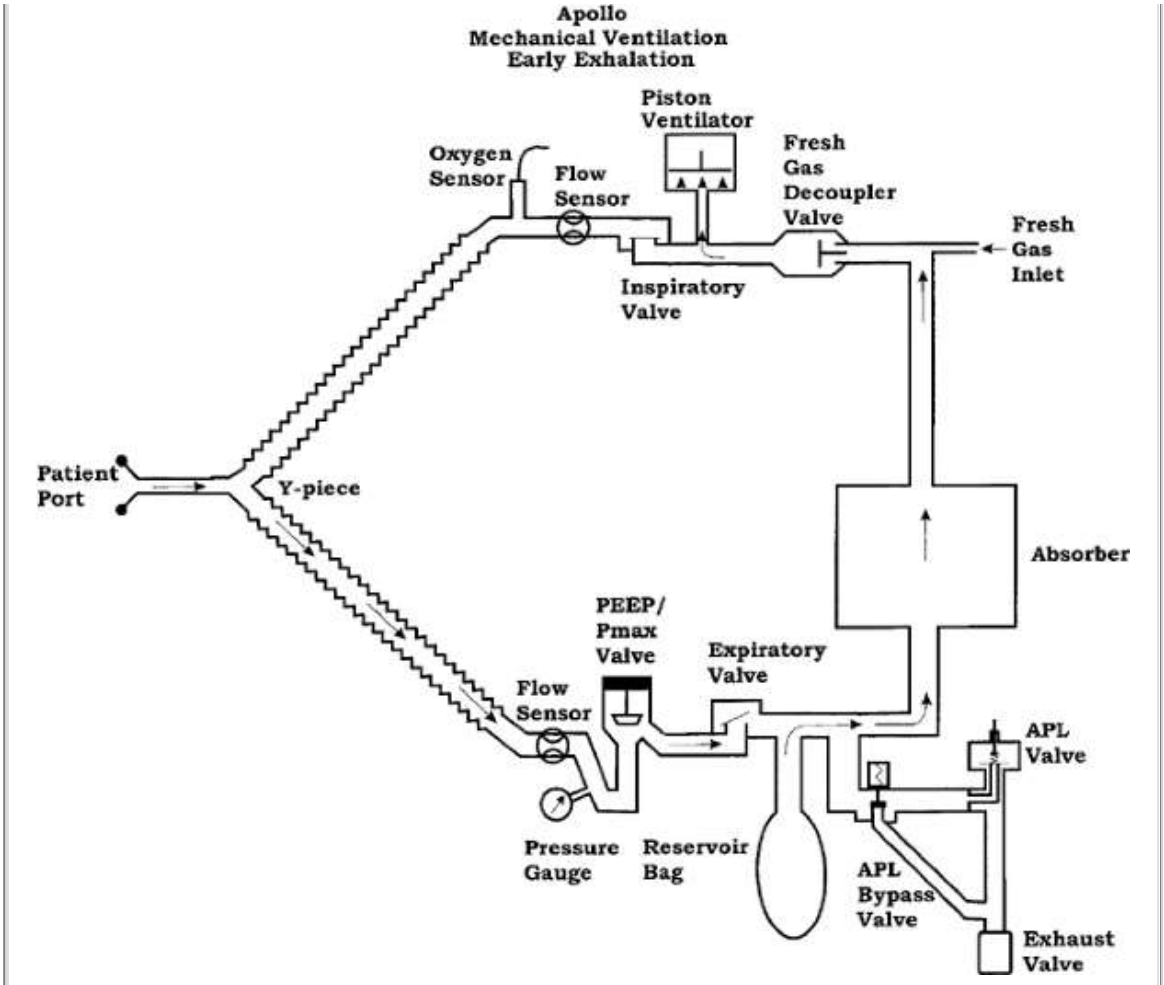


Figure 12.34. Apollo ventilator. Exhalation during mechanical ventilation. PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting. (Redrawn courtesy of Drager Medical.)

Figure 12.42 (see page 355) shows the Ventilator Setup screen. To the left are the choices for ventilation mode. On the right are ventilatory parameters. Some of these parameters can also be set by using the keys at the bottom center of the control panel (Fig. 12.40).

Controls

The controls and their arrangement will depend on which version of the 7900 ventilator is being used. Earlier models had all of the controls on the ventilator itself, while the later models have

them on the screen.

The controls for tidal volume (20 to 1500 mL), Pinspired (the pressure delivered with each pressure controlled breath) (5 to 60 cm H_2O), respiratory rate (4 to 100 bpm in volume control or pressure control ventilation, 2 to 60 bpm in PSV or SIMV), I:E ratio (2:1 to 1:8), airway pressure limit (Plimit, 12 to 100 cm H_2O), and PEEP (OFF or 4 to 30 cm H_2O) are set by using the selection keys.

The following are set through menus: inspiratory pause (0% to 60% of the inspiratory time), Psupport (inspiratory pressure delivered during PSV or SIMV) (2 to 40 cm H_2O), trigger window (which controls the percent of the exhalation phase within which the patient may trigger the next mechanical breath in SIMV and PSV) (0% to 80% in increments of 5%), inspiratory time in SIMV and PSV (0.2 to 5.0 seconds), the flow trigger level (which sets the minimum flow that triggers the ventilator to deliver a mechanical breath during SIMV or PSV (0.2 to

10 L/minute), and the inspiratory terminal level (which sets the percentage of the peak inspiratory flow where the ventilator stops a pressure-supported breath in SIMV or PSV) (5% to 50%).

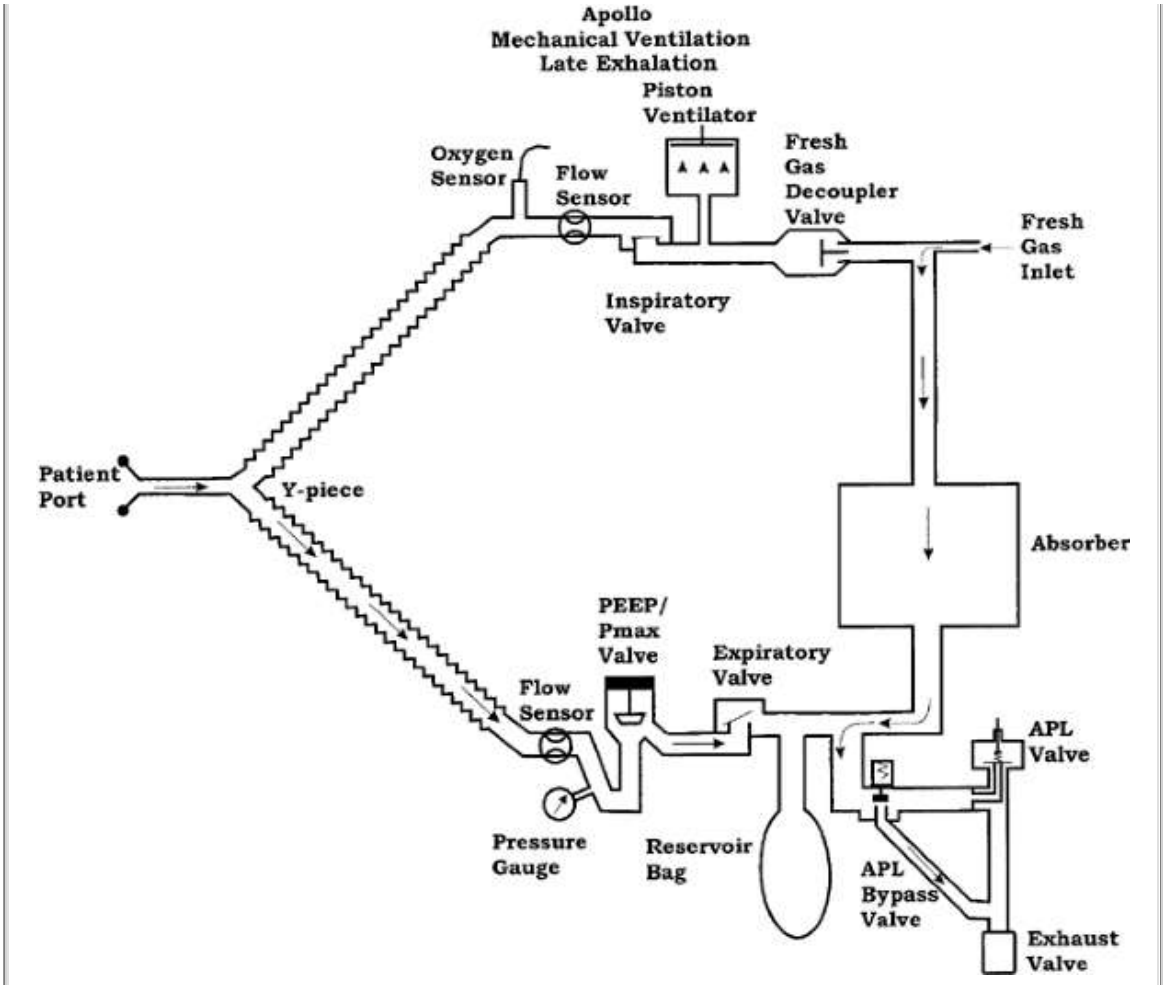


Figure 12.35. Apollo ventilator. Late exhalation during mechanical ventilation. PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting. (Redrawn courtesy of Drager Medical.)

A normal screen is shown in Figure 12.41 (see page 354). Virtual flowmeters are displayed on the left. In the middle are waveforms. To the right are measured parameters.

Alarms

There are variations in the alarms offered, depending on the software installed. In later versions, the alarms are categorized into high, medium, and low priority. A high priority consists of ten tones and a 10-second pause. The cause of the alarm is shown in reverse colors on the screen. The medium priority

alarm consists of three tones with a 25-second pause. A low priority alarm has a single tone.

Alarm limits may be displayed on the screen next to the parameters with which they are associated. They are accessed from the alarm menu. The value to be altered is selected, then set and confirmed by using the rotary mouse.

Alarm messages are displayed at the top of the screen (Fig. 12.40). Alarms can be audio paused (silenced) for 120 seconds by using the button at the upper left of the screen. This time will be counted down on the screen just under the bell with an ĺ€Xĺ€ through it.

Ventilation Modes

Volume control and pressure control ventilation are standard and have been available since this ventilator was first introduced. SIMV and PSV with apnea backup (PSVPro) are optional. PEEP is available in all modes. After a mode is selected, the highlighted control parameters must be set.

Special Features

Battery backup permits approximately 30 minutes of mechanical ventilation and operation of monitors during a power failure.

A heliox mode may be available. This automatically corrects for the lower density of heliox.

Figure 12.36. Bellows assembly of the 7900 ventilator. The Bag/Vent switch, which also turns the ventilator ON or OFF, is between the bellows assembly and the APL valve.

A minimum monitoring mode shows patient data but does not permit mechanical ventilation.

The cardiac bypass mode turns OFF the volume and apnea alarms.

A circuit leak alarm is activated if less than half of the inspired volume is sensed at the exhalation sensor. It can be turned off to prevent nuisance alarms from a known leak (e.g., an uncuffed tracheal tube).

The 7900 ventilator has fresh gas compensation. The bellows excursion is altered to deliver the correct tidal volume by subtracting the fresh gas input during inspiration from the volume that the ventilator delivers. This is mediated by measuring the inspired and exhaled tidal volumes through use of the flow sensors located in the circle system.

Evaluation

The 7900 ventilator has improved pressure and flow capabilities and provides a more stable tidal volume with altered fresh gas flow than older model ventilators from the same manufacturer (4,12).

When the Aestiva 5 version of the 7900 ventilator is in the pressure control mode, increasing respiratory rate decreases the delivered tidal volume more than with an ICU ventilator or the Narkomed 6000 ventilator (2).

The variable orifice flow sensors are sensitive to moisture buildup. Heated humidifiers can also contribute to moisture buildup and probably should not be used with this ventilator (70,71). Water can migrate into the sensor interface board in the ventilator. The first warning that there is a problem may be a reverse flow warning (72,73). A flow sensor designed to minimize moisture buildup has been designed. A similar problem has been noted in operating rooms that are particularly cold (70). Stress fractures where the pneumatic tube enters the sensor have been reported (74,75,76). The sensor or the tubing to it can become fractured and leak (77,78).

Cleaning and Sterilization

When used with the Aestiva machine and breathing system,

nearly all parts except the flow sensors and oxygen sensor that are exposed to respiratory gases are steam autoclavable. The flow sensors can be disinfected by using glutaraldehyde. Autoclavable flow sensors are available.

General Electric Datex-Ohmeda 7100

The 7100 ventilator is similar to the 7900 ventilator. The main difference between them is that the 7100 has fewer features.

Description

The 7100 ventilator is turned ON by setting the Bag/Vent selector switch to the Vent position. Volume measurements are made by using two variable orifice sensors (Chapter 23) at the absorber assembly. The displayed monitored volume is obtained from the exhalation sensor. Information from the inspiratory sensor is used to adjust the delivered tidal volume. This method eliminates the effect of fresh gas on the delivered tidal volume but does not protect from the effect of added volume if the oxygen flush is activated during inspiration (23). This mechanism does not compensate for gas compression or circuit compliance in the breathing system.

The display screen is shown in Figure 12.43 (see page 355). To the left of the screen are two keys. The top key is for audio pausing (silencing) alarms up to 120 seconds. The screen shows the time remaining in the silencing period. Pressing and holding the key for one second when no alarms are active suspends audio tones for medium and low priority alarms for 90 seconds. When the alarms

are audio paused, a large ĺ€Xĺ€ covers the limits. Below this key is an End of Case key.

Figure 12.37. Front panel of the 7900 ventilator. Some values have alarm limits to the right.

To the right of the screen are two keys. The top one turns the volume alarms ON or OFF. Below this is a menu key that allows the operator to access a number of screens used to adjust functions associated with the ventilator. Below this key is a rotary mouse that is used to alter and confirm values on the screen.

There are five keys below the screen. These allow the tidal volume, respiratory rate, I:E ratio, maximum airway pressure, and PEEP to be adjusted. The set values are displayed on the screen above each key. If pressure control ventilation is used, the left-hand box will indicate the inspiratory pressure.

Above the function values on the screen is a space that indicates the mechanical ventilation status (ON or OFF), the ventilation mode (volume or pressure control), and the breathing system being used. Above this on the left are the measured

values for tidal volume, minute volume, respiratory rate, and oxygen percentage. To the right are values for peak inspiratory and mean airway pressure and PEEP. Above is a pressure bar graph or

waveform. The alarm status message display is at the top of the screen.

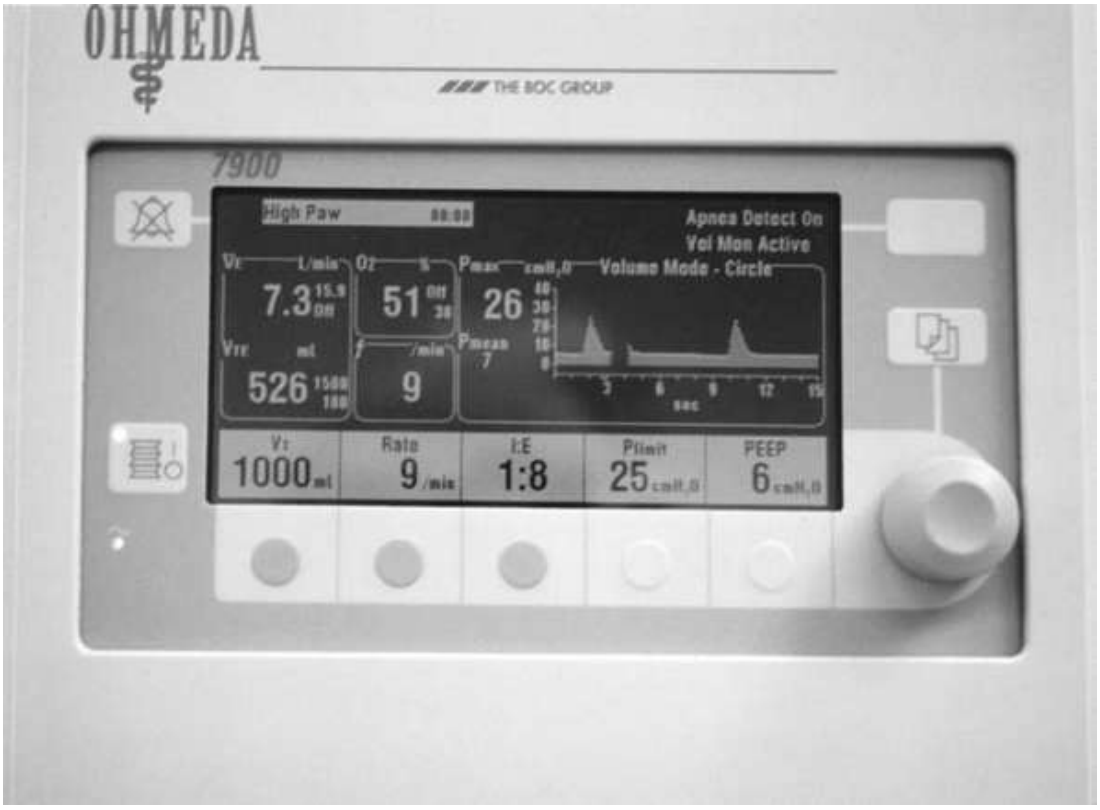


Figure 12.38. Alarm messages are displayed in the upper left part of the screen.

Figure 12.39. Main menu. This allows access to the next set of menus.

Controls

The controls for tidal volume (20 to 1500 mL), Pinspired (the amount of pressure delivered during pressure-controlled ventilation) (5 to 60 cm H_2O), respiratory rate (4 to 100 bpm in volume control or pressure control ventilation, 2 to 60 bpm in PSV or SIMV), I:E ratio (2:1 to 1:8), high airway pressure (P_{limit}, 12 to 100 cm H_2O), and PEEP (OFF or 4 to 30 cm H_2O) are set by using the selection keys at the bottom. The inspiratory pause (0% to 60% of inspiratory time) is set through a menu.

Alarms

The alarm settings are controlled through a menu. The alarm to be altered selected and adjusted by using the control knob, then confirmed by pushing the knob. Alarm limits can be displayed on the screen beside each measured variable.

Figure 12.40. Control panel for newer models of the 7900 ventilator. The screen is the one that appears when the machine is turned ON. It gives instructions for the automatic checking procedure. Note the alarm messages at the top.

Figure 12.41. Normal screen on newer models of the 7900 ventilator.

A high priority alarm includes two bursts of five tones, after which there is a pause and then the audible alarm is repeated. A medium priority alarm sounds three tones followed by a 25-second pause, and the alarm is then repeated. A low priority alarm has a single sound that is not repeated.

Ventilation Modes

The ventilation modes are accessed from the main menu. Volume control is standard, while pressure control is optional.

Special Features

The 7100 ventilator has a battery backup, which will supply power for 90 minutes when fully charged. Under some circumstances, this power will be available for only 30 minutes.

The ventilator adjusts gas flow to the bellows based on the inspiratory volume measured by the variable orifice sensor on the inspiratory breathing system limb (fresh gas compensation). This eliminates the effect of changes in fresh gas flow on tidal volume. During some malfunctions, the ventilator automatically turns OFF volume compensation.

If the anesthesia machine is equipped to use helium, the heliox mode can be selected through a menu. This automatically corrects for helium's lower density.

There is an alarm for circuit leak that is activated when less than half of the inspired volume returns through the expiratory flow sensor during mechanical ventilation.

Evaluation

A problem with the 7100 ventilator has been reported (79). The ventilator would periodically shut down and the sustained pressure alarm would be activated. It was determined that if the flow to the scavenging system was low, waste gas would accumulate in the bag. When the pressure would reach 9 cm H_2O, the ventilator would shut OFF. The manufacturer offers a conversion to full flow for the scavenging system to remedy this problem.

Another reported problem was inability to use volume control ventilation when the flow sensor was subject to significant amounts of moisture (80).

Cleaning and Sterilization

Most of the parts of the 7100 ventilator that have been exposed to the respired gases can be disassembled and steam autoclaved. Parts that cannot be steam autoclaved can be chemically disinfected.

General Electric Datex-Ohmeda AS/3 Anesthesia Delivery Unit

Description

This ventilator is an integral part of the Datex-Ohmeda Anesthesia Delivery Unit (ADU). It is shown in Figure 12.44. The bellows assembly, with an ascending bellows, is located to the

left of the display window. The

AUTO/MAN switch is below the bellows. Turning it to the AUTO position turns on the ventilator.

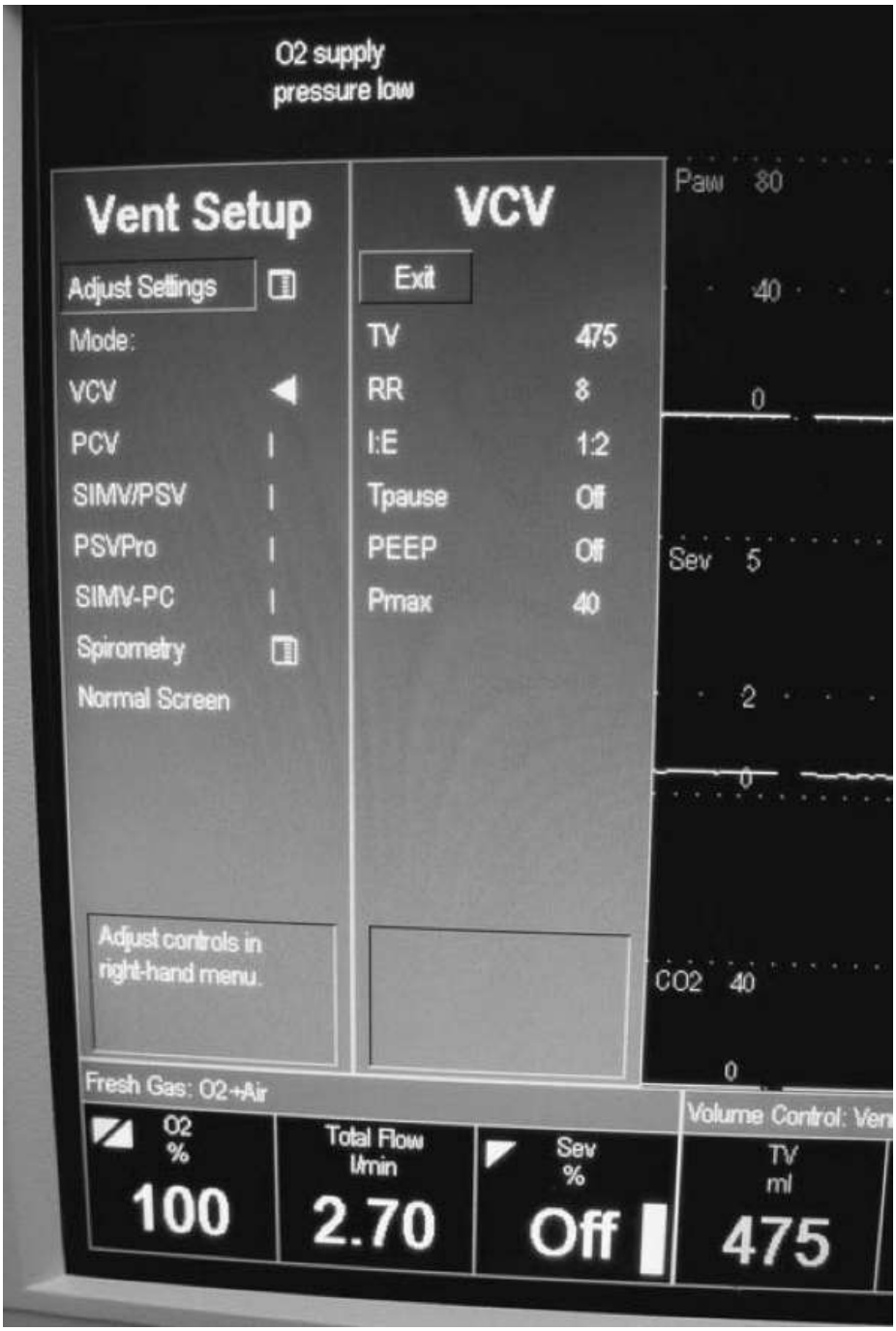


Figure 12.42. Ventilator Setup screen for the 7900 ventilator. This is displayed when the Ventilator Setup key is depressed. It allows a choice of ventilator modes on the left. On the right, ventilator parameters can be set.

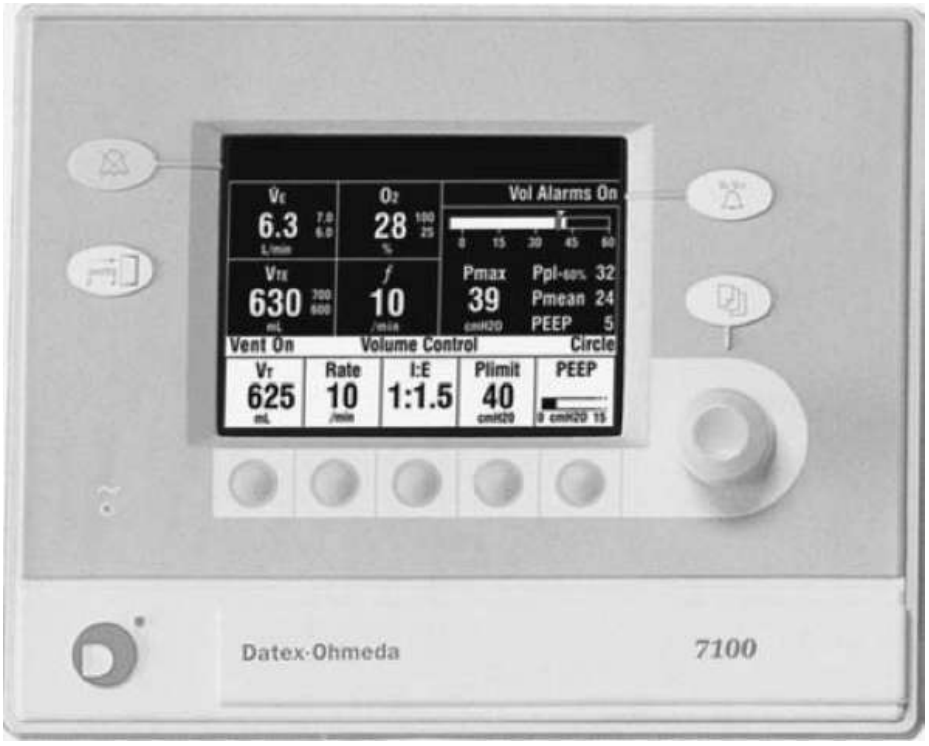


Figure 12.43. Screen for the 7100 ventilator.

Either air or oxygen can be used as the drive gas. If the primary drive gas pressure is lost, the ventilator will automatically switch to the other gas. The maximum inspiratory flow is 80 L/minute. Volume is measured between the breathing system and the patient with a D-lite sensor (Chapter 23).

A diagram of the bellows block is shown in Figure 12.45. During inspiration (Fig. 12.45, *top*), the control unit directs driving gas into the block. The bellows canister is pressurized, driving the bellows downward. At the same time, the pressure in the overflow (spill) valve housing increases, pushing downward on

the rubber membrane and metal lid in the overflow valve. This closes the valve, preventing gas that is inside the bellows from being lost. At the end of the inspiratory phase, the pressure in the outer canister returns to zero.

Figure 12.45, *bottom*, depicts the ventilator during late exhalation. Exhaled gases cause the bellows to return to its uppermost position. The pressure in the overflow valve housing returns to zero, allowing the rubber membrane and metal lid to rise from the seat so that excess gas can escape to the scavenging system.

The ventilator panel is shown in Figure 12.46. The keys vary in position for different versions of this machine. To the right of the screen are keys for ventilatory mode, respiratory rate, I:E ratio, and PEEP. Below the screen is a handwheel. When a parameter is selected, it is adjusted by rotating the handwheel. The new setting is confirmed by pushing the wheel or key or by pushing another key on the display unit. There is also a key to bring up other screens.

At the lower right of the screen, the set tidal volume, minute volume, inspiratory pause, respiratory rate, I:E ratio, I:E times, ventilatory mode, and PEEP are displayed.

To the left of the ventilator settings on the screen is a middle field with gas- and volume-monitoring information or trends. To the left of the middle field is the fresh gas display where flows of oxygen, air, and N_2O are displayed as virtual flowmeters and numerical values. The anesthetic agent setting is displayed in a box to the right of the flowmeter numerical display.

Above the ventilatory settings, two waveforms can be displayed. One is always circuit pressure. End-tidal and inspired carbon dioxide may be displayed if the carbon dioxide waveform is shown. An alarm message field is at the top.

Pressing the ventilator key to the right of the PEEP key brings up a menu that allows the ventilatory mode (volume, pressure, or SIMV) to be selected. Tidal volume, set pressure, respiratory rate, I:E ratio, and PEEP also may be altered from this menu.

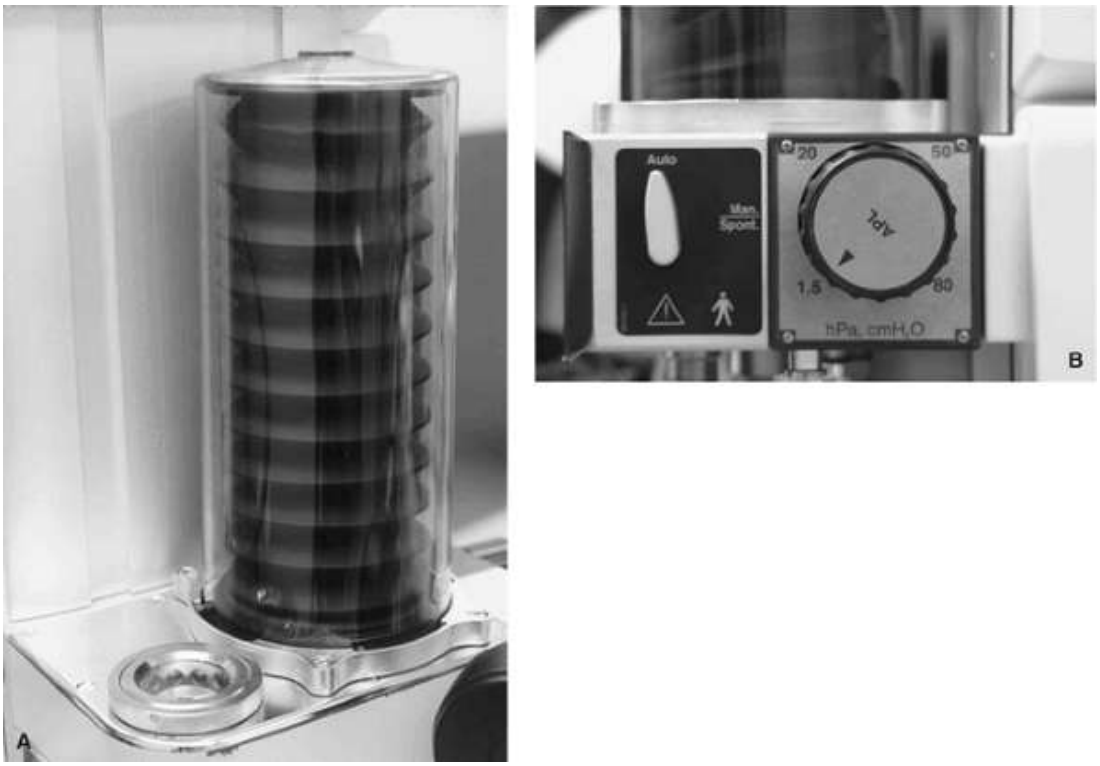


Figure 12.44. A: Datex-Engstrom AS/3 Anesthesia Delivery Unit ventilator. To the right of this is the APL valve. **B:** Close-up view of the bottom of the ventilator.

The options window is accessed through the ventilator menu. Subheadings include the trigger window (which is used in SIMV and PSV), inspiratory pause (which can be used in the volume and SIMV modes), inspiratory rise time (which is used in the pressure control mode), and sigh (which can be used in the volume control mode).

Controls

There are a number of different software versions available, so there may be some discrepancy between the user's machine and the information presented here. Tidal volume (20 to 1400 mL), minute volume, inspiratory pause (0% to 60% of inspiratory time) (Figs. 12.47, 12.48, see pages 358, 359), respiratory rate (2 to 60 bpm), I:E ratio (1:4.5 to 2:1, default 1:2), I:E times

(inspiratory time 0.35 to 20 seconds), the ventilatory mode (Volume Control, Pressure Control, Pressure Support, or SIMV) and PEEP (OFF or 5 to 20 cm H_2O) are set by using the keys below the screen. PEEP is limited to 10 cm H_2O if the tidal volume is less than 100 mL. In pressure control ventilation, the pressure (5 to 40 cm H_2O above PEEP) can be set by using a key. Changes are made by the ventilator over several respiratory cycles.

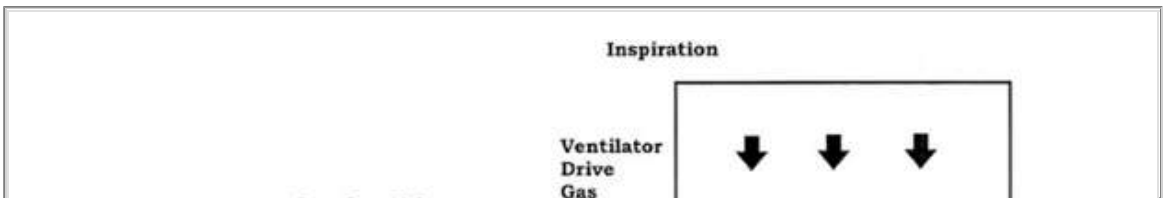
The following are set through menus: trigger sensitivity (-5.0 to -0.5 cm H_2O), trigger window (5% to 95% of the expiratory time, default 95%) (Fig. 12.49, see page 359), inspiratory time (0.35 to 20 seconds), inspiratory rise time (slow, medium, or fast) (Fig. 12.48), and inspiratory pause (0% to 60% of inspiratory time) (Fig. 12.47). A fast rise time reaches the targeted pressure in the first 10% of the inspiratory time, medium in 50%, and slow in 90%. When the sigh is used, the ventilator delivers a tidal volume that is 1.5 times larger than the normal tidal volume every 100th breath. It is limited to 1400 mL.

There is an adjustable (5 to 40 cm H_2O above PEEP) maximum airway pressure release. The ventilator automatically switches to expiration when the pressure is reached.

Alarms

Alarms are accessed through the Alarm Setup key to the upper right of the screen and set by using the wheel below the screen. Alarms are arranged by priority. A high-priority alarm is red and is annunciated by five beeps followed by a 1-second delay and then five more beeps followed by a 5-second delay. This is repeated. A medium priority alarm is yellow and is annunciated with three

beeps and a 19-second pause, then repeated. An advisory note is white, and a beep sounds every 60 seconds.



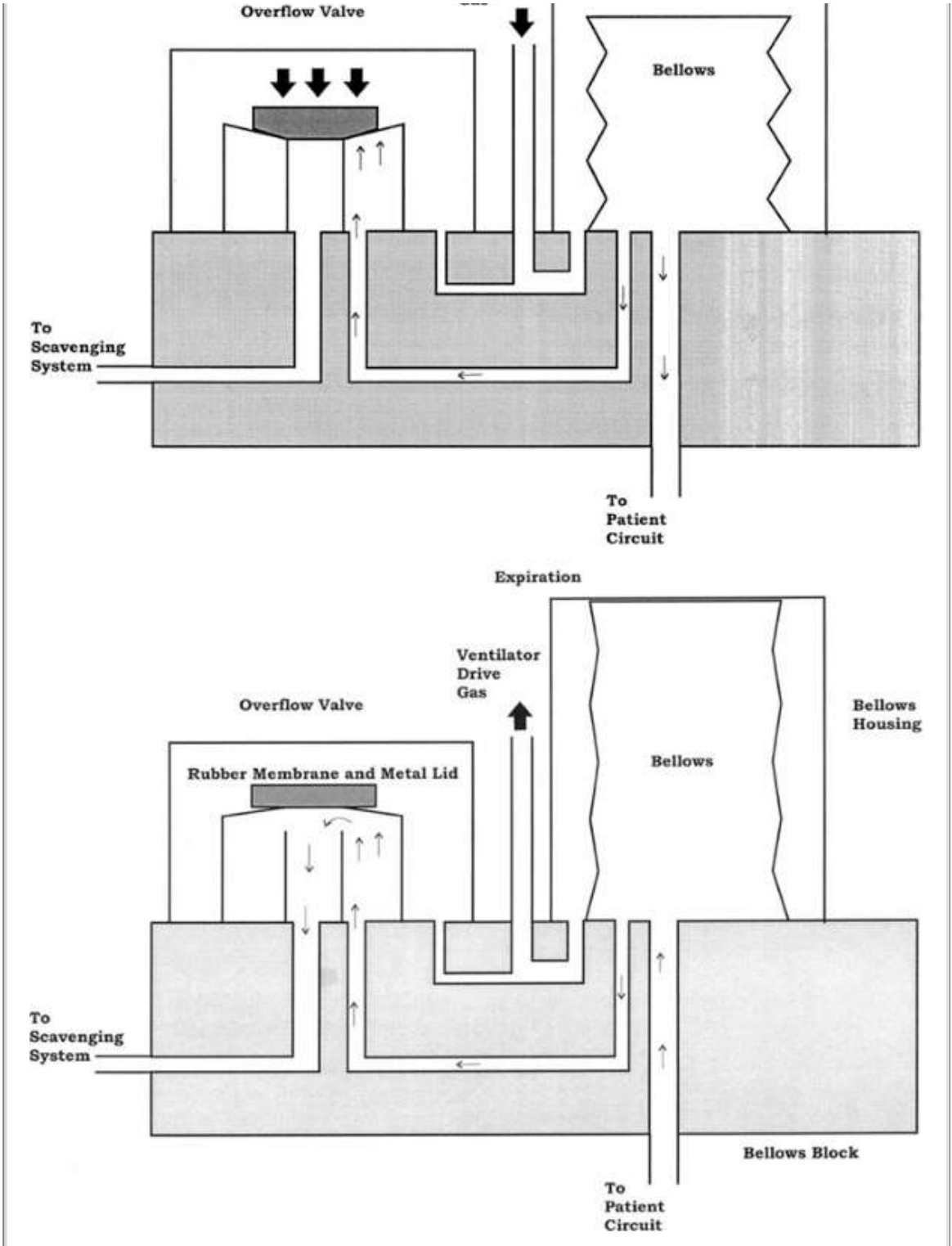


Figure 12.45. Datex ventilator. **Top:** Inspiration. **Bottom:** Expiration.

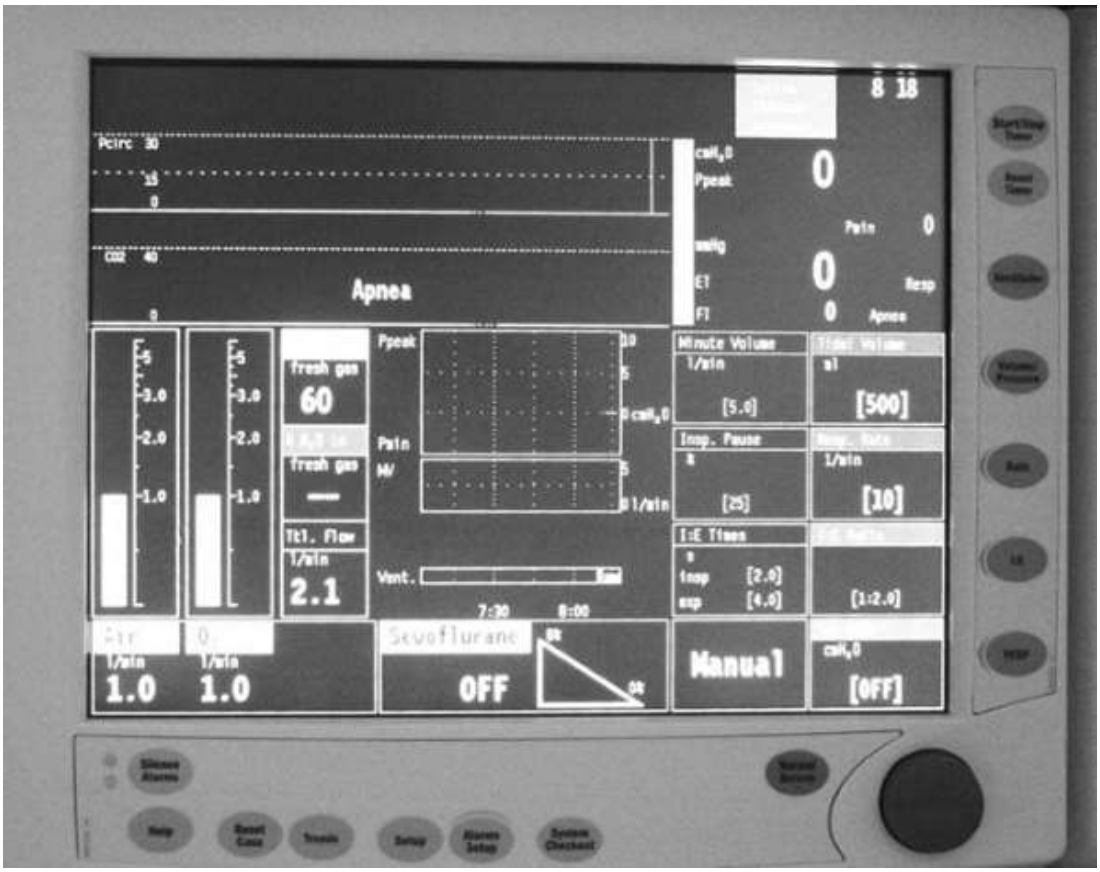


Figure 12.46. Panel for Datex ventilator.

Ventilation Modes

Volume control, pressure control, and SMIV are standard. PSV is optional. Breaths that are pressure supported are colored red on the pressure waveform.

Special Features

There is an overpressure release valve that is set at 80 cm H_2O.

During spontaneous breathing, subatmospheric pressure is limited to -3 cm H_2O.

This machine has battery backup for the entire machine as well

as the ventilator for at least 20 minutes with fully charged batteries. There is a battery charge

indicator. When about 30 seconds remain in the battery, a red alarm message indicates ‘€Battery Empty, Go Manual.‘€

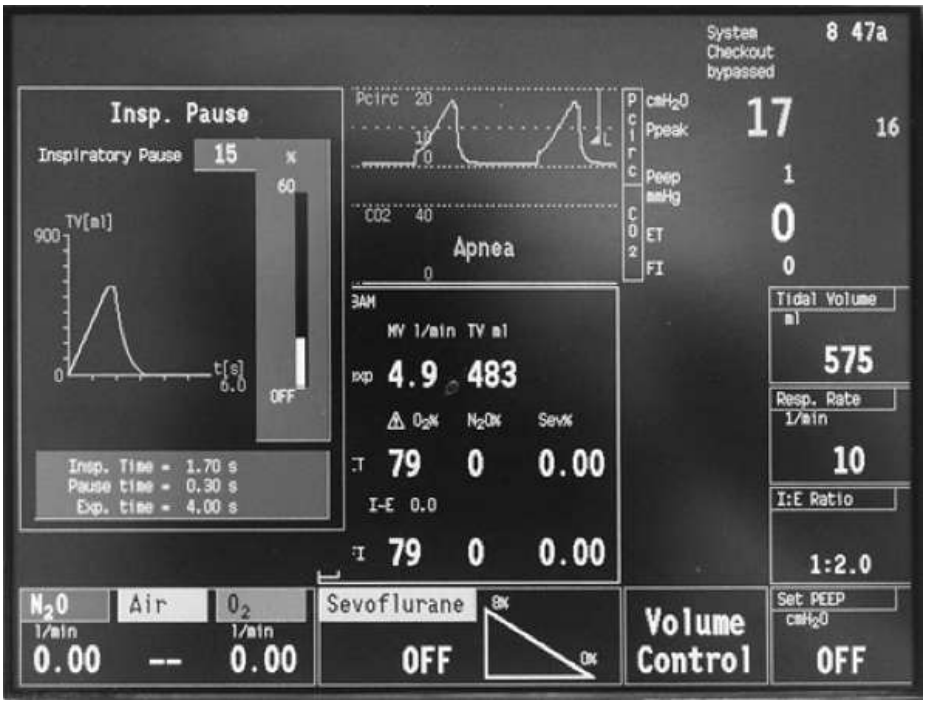


Figure 12.47. The inspiratory pause can be displayed on the left part of the screen. It is changed by using the rotary mouse.

Figure 12.48. The inspiratory time can be displayed on the left part of the screen. It is changed by using the rotary mouse.

There is an automatic checkout procedure that can be performed before the patient is connected to the unit. The full checkout is recommended on each machine power-up but can be bypassed. Breathing system compliance, compression volume, and leakage are measured. If the bypass command is selected, the default value for compressible volume is 2 mL/cm H_2O. The delivered tidal volume may not be correct if the compressible volume differs from this value.

The amounts of fresh gas and liquid anesthetic agent used since power-up are calculated and can be displayed. Gas usage can be displayed.

If the patient's weight is entered, the ventilator automatically calculates and suggests settings for tidal volume, respiratory rate, and minute volume. The default

weight is 60 kg and corresponds to a tidal volume of 500 mL and a respiratory rate of 10.

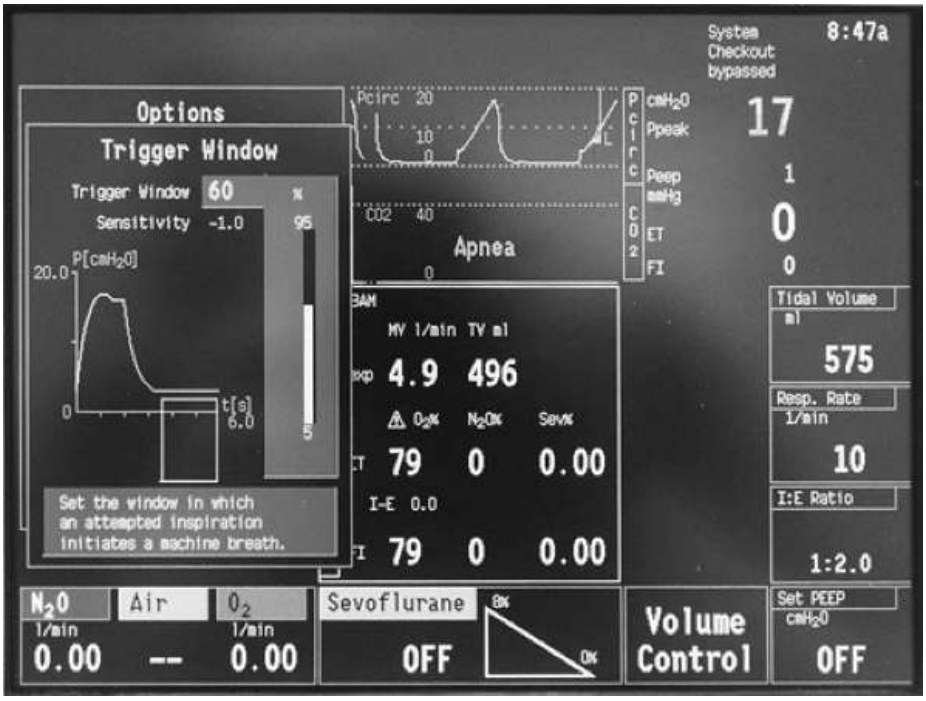


Figure 12.49. The trigger window can be displayed on the left part of the screen. It is changed by using the rotary mouse.

The ventilator has compensation for fresh gas flow and circuit compliance.

The ADU measures the fresh gas flow continuously. The delivered volume is calculated from these values. This does not protect the patient from an increased tidal volume if the oxygen flush is activated during inspiration (23).

Hazards

With a very high fresh gas flow, the fresh gas flow compensation may cause ventilator standstill (81).

Cleaning and Sterilization

Most of the parts of the ventilator and breathing system can be steam autoclaved at a maximum of 121ยฐC. Refer to the user manual for cleaning, disassembly, and disinfection of individual components.

Datascope Anestar

This ventilator is an integral part of the Anestar anesthesia system (20,23). The Anestar S is a scaled-down version with some functional differences.

Description

The Anestar breathing system is positioned at the front left of the machine (Fig. 12.50). A heated aluminum block engages with a motorized docking station. When attached to the docking station, the breathing system's pneumatic and electronic connections are secured. The hanging bellows and housing are located below the aluminum block. The breathing system contains a negative

pressure relief (room air, emergency air) valve. It opens to atmosphere whenever the pressure falls 3 cm H_2O or more below ambient pressure.

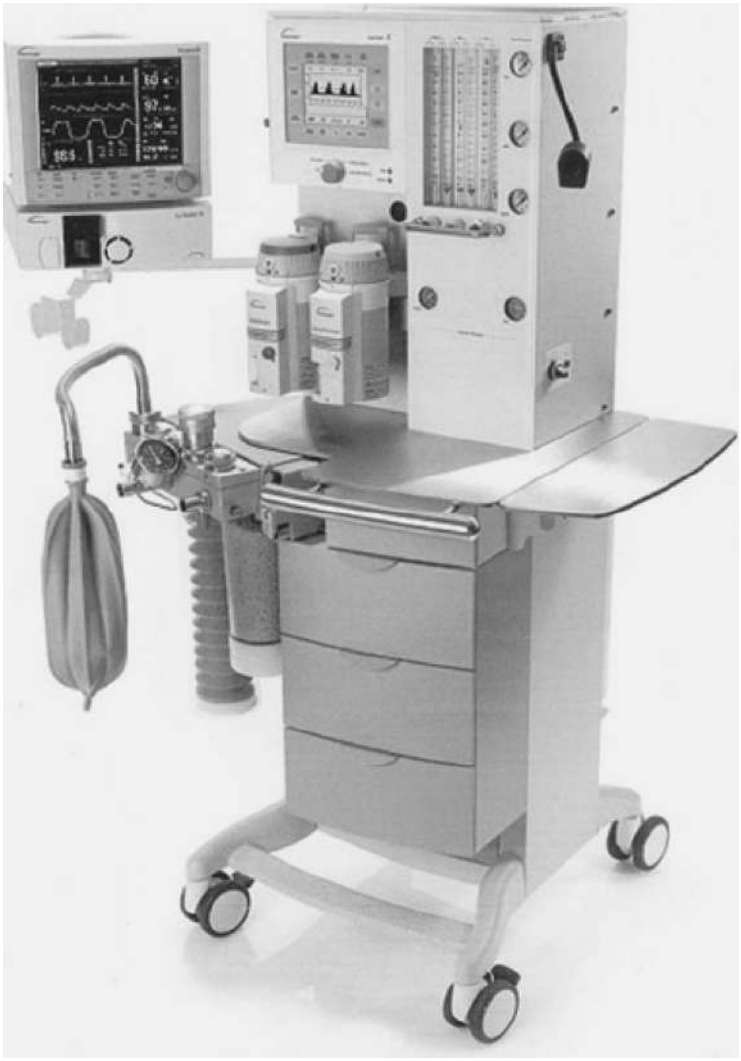


Figure 12.50. Anestar anesthesia machine. The bellows assembly with a descending bellows is located to the left and below. The dial below the screen and above the vaporizers has four positions: standby, manual ventilation, child (40 to 400 mL), and adult (300 to 1400 mL).

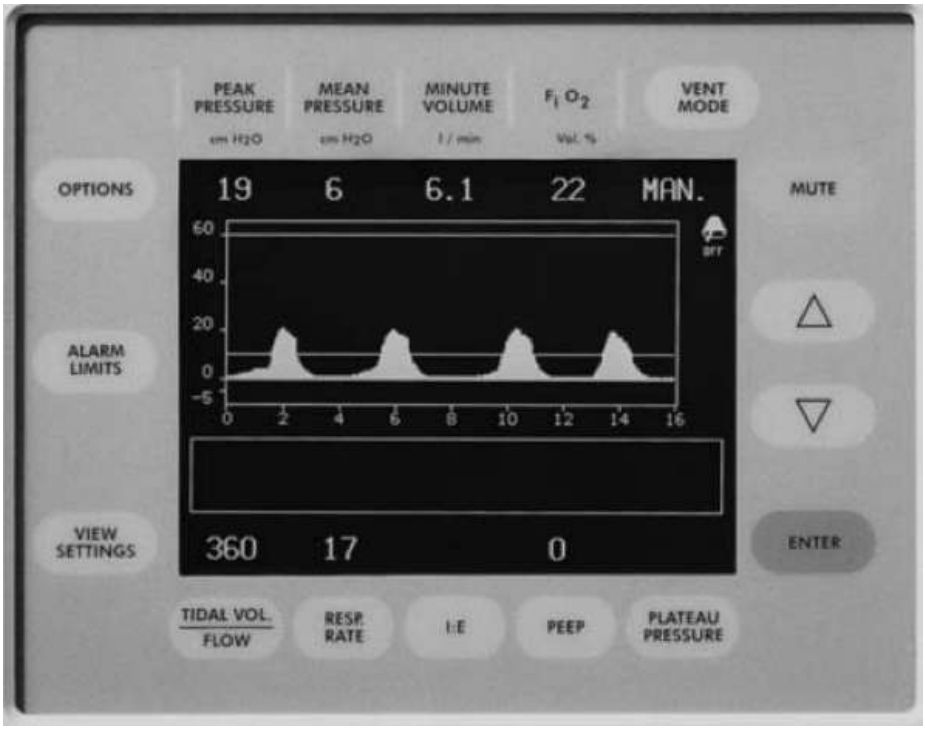


Figure 12.51. Anestar anesthesia machine screen. Manual ventilation.

Either air or oxygen can be used as the driving gas for the ventilator. If line pressure is unavailable, the machine will automatically switch to cylinders for driving gas if the cylinders are open.

Airway pressure is measured in the inspiratory limb. Expired volume is measured in the expiratory limb by using a hot-wire anemometer (Chapter 23). During mechanical ventilation, the delivered tidal volume is confirmed by using an internal flow sensor.

The touch screen is shown in Figures 12.51, 12.52, and 12.53. Ventilator functions are adjusted using the keys surrounding the screen. When the parameter to be changed is touched, the screen value is highlighted. The up and down keys to the right of the screen are used to increase or decrease the selected parameter. The change is confirmed by pushing the ENTER key at the lower right. The VIEW SETTINGS key at the lower left corner can be used to view the settings along the bottom of the

screen. Across the top of the screen are measured values for peak pressure, mean pressure, minute volume, inspired oxygen concentration, and ventilatory mode. The vent mode key is at the top right of the screen.

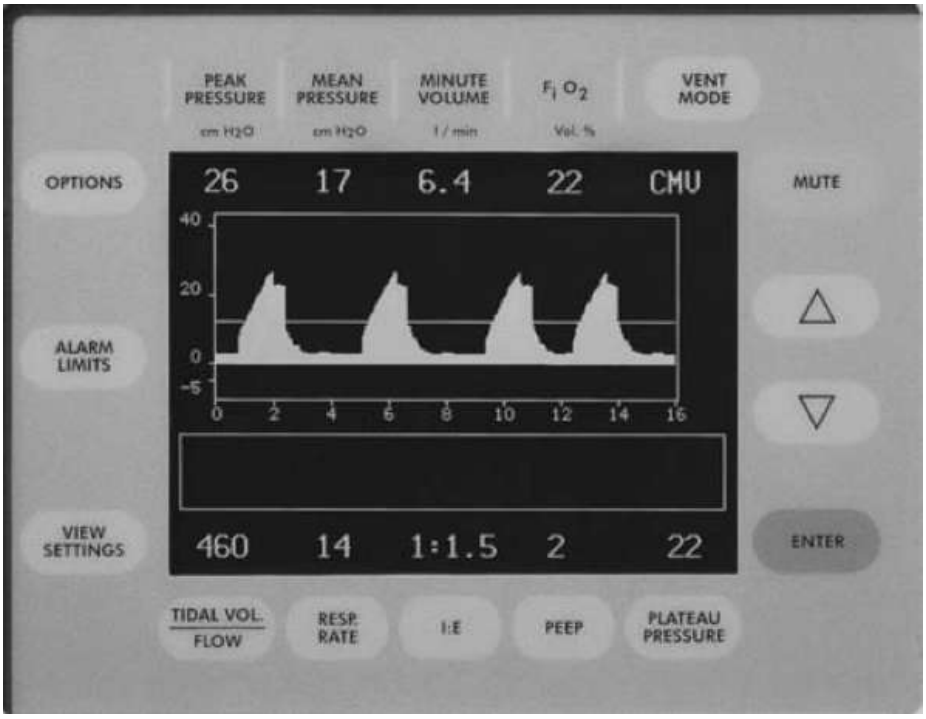


Figure 12.52. Anestar anesthesia machine. Volume control ventilation.

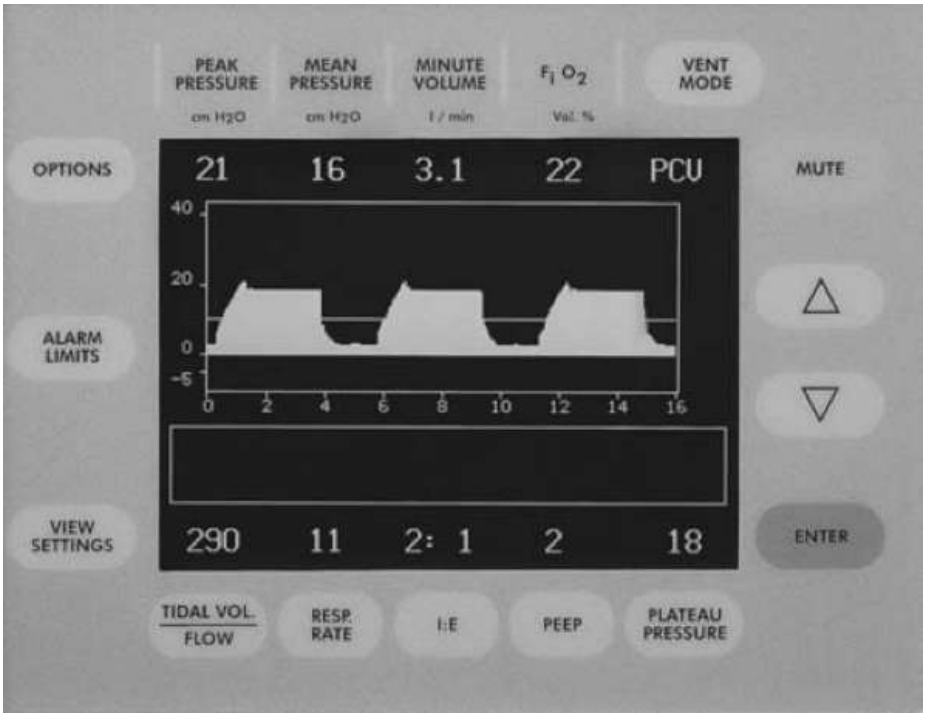


Figure 12.53. Anestar anesthesia machine. Pressure control ventilation.

In the middle of the screen is a pressure versus time graph. Below this is a box where alarm conditions are displayed. During the start-up for the machine, pertinent information and instructions that are needed to complete the start-up are displayed on the data screen.

The OPTIONS key to the left of the screen at the top provides access to the utilities that are available when the ventilation mode dial is in the standby position. These include compliance, oxygen calibration, leak testing, running hours, breathing system temperature, breathing system ejection control (Anestar only), and display screen contrast.

The ALARM LIMITS key activates and deactivates the alarm screen.

Controls

In volume control ventilation, tidal volume can be varied from 40 to 400 (default 200) mL in the child mode and 300 to 1400

(default 500) mL in the adult mode. The tidal volume/flow key, which is only on the Anestar, allows the operator to adjust the inspiratory flow rate, which can be varied from 10 to 60 (default 40) L/minute. Plateau pressure can be set to OFF, 20% or 30% (default OFF) of inspiratory time. The respiratory rate can be varied from 10 to 60 (default 20) bpm in the child mode and 4 to 30 (default 10) bpm in the adult*mode. The I:E ratio range*

is 4:1 to 1:5 (default 1:2). PEEP is adjustable from 3 to 15 cm H_2O (default OFF).

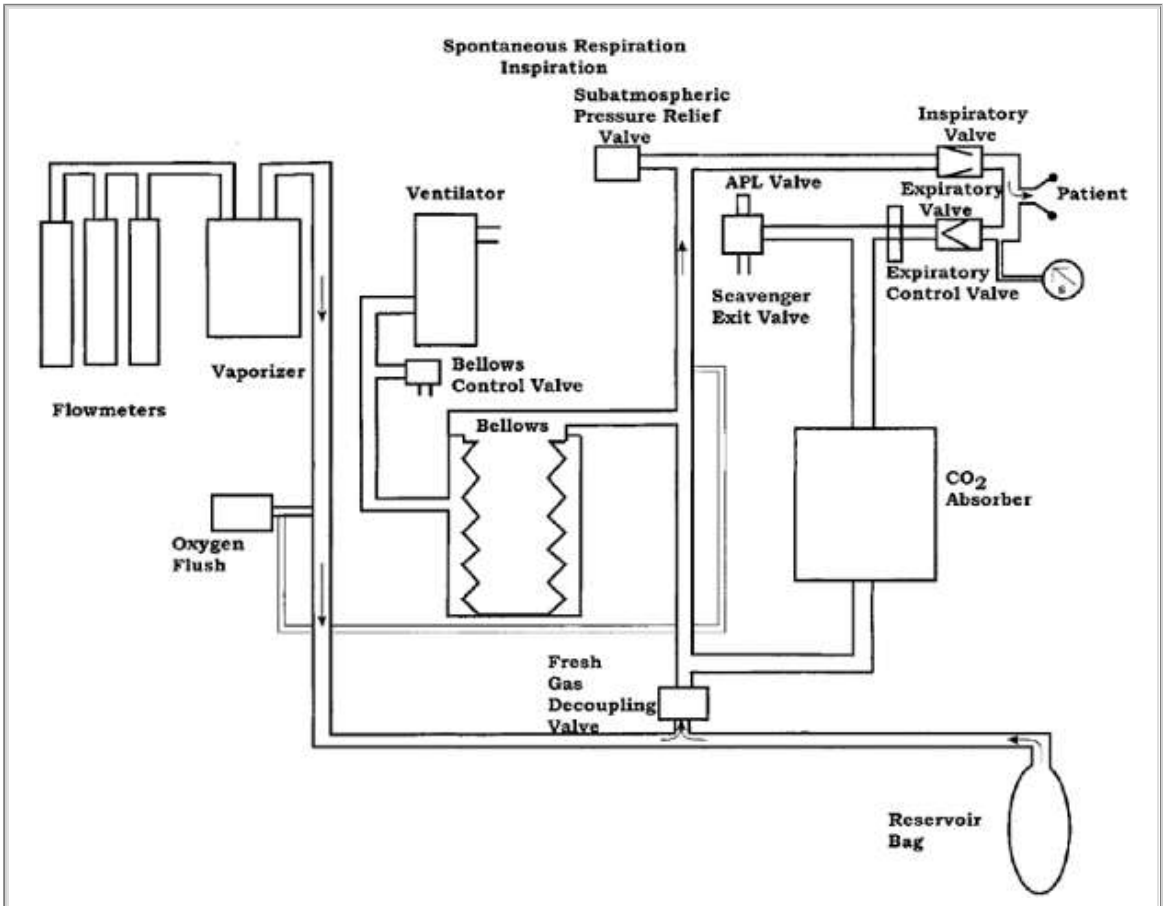


Figure 12.54. Anestar anesthesia machine. Inspiration during spontaneous respiration. Fresh gas from the anesthesia machine and gases from the reservoir bag flow through the inspiratory valve to the patient. If the bag empties, the subatmospheric pressure relief valve will open and admit room air into the system. APL, adjustable pressure limiting.

The plateau pressure key is used during pressure control ventilation to set the inspiratory (plateau) pressure, which can be varied from 10 to 60 (default 20) cm H_2O in both adult and child modes.

Alarms

The alarm limits key is to the left of the data screen. Pressing it opens a window on which alarm settings and alarm volume can be altered. Alarms are accessed by touching the screen and are set by using the up and down keys. There is a MUTE above the up and down arrow keys, which audio pauses alarms for 2 minutes. The alarms vary with the mode of ventilation.

Ventilation Modes

The Anestar has both volume control and pressure control ventilation. When switching between modes, settings are saved and will resume when returning to a mode. The Anestar S has only volume control ventilation.

The Anestar breathing system is shown in Figures 12.54 to 12.60 (see pages 362,363,364,365,366,367,368). The reservoir bag serves to hold fresh gas. During mechanical ventilation, the bag is full and appears to pulsate, inflating slightly during inspiration. The bag, rather than the bellows, provides a visual indication of a disconnection. If a leak occurs and the volume of gas lost is less than the fresh gas flow, the bag will pulsate more deeply. In case of a disconnection or major leak, the reservoir bag will deflate after a few breaths.

The APL valve should always be set to the OPEN position while in the CVM or PCV modes.

Spontaneous Breathing

During spontaneous breathing, the bellows remains fully expanded. During inspiration (Fig. 12.54), gas flows from the reservoir bag. If the bag empties, the subatmospheric pressure relief valve opens, and air is drawn into the system. During exhalation (Fig. 12.55), exhaled gases pass through the absorber and mix with fresh gas in the reservoir bag. Excess gas is vented to the scavenging system through the APL valve.

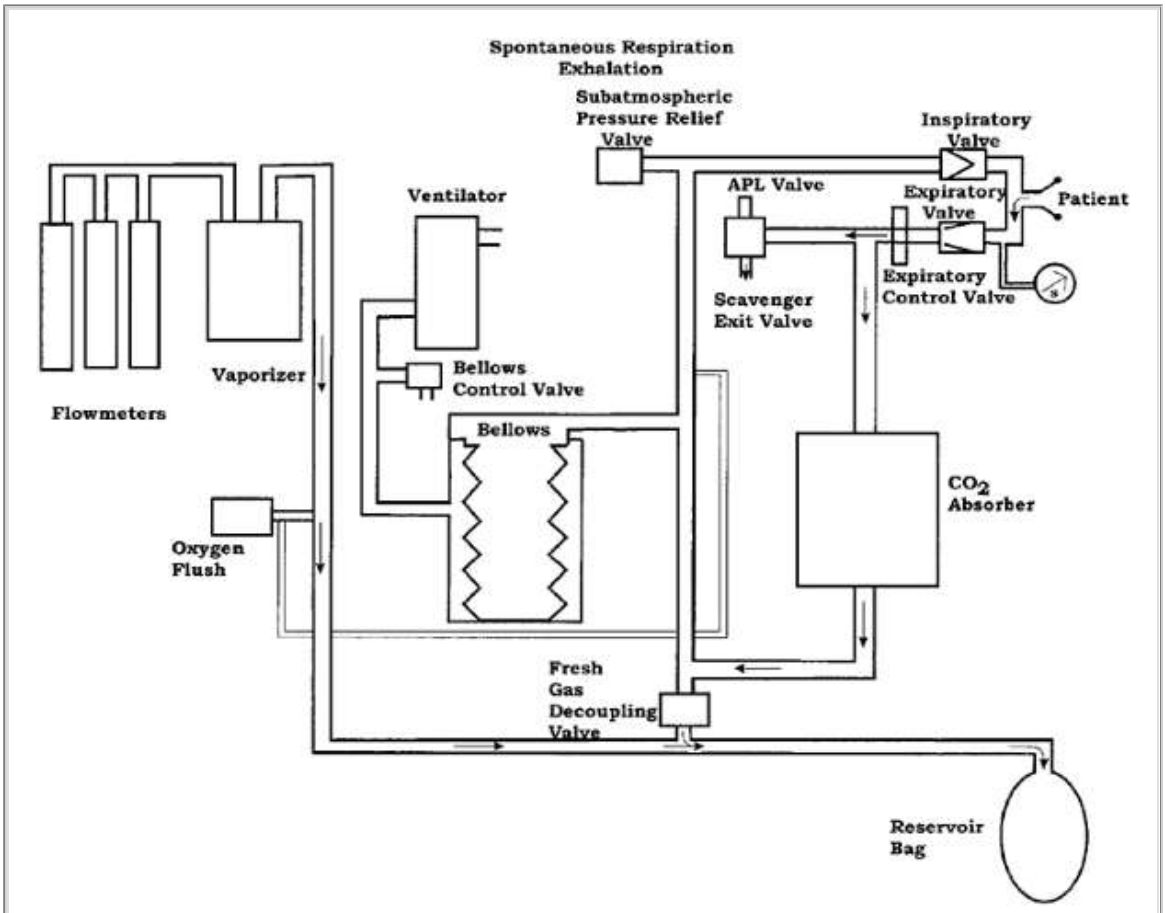


Figure 12.55. Anestar anesthesia machine. Exhalation during spontaneous respiration. Gases exhaled by the patient flow through the absorber and join fresh gases flowing into the reservoir bag. At the end of exhalation, excess gases flow through the APL valve to the scavenging system. APL, adjustable pressure limiting.

Manual

With manual ventilation, the bellows stays fully expanded. During inspiration (Fig. 12.56), the reservoir bag is squeezed so that gases flow to the patient. These include fresh gas and gas that has passed through the absorber. During the latter part of inspiration, some gas may be vented through the partly open APL valve. During exhalation (Fig. 12.57), the inspiratory unidirectional valve closes. Fresh gas flows into the reservoir

bag. Exhaled gas passes through the absorber and mixes with fresh gas in the reservoir bag.

Mechanical

During inspiration (Fig. 12.58), the fresh gas decoupling, expiratory control, and bellows control valves close. Fresh gas flows into the reservoir bag. Once the bag is filled, excess gas flows to the scavenging system through the APL valve.

During exhalation (Figs. 12.59, 12.60), the fresh gas decoupling valve is open so that fresh gas flows into the bellows and inspiratory limb. Exhaled gases pass through the expiratory unidirectional valve and the absorber. The open bellows control valve vents the drive gas to atmosphere, allowing the bellows to refill. First fresh gas, then the exhaled gas, then possibly gas in the reservoir bag fills the descending bellows. In the event that fresh gas flow is lost, the subatmospheric pressure relief valve prevents a negative pressure in the circuit by allowing ambient air to enter the system. After the bellows has filled (Fig. 12.60), the pressure in the breathing system increases. When it reaches approximately 2 cm H_2O, excess gas passes through the APL valve to the scavenging system.

PEEP is created by adjusting the expiratory control valve. Closing the valve before the start of the next inspiration traps volume returning from the patient. The timing is fine tuned over several breaths to trap the appropriate volume in the expiratory limb in order to maintain the desired level of PEEP.

Special Features

During mechanical ventilation, tidal volume is unaffected by system compliance. The computer compiles the necessary information during the startup procedure.

This task, which takes 30 seconds, can be bypassed and the previous measurement retained for emergency cases. Tidal volume is unaffected by fresh gas flow.

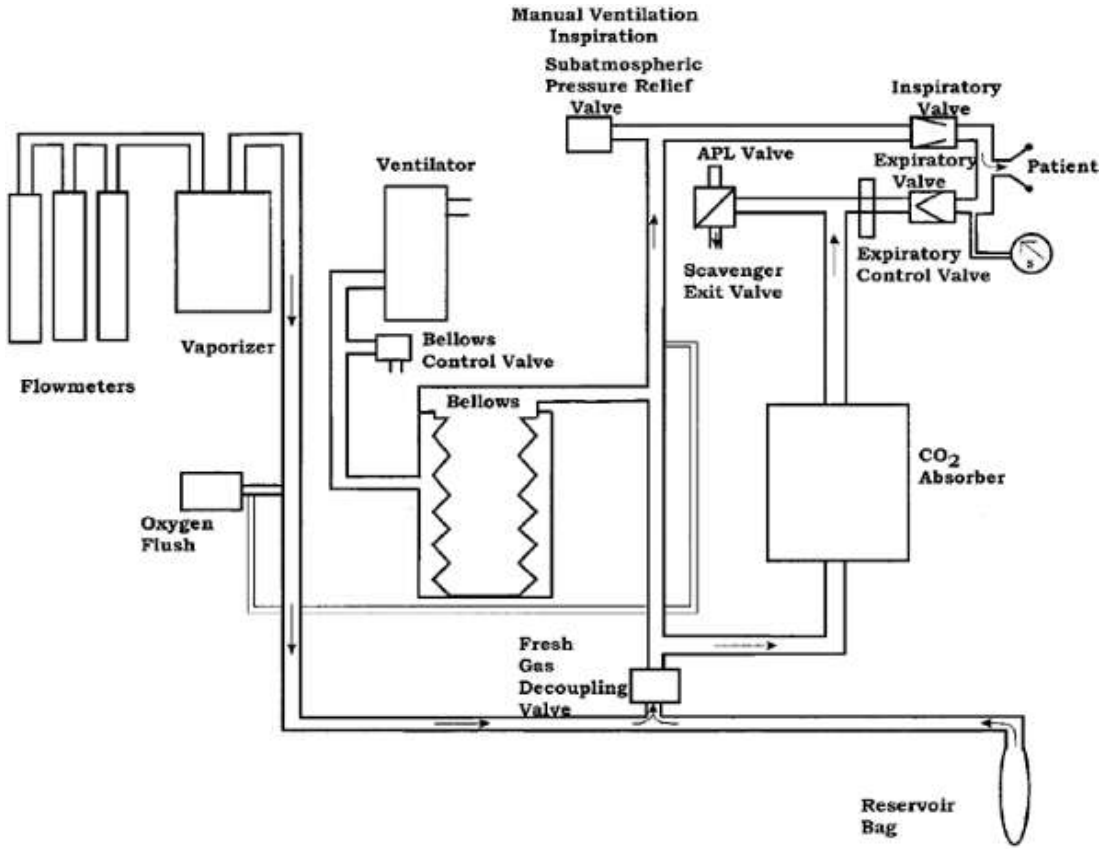


Figure 12.56. Anestar anesthesia machine. Inspiration during manual ventilation. When the bag is squeezed, gases from it and fresh gases flow through the inspiratory valve to the patient. APL, adjustable pressure limiting.

The maximum inspiratory pressure limit is 80 cm H_2O.

The breathing system is heated to 35ยฐC (97ยฐF). This warms inspired gases and eliminates moisture condensation within the breathing system, even with low fresh gas flows.

In the event of power failure, a fully charged battery will power the ventilator and its integrated monitor for 30 minutes. After 30 minutes, manual and assisted ventilation is possible, and monitoring continues until the battery is depleted.

A subatmospheric pressure (room air) valve prevents negative pressure by entraining room air if the pressure in the breathing system falls 3 cm H_2O or more below ambient pressure. An

alarm is activated and a screen message appears if there is ambient air intake.

The Anestar has a pressure relief button that rapidly discharges airway pressure if depressed. This red button is located on the breathing system near the APL valve.

Cleaning and Sterilization

Directions for assembly and disassembly of the breathing system are given in the operating manual. Most of the parts of the breathing system that are exposed to respiratory gas can be steam autoclaved at 124ยฐC.

Pediatric Ventilation

In the past, pediatric ventilation has caused uneasiness among anesthesia providers because the large amount of space in the absorber, tubings, and ventilator resulted in relatively large loss of volume from gas compression and compliance of these components (82,83). Experience has shown that volume control ventilation of infants with newer ventilators is safe and effective, although the delivered tidal volume may be somewhat imprecise (60,61). Pressure control ventilation can also be used with pediatric patients (27,28,59,83,84). Some ventilators have a pediatric mode that is tailored to small infants and children.

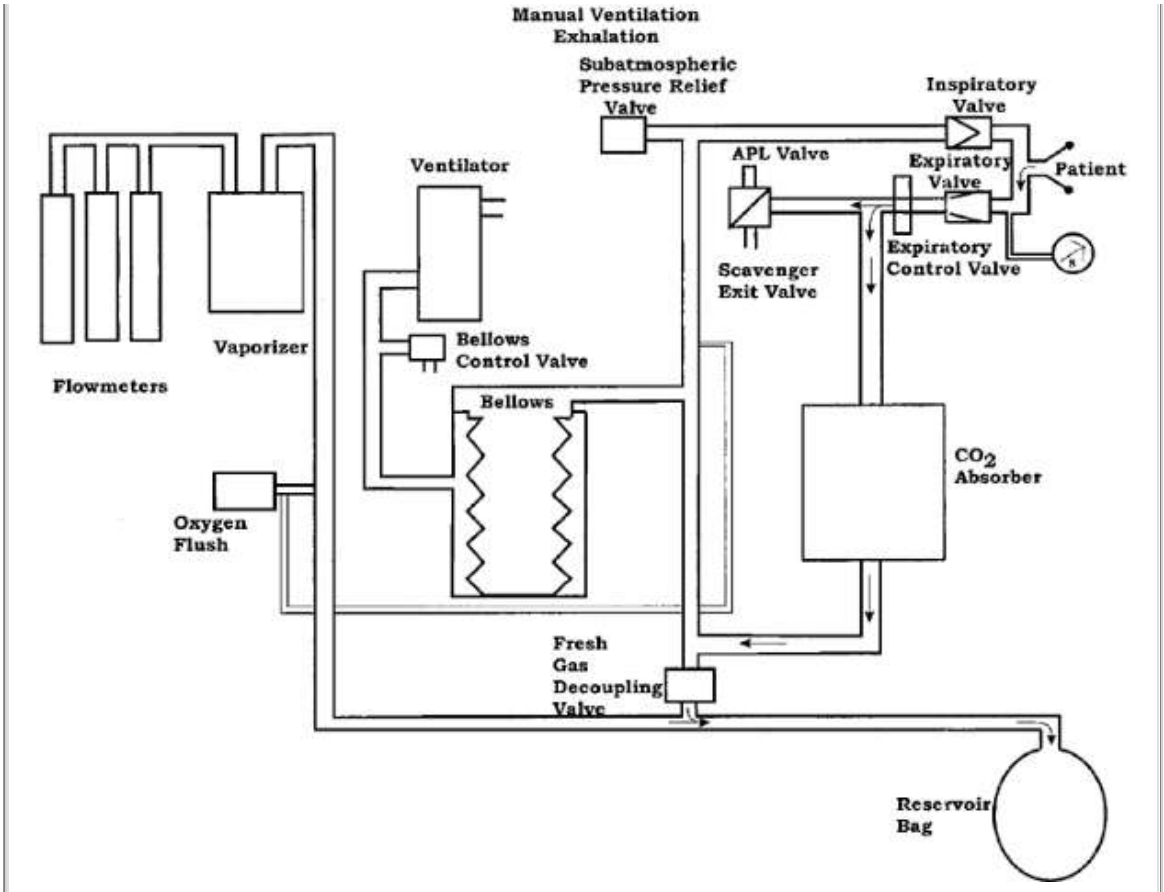


Figure 12.57. Anestar anesthesia machine. Exhalation during manual ventilation. Exhaled gases from the patient pass through the absorber and join fresh gas flowing into the reservoir bag. When the pressure set on the APL valve is exceeded, excess gases will pass through it to the scavenging system. APL, adjustable pressure limiting.

Magnetic Resonance Imaging Ventilators

Considerations for practicing anesthesia in the magnetic resonance imaging (MRI) unit are discussed in Chapter 30. Standard ventilators with ferrous material cannot be used, because the electromagnetic environment will interfere with the controls and the ventilator can interfere with the radiofrequencies of the MRI. Anesthesia ventilators suitable for use in an MRI unit are available. ICU ventilators can be modified so that they are suitable for such use (85).

There is a report of a patient death due to an oxygen cylinder emptying while a pneumatically driven ventilator was being used in an MRI suite (86). Although there was an alarm, it was not noticed by personnel. In unusual situations such as an MRI suite, the ventilator should be attached to the central pipeline system when the ventilator is being used. If this is not available, extra nonferrous cylinders need to be present and the machine, ventilator, and patient carefully watched.

General Hazards

Hypoventilation

Ventilator Failure

Most anesthesia ventilators perform reliably for long periods of time. Nevertheless, one may occasionally fail to work properly. Some problems are insidious and result in less-than-total failure. Malfunction may not be readily apparent, and a false sense of security may be generated by the sound that the ventilator makes.

Causes of ventilator failure include disconnection from or failure of the power source (electricity or driving gas) and internal dysfunctions. An intermediate frequency setting may cause cycling failure (87). On some ventilators, with fresh gas flow compensation, a very high fresh gas flow can cause ventilator standstill (81). Problems with the electric motor or power supply may cause the ventilator to stop functioning (64,65,68,88). Fluid entering the electronic circuitry may cause the ventilator to stop working (89).

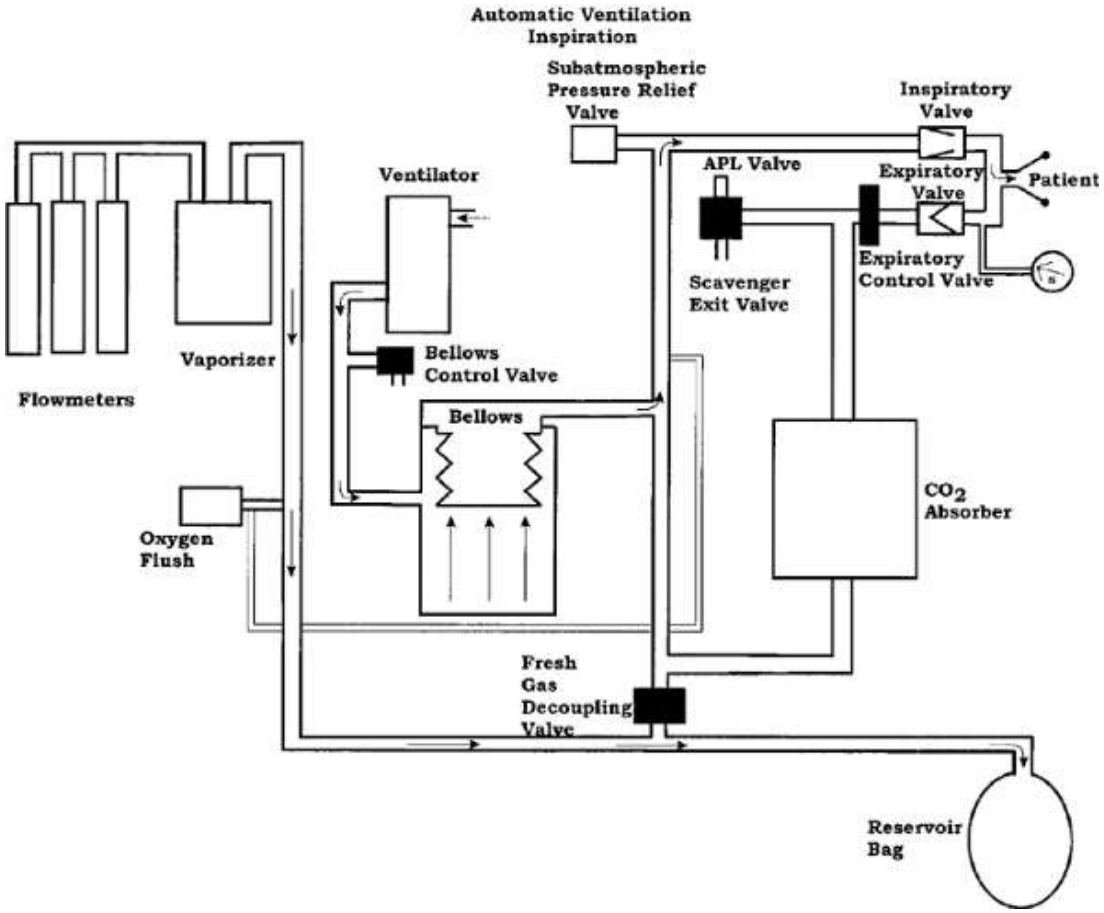


Figure 12.58. Anestar anesthesia machine. Inspiration during automatic ventilation. The fresh gas decoupling valve is closed, so all of the fresh gas flows into the reservoir bag. The bellows is compressed so that gas flows through the inspiratory valve to the patient. APL, adjustable pressure limiting.

If the bellows housing is not tightly secured, driving gas can leak, causing a reduction in tidal volume (90). The housing may dislocated by hitting ceiling columns or other objects as the ventilator is moved. Operating room personnel may attempt to move a ventilator by grabbing the housing, loosening it, or causing it to break.

A malfunction in a computer-controlled ventilator may interrupt cycling. It is good practice to turn the anesthesia machine OFF and restart it by using the electronic checkout procedure at least

daily so that the computer has fresh information in its data bank. A cycling failure may sometimes be solved by turning the anesthesia machine OFF and then ON but usually requires reference to the operation manual or a call to the manufacturer.

Low maximum flow rates and variability in flow rates with increased airway pressure with older anesthesia ventilators can reduce the tidal volume that can be delivered. Although this is usually not a problem in patients with normal lungs, it can become important in patients with expiratory airflow obstruction, for whom a prolonged expiratory phase may be necessary to avoid autoPEEP.

Loss of Breathing System Gas

Older anesthesia ventilators have no means of compensating for gas loss in the breathing system. New computer-controlled ventilators can compensate for small leaks. A ventilator may cycle but fail to occlude the exit port of the spill valve, blowing part or all of the tidal volume into the scavenging system (53,54,91).

If there is loss of breathing system gas and an ascending bellows ventilator is in use, the bellows may not return to its fully expanded position. This usually will be obvious. However, with the introduction of closed scavenging systems, the bellows may remain expanded if there is a disconnection (92). A descending bellows ventilator may appear to function normally in the face of loss of breathing system gas.

Incorrect Settings

In a crowded anesthetizing area, ventilator switches or dials may be inadvertently changed as personnel move about. An operator may fail to adjust settings for a new case (93). For ventilators that provide a control for limiting the peak inspiratory pressure, setting that pressure

too low may result in an inadequate tidal volume being delivered.

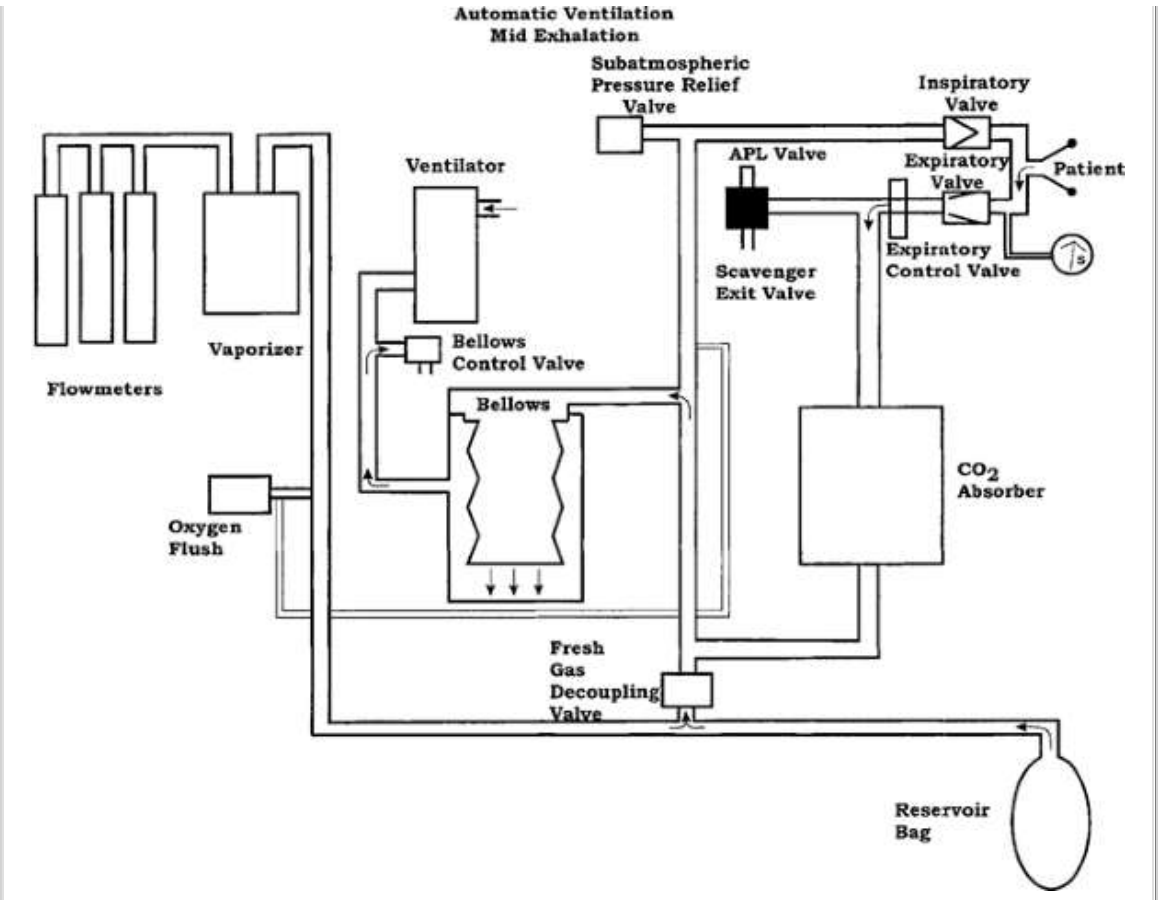


Figure 12.59. Anestar anesthesia machine. Mid exhalation during automatic ventilation. The bellows expands, drawing in fresh gas and gas from the reservoir bag. Gas exhaled by the patient passes toward the absorber. APL, adjustable pressure limiting.

If an anesthesia machine is turned OFF and then turned back ON, the ventilator may default to different settings than were being used (94).

It is essential that there be sufficient inspiratory time for the desired tidal volume to be delivered. Insufficient inspiratory time may be indicated by a bellows that does not make a full excursion, causing a decrease in the tidal volume.

Ventilator Turned OFF

There are times during anesthesia when the ventilator must be turned OFF, such as during radiological procedures where

movement would compromise the image quality. The operator may forget to turn it back ON.

Flow Obstruction

As will be pointed out in Chapter 14, restricted or occluded gas flow can occur at a variety of sites and be caused by a variety of mechanisms. including failure to change the position of the bag-ventilator selector valve when converting to automatic ventilation. If the valve is left in the bag position, the ventilator will operate against a dead end.

With obstruction to flow, the excursion of the bellows will be reduced but not totally eliminated. The pressure shown on the system pressure gauge will vary, depending on the locations of the obstruction and the gauge.

Positive End-expiratory Pressure

Addition of PEEP may decrease the tidal volume delivered with some ventilators (21,22). The effect is more pronounced with low tidal volumes but less if lung compliance is low.

Hyperventilation

In one reported case, ventilator settings for a patient with low compliance were not modified prior to the next case, a patient with normal lung compliance (93). The result was excessive tidal volume.

With a hole in the bellows or a loose connection between the bellows and its base assembly, driving gas from the housing can enter the bellows, causing an unexpectedly high tidal volume (95). This can be

accentuated by a high inspiratory flow rate. A small hole in the bellows may not cause a change in the tidal volume (96).

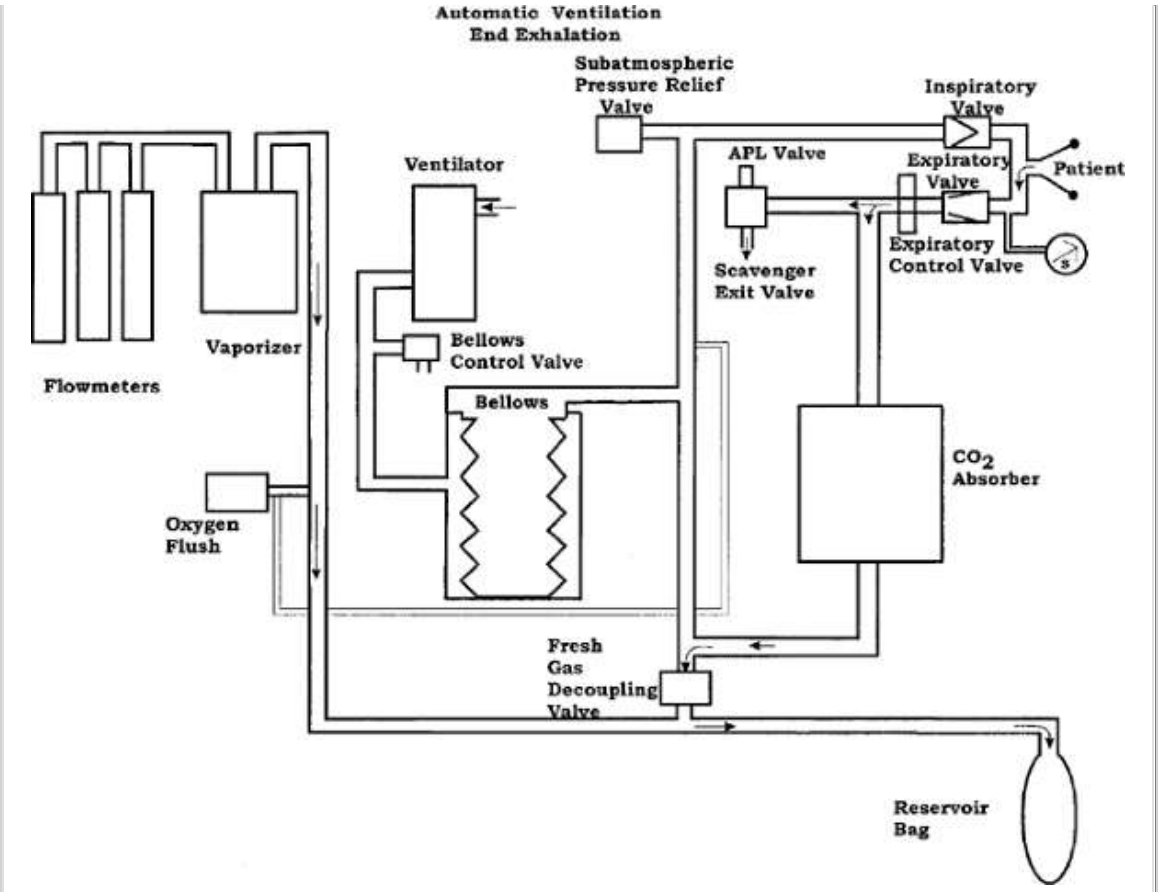


Figure 12.60. Anestar anesthesia machine. End exhalation during automatic ventilation. The APL valve opens, allowing excess gases to flow into the scavenging system. APL, adjustable pressure limiting.

Hyperoxia

A hole or tear in the bellows with oxygen as the driving gas can result in an increase in the inspired oxygen concentration and lower-than-expected anesthetic concentrations (95,97,98). However, with a small tear, there may be no effect (96).

Excessive Airway Pressure

Excessive airway pressure can develop very rapidly, especially if high fresh gas flows are being used. Quick action may be required to prevent patient injury.

Because the ventilator spill valve is closed during inspiration and

the APL valve in the breathing system is closed or isolated, activating the oxygen flush during the inspiratory phase can result in barotrauma. Fresh gas decoupling reduces this danger by diverting the oxygen to the reservoir bag. Ventilators that compensate by altering the bellows excursion may not always be able to prevent excessive airway pressure if the oxygen flush is used during inspiration.

A hole in the bellows or a loose connection between the bellows and its base may allow driving gas to enter the bellows, resulting in a higher-than-expected pressure during inspiration. Pressure on the ventilator spill valve can result in excess pressure (54,56,57). In one case, a muffler designed to silence the exhaust of driving gas from the ventilator became saturated with water and prevented gas from exiting the bellows housing (49).

Sufficient time to allow full exhalation must be allowed. Insufficient expiratory time may be indicated by a bellows that does not expand fully and carries the risk of air trapping and auto (occult, intrinsic) PEEP (99).

A properly set pressure limiting mechanism should reduce the risk of barotrauma. Some ventilators have adjustable high-pressure alarms. On others, the alarms are preset. Such an alarm may give warning of a problem in time to prevent harm to the patient. The risk of

barotrauma and volutrauma are reduced with fresh gas decoupling (100).

When there is high airway pressure, a disconnection should be made immediately at the tracheal tube and manual ventilation instituted. Taking time to find the source of the problem may result in harm to the patient.

Negative Pressure during Expiration

Negative pressure is considered undesirable under most circumstances because of adverse effects on pulmonary function and increased risk of air embolism. A ventilator with a weighted hanging bellows can generate subatmospheric pressure during the early part of expiration if expiratory flow is not impeded. This will be accentuated if the fresh gas flow is low. Newer ventilators with a hanging bellows have a negative pressure valve to admit air if negative pressure develops.

Alarm Failure

Although low-pressure alarms have significantly advanced patient safety, they can fail. When the low airway pressure alarm threshold is adjustable, it should be set just below the peak inspiratory pressure. Cases have been reported where resistance (from tracheal tube connectors, Y-pieces, filters, and other components or from the patient port of the breathing system being pressed against the patient or a pillow) coupled with high inspiratory flow rates created sufficient back pressure to generate a false-positive signal at the sensing site when the threshold was set too low.

The use of a PEEP valve in the breathing system may cause a low-pressure alarm not to be activated if the PEEP valve raises the pressure above the alarm threshold.

Electromagnetic Interference

Ultra-high-frequency (UHF) radios and GSM cell phones may interfere electromagnetically with ICU and operating room ventilators (101). Effects include faulty readings, misleading alarm messages, modification of ventilation parameters, and output interruption and were temporary.

Loss of Electrical Power

Most ventilators in use today are electrically powered. If there is a power failure, there must be a battery backup for at least 30 minutes (6). The screen will note the changeover to battery power and give an indication of battery life. When all electrical energy is lost, most anesthesia machines will default to a manual/spontaneous breathing mode. The anesthesia provider may need to initiate this move. Without the ventilator or machine monitors, most machines will provide oxygen to the breathing system, and sometimes volatile agent. Since machines handle this problem in different ways, the user needs to determine how a particular machine will react to a power outage and develop a plan of action if this problem occurs.

Advantages

1. Use of a ventilator allows the anesthesia provider to devote

time and energy to other tasks and eliminates the fatigue resulting from squeezing a bag (102).

2. A ventilator produces more regular ventilation with respect to rate, rhythm, and tidal volume than manual ventilation.

Disadvantages

1. Probably the greatest disadvantage to the use of a ventilator is the loss of contact between the anesthesia provider and the patient. The feel of the bag can reveal such things as disconnections, changes in resistance or compliance, continuous positive pressure, and spontaneous respiratory movements. With mechanical ventilation, these may go undetected for a considerable period of time.
2. A ventilator may induce a false sense of security in the user if it continues to make the appropriate sounds even when it malfunctions.
3. Some anesthesia ventilators do not include all the newer modes of ventilation, and some cannot develop high enough inspiratory pressures or flows to ventilate certain patients (1,103). It may be necessary to take a critical care ventilator into the operating room to provide adequate ventilation for critically ill patients.
4. Components that are subject to contamination may not be easy to remove or clean, especially those on older ventilators.
5. Some ventilators lack user-friendliness. There is room for improvement in the design and grouping of controls.
6. Some ventilators are disturbingly noisy or too quiet.
7. Some ventilators require relatively high flows of driving gas (15). Gas consumption increases with increased minute volume and with some ventilators, an increased I:E ratio. A ventilator with a piston will not consume driving gas.

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Questions

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

1. A hole or tear in the bellows may result in

Hyperventilation

Hyperoxia

Barotrauma

Patient awareness

View Answer

2. Excessive airway pressure may be caused by

Activating the oxygen flush during inspiration

A hole in the bellows housing

A stuck spill valve

Ascension of the bellows

View Answer

3. A standing bellows

Is attached at the top

Expands during exhalation

Imposes no pressure during exhalation

Makes it easy to detect disconnections

View Answer

4. When a ventilator with a piston is used,

PEEP of 2 to 4 cm H_2O is usual

Air entrainment may occur

The reservoir bag is isolated from the breathing system during exhalation

The reservoir bag may expand and contract with mechanical ventilation

View Answer

5. Regarding pressure control ventilation,

Flow is highest at the beginning of inspiration

Tidal volume is not constant

It is often used with supraglottic devices

It is useful for detecting a partially occluded tracheal tube

View Answer

6. Regarding SIMV,

The ventilator has a secondary source of gas flow for spontaneous breaths

It is often used for weaning patients from mechanical ventilation

A mandatory tidal volume and minimum mechanical ventilation rate must be selected

Positive pressure (mandatory) breaths occur at regular intervals

View Answer

7. Regarding PSV,

Most ventilators have a backup or ‘€apneic‘€ rate

The optimal initial inspiratory flow is highest in patients with high compliance

The pressure waveform has a square, flat-topped shape

It is associated with a decrease in functional residual capacity

View Answer

Chapter 13
Controlling Trace Gas Levels

Introduction

Before scavenging was instituted, excess anesthetic gases and vapors were discharged into room air. As a consequence, operating room personnel were exposed to low concentrations of these drugs with little concern about any detrimental effects that could possibly result from such exposure. Questions have been raised about possible hazards from exposure to trace amounts of anesthetic gases and vapors (1). (For the remainder of this chapter, anesthetic gases and vapors will be referred to as *gases*, because most vapors behave as gases.)

A trace level of an anesthetic gas is a concentration far below that needed for clinical anesthesia or that can be detected by smell (2). Trace gas levels are usually expressed in parts per million (ppm), which is volume/volume (100% of a gas is 1,000,000 ppm; 1% is 10,000 ppm).

Reported trace gas concentrations in operating rooms vary greatly, depending on the fresh gas flow, the ventilation system, the length of time that anesthesia has been administered, the measurement site, anesthetic technique, and other variables. Trace gas levels tend to be higher with pediatric anesthesia (3,4), in dental operatories (1,5), and in poorly ventilated postanesthetic care units (recovery rooms) (6,7,8,9,10).

Methods of Study

Despite many studies and much discussion, opinions differ on whether or not a problem exists and what levels should be allowed in the working environment (11). To interpret the data, it is first necessary to understand how it was collected. Four basic methods of study have been used. All have major limitations and disadvantages.

Animal Investigations

During animal studies, laboratory animals are exposed to varying levels of gases for varying periods of time and are studied to determine the effects.

These studies should be interpreted warily. Large numbers of animals need to be studied to achieve statistical significance. In

animals, diet affects tumor susceptibility, and stress affects reproduction (12). Toxicity usually depends on both exposure time and concentration, and it is difficult to correlate exposure time in animals with that in humans because their life spans are so different. Finally, variations in drug effects among species create uncertainty about the relevance of these findings to humans.

Human Volunteer Studies

Human volunteers have been used to study the effects of trace gases on skilled performance, immune responses, and drug metabolism.

Epidemiologic Studies of Exposed Humans

A number of epidemiologic studies of exposed personnel have been performed. Most were retrospective and used questionnaires. They suffer from low response rates, inappropriate control groups, poor recollections and biases on the part of the respondents, poor wording, failure to include significant points in the questionnaires,

and misinterpretations due to differences in education and experience on the part of the respondents (12,13,14,15,16). Data interpretation is hampered by a lack of agreement as to what level of significance to accept (12,17). Finally, many of the studies have not been designed to test the cause-and-effect relationship between trace gases and problems in exposed personnel. Some studies show increased risk for specific groups but not for other equally exposed groups (18). Others have shown problems in groups with and without exposure to trace gases, suggesting that the risk may be related to some other factor. Finally, many of the studies were performed before scavenging and other methods to control trace gas levels were implemented.

Mortality Studies

Studies on the causes of death and the age at which death occurred among anesthesiologists have provided interesting data. One study found that anesthesiologists do not have an increased risk of death from cancer or heart disease but do have higher rates of death due to suicide, substance abuse, other external causes and cerebrovascular disease than internists (19). There was also an increased rate of death from HIV and viral hepatitis in male anesthesiologists. Another study found that while anesthesiologists have a significantly younger mean

age of death, there was no statistical difference in age-specific mortality (20).

Problems Attributed to Trace Gases

Spontaneous Abortion

Epidemiologic Studies

Epidemiologic studies from several countries have shown higher rates of spontaneous abortion in operating room and dental operatory personnel than in women in different environments (21,22,23,24,25,26,27,28,29,30,31,32,33). Other studies have failed to find significant increases in spontaneous abortions in exposed personnel (34,35,36,37,38,39,40). One study found that the frequency of miscarriages among nurses working in intensive care units was approximately equal to that of nurses in the operating room, suggesting that other factors such as stress may play a role (27,41). A study of midwives who were often exposed to nitrous oxide found that the risk of spontaneous abortion was not increased with nitrous oxide exposure but was increased with night work and high workload (42).

Animal Studies

Halogenated Agents

Investigations have found no evidence of increased spontaneous abortion in mice exposed to high levels of isoflurane, enflurane, or halothane (43,44,45,46,47,48,49).

Nitrous Oxide

One study found that prolonged exposure to 1,000 ppm nitrous oxide caused fetal death, but no effect was seen when 500 ppm was used (50). A later study found that the threshold for fetal death was higher (between 1,000 and 5,000 ppm) with intermittent exposure (51).

Mixtures

Investigations using mixtures of halothane and nitrous oxide found no effect with concentrations as high as 1,600 ppm halothane plus 100,000 ppm nitrous oxide (49). Nitrous oxide 500,000 ppm plus isoflurane 3,500 ppm also had no effect on spontaneous abortions (52).

Spontaneous Abortion in Spouses

Although several studies have shown an increased spontaneous abortion rate in wives of exposed males (23,53,54), the majority suggest that there is no increase (16,21,25,40). One study found no changes in sperm concentration or morphology in male anesthesiologists working in health care facilities with scavenging equipment (55). Studies have failed to show any adverse effect on reproductive processes of male animals exposed to up to 5,000 ppm enflurane (44,56) or 10 ppm halothane plus 500 ppm nitrous oxide (57).

Infertility

Epidemiologic Studies

Several studies have found higher-than-expected rates of involuntary infertility among exposed personnel (24,53,58). A more recent study found no evidence that female anesthetists have increased risk of infertility (59). One study found decreased fertility in dental operatory staffs who were exposed to considerably higher levels of nitrous oxide than those who were operating room personnel (5). One study found no effect from paternal exposure (25), and no changes in sperm count or morphology were found in male anesthesiologists working in scavenged operating rooms (55).

Animal Studies

Halogenated Agents

Numerous studies of animals exposed to high concentrations of isoflurane, enflurane, or halothane showed little or no effect on fertility (43,45,56,60,61,62,63).

Nitrous Oxide

No changes in male fertility and no sperm abnormalities were found in mice after exposure to up to 800,000 ppm (60,64). However, prolonged exposure of male rats to 200,000 ppm resulted in abnormalities in spermatogenic cells (65). Exposure to up to 800,000 ppm caused no changes in fertility in male or female flies (61).

Mixtures

Decreased fertility was seen in female rats exposed to halothane 10 ppm plus nitrous oxide 500 ppm before mating (57). Male rats exposed to these concentrations showed greater frequency of chromosomal aberrations in spermatogenic cells, but the

aberrations were probably too infrequent to cause decreased fertility (61).

Birth Defects

Epidemiologic Studies

Several studies in humans have found an increase in congenital abnormalities in children of exposed personnel (21,23,24,28,34,37,53,54,66,67). Interpretations of the data have been questioned (12,17,18,68). Several investigators have found no increase in birth defects among the offspring of exposed parents (16,25,26,27,29,36,40). No increase in chromosomal abnormalities in exposed nurses or changes in sperm morphology have been found in male anesthesiologists working in operating rooms (55,69).

Animal Studies

Studies of laboratory animals exposed to concentrations of inhalational agents well above those found in even unscavenged operating rooms have failed to find any significant teratogenic effects (44,45,47,48,49,50,52,57,60,64,70,71,72).

Impaired Performance

Operating room personnel are subjected to many stimuli that require precise, rapid, and complicated responses. Because the patient's survival depends on the alertness and performance of the professional team, anything that interferes with its ability to perceive changes and react quickly and appropriately may result in harm to a patient.

Although a few studies have found that volunteer exposure to trace gas concentrations caused significant decreases in performance (73,74,75,76), efforts to duplicate these results have failed (41,77,78,79,80,81,82,83,84,85,86). These studies found that the concentrations needed to decrease performance were hundreds of times greater than the average levels found in unscavenged operating rooms. In another study, neuropsychological symptoms and tiredness were reported more by individuals in operating rooms where scavenging was used less often (87). One study determined that personnel exposed to 51 to 54 ppm of nitrous oxide had slowed reaction times compared with workers not exposed to trace gases (88).

Cancer

Epidemiologic Studies

A large study found no increase in cancer in exposed males but indicated that females in the operating room were at higher risk for cancer than nonexposed females (21). The significance of these data has been questioned (17,18). Similar results have been reported for female dental operatory assistants (23). Two studies of dentists have shown that the incidence of cancer is not significantly different among those exposed and those not exposed to trace concentrations of anesthetics (23,54). One study found a higher rate of melanoma among anesthesiologists (89). A review of combined data from six studies found an increased cancer risk among women but not men (41,90).

Mortality Studies

There is no increased death rate from cancer in male anesthesiologists (19,91,92,93,94,95,96). The death rate from cancer among female anesthesiologists is higher when compared with male anesthesiologists and control groups (93), but the numbers are too small to permit any strong conclusions. Various therapeutic modalities have resulted in higher cancer cure rates, so the incidence of cancer cannot be inferred by using only mortality data.

Animal Studies

Studies have found no evidence of increased carcinogenicity in animals exposed to up to 5,000 ppm halothane or 10,000 ppm enflurane (97,98,99). One study found hepatic neoplasms in mice exposed during gestation and early life to 1,000 to 5,000 ppm isoflurane (100), but the validity of this study has been questioned, and it appears that the increased incidence of tumors may have been the result of other factors. In later studies, no evidence of increased carcinogenicity was found in animals exposed to up to 6,000 ppm isoflurane (98,101). No evidence of increased carcinogenicity in mice has been found with exposure to up to 800,000 ppm nitrous oxide (98,102). No increase in neoplasms was found in rats exposed to 10 ppm halothane plus 500 ppm nitrous oxide (103).

Mutagenicity Testing

Human Studies

Cytogenetic methods are increasingly used for evaluating the effects of exposure to potential mutagens in the environment (105,106,107,108,109,110,111,112,113,114,115). Some studies found no association between occupational exposure to waste

anesthetic gases and cytogenetic damage (104,108,110,113,116,117,118,119,120). Others suggest that there may be an association (105,106,107,111,112,114,115,121,122,123). One study found that the waste gas levels recommended by the National Institute for Occupational Safety and Health (NIOSH) appear to be safe, whereas exposure to higher levels were associated with an increase in chromosome damage (109).

Animal Studies

Several studies have found that halothane and its metabolites are not mutagenic (124,125,126,127,128,129). Others have found that halothane and/or its

metabolites are weakly mutagenic (130,131,132,133). Investigators have been unable to demonstrate mutagenic effects from enflurane (125,134,135) or isoflurane (125,127,135). Investigations have found that nitrous oxide is not mutagenic (125,136). One investigation found that halothane plus nitrous oxide did not increase mutagenesis (128). Another found that nitrous oxide had no effect on the mutagenicity of halothane (130). The same study found that there was no mutagenicity with mixtures of nitrous oxide and enflurane or isoflurane.

Liver Disease

Epidemiologic Studies

Studies have found that operating room and dental operatory personnel have higher-than-expected rates of hepatic disease (11,19,21,23,54,89,90,137). Interpretation of these data has been questioned (17).

Recurrent hepatitis following exposure to halothane has been demonstrated in a few individuals (138,139,140,141,142), and exposure to trace anesthetic agents enhances hepatic metabolism of some drugs (143,144). Elevated serum autoantibodies that react with specific hepatic proteins have been found in anesthesia personnel, especially females and pediatric anesthesiologists (145). The relevance of these facts to the effects of trace concentrations is not clear.

Animal Studies

Halothane exposure in concentrations as low as 20 ppm may be associated with mild toxic effects to the liver in rats (146,147,148). No evidence of such effects has been found from

exposure to enflurane or isoflurane (146,148).

Renal Disease

One study found that female operating room nurses, technicians, and anesthesiologists had a higher risk of kidney disease than did comparable groups outside the operating room (21). These results have been questioned (17). Another study failed to find any increase in kidney disease in male anesthesiologists (11).

A study showed an increase in renal disease in exposed dentists and female chair-side assistants (23). No increase in deaths caused by renal disease has been found among anesthesiologists (93).

Hematologic Studies

Epidemiologic Studies

In one study, a higher-than-expected rate of leukemia was found in female anesthesiologists, but the small database made any valid conclusions difficult (21). Other studies found no significant alterations in hematologic function in exposed individuals (149,150,151,152). However, 3 of 20 dentists exposed to concentrations of nitrous oxide higher than those normally found in operating rooms showed abnormalities in their bone marrow, and two had abnormalities in their peripheral blood (153).

Animal Studies

In mice, no hematologic effects were found from exposure to 500 ppm halothane (97). Exposure to 3,000 ppm enflurane had no effect on hematopoiesis in mice (154). Exposure to 10,000 ppm nitrous oxide caused no changes in hematopoiesis in rats (155). Cytogenetic damage to bone marrow was found in rats exposed to 10 ppm halothane plus 500 ppm nitrous oxide (56).

Neurologic Symptoms

A nonspecific polyneuropathy following chronic exposure to nitrous oxide has been described (156,157). Two studies found an increase in neurologic symptoms (numbness, tingling, and/or muscle weakness) in dentists and female chair-side assistants who are exposed to anesthetic gases (23,158). Another study showed no difference in neurologic symptoms or signs, sensory perception, or nerve conduction between dentists who use nitrous oxide extensively and those who use it sparingly or not at all (159). High levels of nitrous oxide have not been shown to cause neuromuscular or neurologic abnormalities in animals

(159).

Alterations in Immune Response

Several studies have found that work in operating rooms does not change the immunologic profile of individuals (160,161,162,163,164). A study of people working in unscavenged rooms with trace gas concentrations several times the recommended levels had changes that reversed when they were removed from that environment (165).

Cardiac Disease

Studies have shown a greater-than-expected frequency of hypertension and dysrhythmias (11,166), and there is one case report of atrial fibrillation secondary to halothane exposure (167). However, mortality studies give no evidence that anesthesiologists have a higher-than-expected risk of dying from heart disease (91,92,93,94,95,96).

Miscellaneous

Various studies have reported higher-than-expected incidences of bone and joint disease (11), ulcers (11,166), ulcerative colitis (166), gallbladder disease (11), migraine (166), and headache and fatigue (168) in exposed personnel. Case reports of exposed personnel who developed asthmatic symptoms (169), laryngitis (170), ophthalmic

hypersensitivity (171), conjunctivitis (172), exacerbation of myasthenia gravis (173), and skin eruptions (174,175) have been published. Mortality statistics show a high incidence of suicide and substance abuseÏ€“related deaths among anesthesiologists (19,91,93).

Summary

The evidence that trace anesthetic gases are harmful is at present suggestive rather than conclusive (176). The hazard, if it exists, is not great and is more properly regarded as disquieting than alarming. Researchers who have systematically examined the published data have concluded that reproductive problems in women were the only health effects for which there is reasonably convincing evidence (14). While it is reassuring to note that studies have shown that anesthesiologists have a mortality rate less than that expected for physicians or the general population (92,93,94), reproductive problems are not reflected in mortality data, and high cure rates may be responsible for the low

mortality. One study showed an increased rate of early retirement as a result of permanent ill health and a high rate of deaths while working among anesthesia personnel (177).

A cause-and-effect relationship between occupational exposure and the problems described has not been firmly established. If there is an increased risk, it may be related to other factors such as mental and physical stress; strenuous physical demands; disturbed night rest; need for constant alertness; long and inconvenient working hours that often interfere with domestic life; irregular routine; exposure to transmissible infections, solvents, propellants, cleaning substances, lasers, methylmethacrylate, radiation, or ultraviolet light; pre-existing health and reproductive problems; hormonal or dietary disturbances; the physical or emotional makeup of those who choose to work in operating rooms; socio-economic factors; or some other as yet undefined factor (178).

The Committee on Occupational Health of Operating Room Personnel suggests that health care institutions bring to the attention of operating and recovery room personnel pertinent information on the claimed risks of excess anesthetic gases and ways by which these risks can be minimized (179). A sample letter is available (180).

Control Measures

Complete elimination of all anesthetic molecules from the ambient atmosphere is impossible. The goal should be to reduce concentrations to the lowest level consistent with a reasonable expenditure of effort and money. To achieve this, attention should be focused on four areas: scavenging, equipment leaks, work techniques, and the room ventilation system.

Scavenging Systems

Scavenging is the collection of excess gases from equipment used to administer anesthesia or exhaled by the patient and the removal of these gases to an appropriate place of discharge outside the work environment. Scavenging systems are also referred to as evacuation systems, waste anesthetic gas disposal systems, anesthesia waste exhaust, and excess anesthetic gas-scavenging systems. Installation of an efficient scavenging system is the most important step in reducing trace gas levels, lowering ambient concentrations by up to 90% (181,182,183,184,185,186,187,188,189,190,191).

A scavenging system consists of five basic parts (Fig. 13.1): a gas-collecting assembly, which captures gases at the site of

emission; a transfer tubing, which conveys collected gases to the interface; the interface, which provides positive (and sometimes negative) pressure relief and may provide reservoir capacity; the gas-disposal tubing, which conducts the gases from the interface to the gas-disposal system; and the gas disposal system, which conveys the gases to a point where they are discharged. Frequently, some or all of these components are combined.

A U.S. standard (192) and an international standard (193) for scavenging systems have been published. The international standard differs from the U.S. standard in that some fittings are male rather than female and vice versa.

Gas-collecting Assembly

The gas-collecting assembly (scavenger adapter; gas-capturing assembly, device, or valve; scavenging trap or valve; collecting or collection valve; scavenging exhale valve; evacuator; antipollution valve; ducted expiratory valve; collecting system exhaust valve; scavenging trap, collecting system) collects excess gases and delivers them to the transfer means. It may attach to, or be an integral part of, a source. Frequently, the outlets of two or more sources are joined together. The American Society of Testing and Materials (ASTM) standard and international standards (192,193) specify that the outlet connection must be a 30-mm male fitting. In the past, 19-mm fittings were permitted, but they are being phased out. The size is important, because it should not be possible to connect components of the breathing system to the outlet. Some early assemblies had 22-mm fittings, and cases of misconnection with breathing system tubes occurred (194,195).

Breathing Systems

Systems Containing an Adjustable Pressure-Limiting Valve

Systems with an adjustable pressure-limiting

(APL) valve (Chapter 7) include the circle system and the Mapleson A, B, C, and D systems. The APL valve is essentially fitted with a shroud (Fig. 13.2). With the circle, Bain, and Lack variant of the Mapleson D systems, the weight of the assembly can be supported by the anesthesia machine, and the transfer means can be quite short. Smaller and lighter APL valves with gas-collecting assemblies are available for the other Mapleson systems.

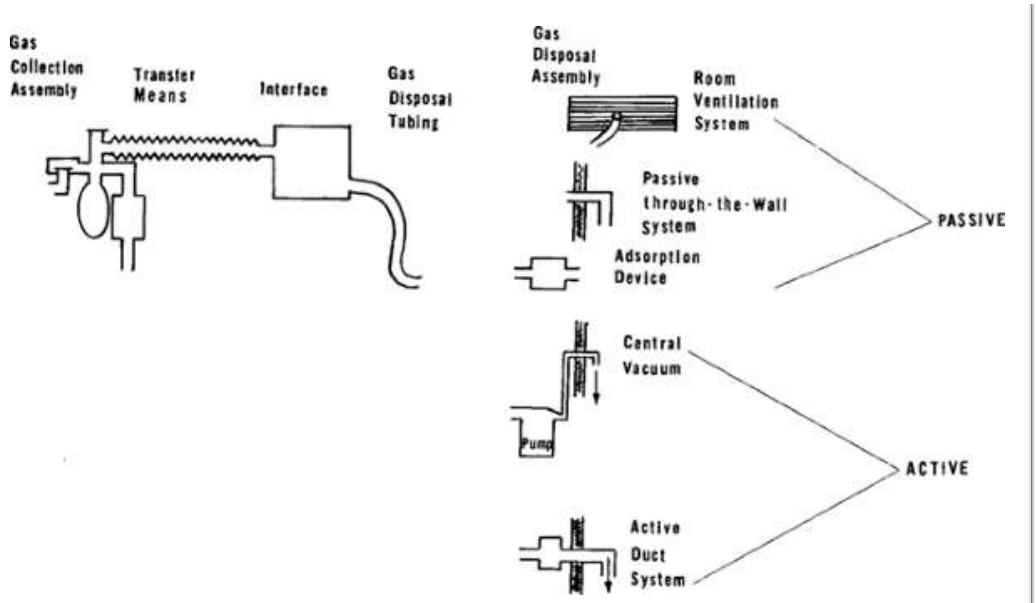

Figure 13.1 Complete scavenging system. The gas-collecting assembly may be an integral part of the breathing system, ventilator, gas monitor, or extracorporeal pump oxygenator. The interface may be an integral part of the gas-collecting assembly or some other portion of the scavenging system.

An APL valve may have a built-in mechanism that prevents positive or negative pressure from the scavenging system being transmitted to the breathing system (196).

Figure 13.2 Gas-collecting assembly attached to an APL valve.

T-piece Systems without an Adjustable Pressure-Limiting Valve

Numerous devices for removing gases from the bag have been described (197,198,199,200,201,202,203,204,205,206,207,208,209,210,211,212,213,214). Other methods use a container that is attached to suction (215,216). Other methods attach the gas-collecting assembly between the bag and its attachment to the tubing (217,218,219,220).

Resuscitation Equipment

Nonrebreathing valves with a scavenging adapter are commercially available. It is fairly simple to attach a collection assembly to the exhalation port of some existing nonrebreathing valves without affecting valve function.

Masks or Nasal Cannulae

It is common practice in some institutions to administer anesthetic gases to patients through a nasal cannula or face mask for sedation. Placing a tent or hood around the patient's head and attaching a suction source can reduce the ambient concentrations of gases (221,222,223). A double mask consisting of a smaller inner mask separated from a larger outer mask by a space connected to a scavenging device will reduce ambient concentrations (224,225).

Ventilators

Anesthesia ventilators are now equipped with gas-collecting assemblies. The waste gas is directed to the same interface that is used by the breathing system. In most cases, the drive gas which is composed of oxygen, air, or a combination of the two, is expelled into the room.

On some older ventilators, the exhaust includes not only excess breathing system gases but also the driving gas for the ventilator. In this situation, a disposal system that is capable of handling high gas flows is required. A scavenging system that functions efficiently with spontaneously breathing or manually ventilated patients may fail to do so when used with ventilators

that discharge the driving gas into the scavenging system (226).

Extracorporeal Pump Oxygenators

The outlet port of an extracorporeal pump oxygenator is a potential source of anesthetic pollution (227,228). Gas-collecting assemblies for these are available (229). It is important to provide an effective interface with these devices because significant positive or negative pressure alterations at the outflow port can markedly alter oxygenator functioning (230).

Respiratory Gas Monitors

A diverting gas monitor (Chapter 22) withdraws gas from the breathing system and transports it into the monitor. The gas then needs to be either returned to the breathing system or diverted into the scavenging system. This source of contamination is often ignored (231,232,233,234). Monitors manufactured in recent years are equipped with an outlet to facilitate scavenging (235) (Fig. 13.3).

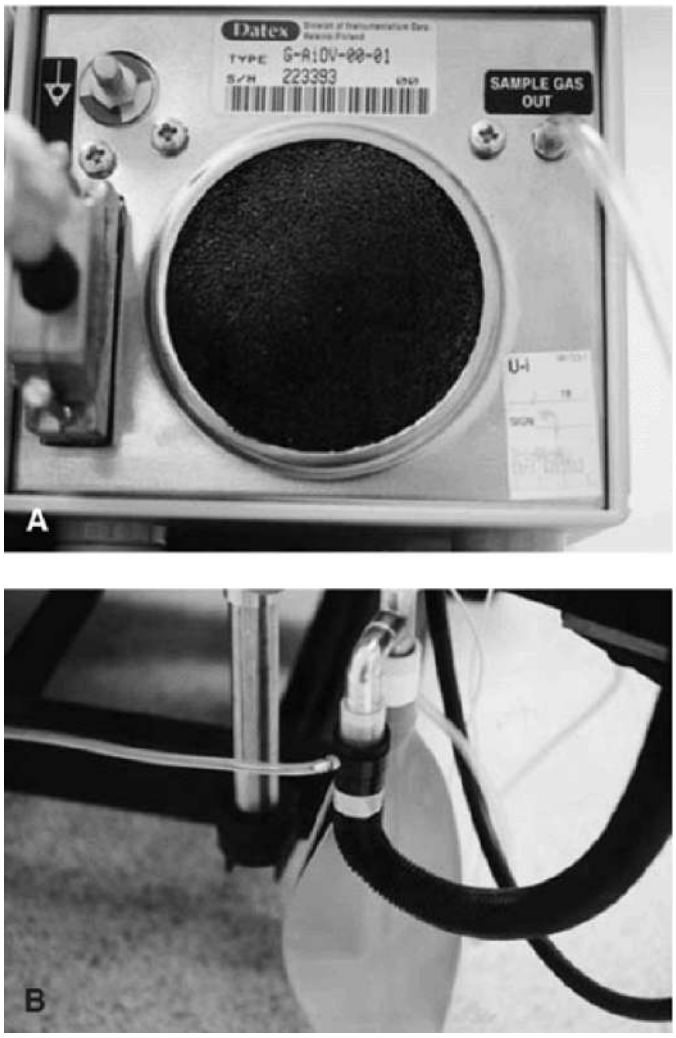

Figure 13.3 **A:** Gas monitor with sample gas outlet (at **upper right**). **B:** Connection of transfer tubing near the interface.

Cryosurgical Units

Some cryosurgical units use nitrous oxide. These can contribute to operating room contamination (236). These units should be fitted with scavengers, or carbon dioxide should be used instead of nitrous oxide (237).

Leak Sites

When there is a definite leak site (such as when a face mask is used or a vaporizer is filled), or in the postanesthesia care unit,

close (local) scavenging of contaminated air through a separate scavenging device or a low negative pressure hood can be used to lower ambient concentrations (210,238,239,240,241). A face mask that has the ability to reduce the concentration of anesthetic gases in the recovery room has been described (8).

Transfer Tubing

The transfer tubing (exhaust tubing or hose, transfer means, transfer system) conveys gas from the collecting assembly to the interface when the interface is not an integral part of the gas-collecting assembly.

The transfer tubing is most commonly a length of tubing with a connector at either end. The inlet and outlet fittings should be either 19 or 30 mm. It should be as short as possible (this is facilitated by mounting the interface on the anesthesia machine) and wide enough to carry a high flow of gas without a significant increase in pressure. It should be resistant to kinking. It should not touch the floor, but if it does, it should be designed to prevent occlusion. It should be easily seen and easy to disconnect from the gas-collecting assembly in the event of malfunction or scavenging system occlusion. To discourage misconnections, it is recommended that the transfer tubing be different (by color and/or configuration) from the breathing system tubing (Fig. 13.6).

Interface

The interface (balancing valve or device, pressure balancing valve or device, interface system or block, intermediate site, safety block, air break receiver, receiver unit, air break, receiving system, interface valve, scavenging valve, reservoir) serves to prevent pressure increases or decreases in the scavenging system from being transmitted to the breathing system, ventilator, or extracorporeal oxygenator. The U.S. and international standards (192,193) require that the pressure immediately downstream of the gas-collecting assembly be limited to between -0.5 and +3.5 cm H_2O during normal operating conditions and up to +15 cm H_2O with obstruction of the scavenging system.

The interface inlet must have a 19- or 30-mm (preferred) male connector. The size of the outlet is optional but should be different from breathing system connectors and from the inlet connector if the device is sensitive to the direction of flow.

The interface should be situated as close to the gas-collecting

assembly as possible, where it can be readily observed and reached by anesthesia personnel.

There are three basic elements to an interface: positive pressure relief, negative pressure relief, and reservoir capacity. Irrespective of what type of disposal system is used, positive pressure relief must be provided to protect the equipment and patient if occlusion of the scavenging system occurs. If an active disposal system is used, negative pressure relief is needed to limit subatmospheric pressure. A reservoir is necessary to match the intermittent flow from the gas-collecting assembly to the continuous flow of the disposal system. A device that gives an audible signal may be fitted to the interface to indicate operation of the positive or negative pressure relief device. A flow indicator may be provided to monitor flow from the interface to the gas-disposal system (Figs. 13.4, 13.5).

The reservoir may be a rigid container, wide tubing, a bag, or a combination of these. A distensible bag allows gas removal by the scavenging system to be monitored. It should only be used with active disposal systems and should be of a different color from, and situated away from, the reservoir bag in the breathing system. The connection between the bag and the interface should be a different size from the mount for the reservoir bag in the breathing system.

Interfaces can be divided into two types: open and closed, depending on the means to provide positive and negative pressure relief.

Open Interface

An open interface (air break receiver unit) (242,243,244) (Fig. 13.4A) has one or more openings to atmosphere (allowing positive and negative pressure relief) and contains no valves. It should be used only with an active disposal system. The inlet, the disposal system connection, and the opening(s) to atmosphere should be arranged so that waste gases are removed before room air is entrained.

Because the discharge of waste gases is usually intermittent and flow through an active disposal assembly is continuous, a reservoir is needed to hold the surges of gas that enter the interface until the disposal system removes them. The reservoir allows the flow rate in the disposal system to be kept just above the average flow rate of gases from the gas-collecting assembly.

It is important that the reservoir have adequate capacity, especially if a ventilator in which the driving gas mixes with

waste gases is used or if high tidal volumes or high nitrous oxide flows are used (245).

The safety afforded by an open system depends on the patency of the vents to atmosphere, so it is important to have redundancy in case some are accidentally blocked (246,247). The vents should be checked

and cleaned regularly. Plastic bags and surgical drapes should be kept away from the vents.

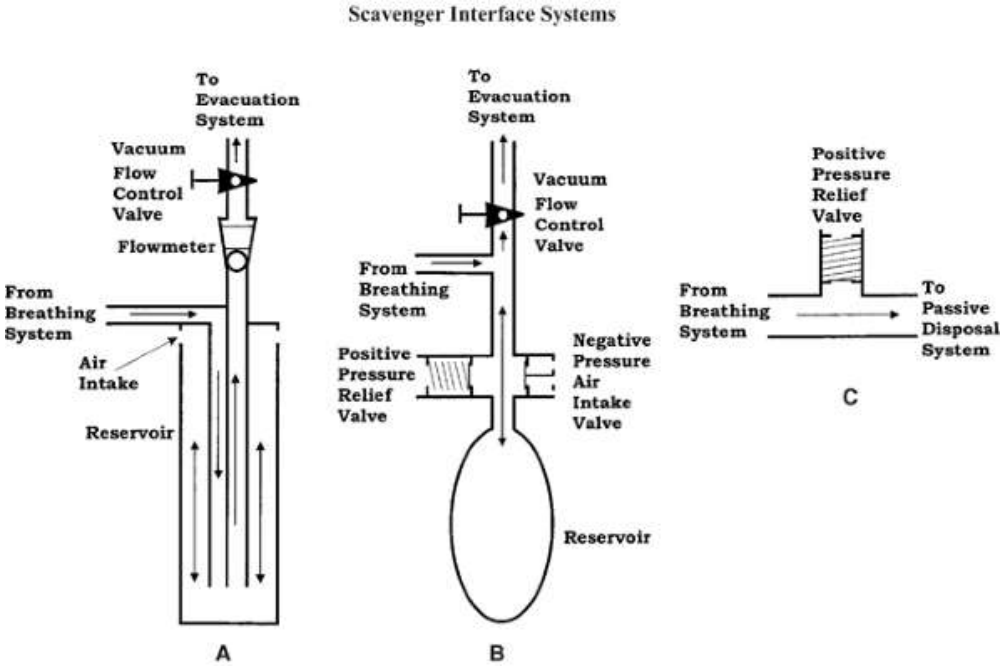

Figure 13.4 A: An open interface. Note the escape-inlet ports at the top of the reservoir. These provide positive and negative pressure relief. **B,C:** are closed interfaces. **(A)** and **(B)** are active systems. **(C)** is a passive system.

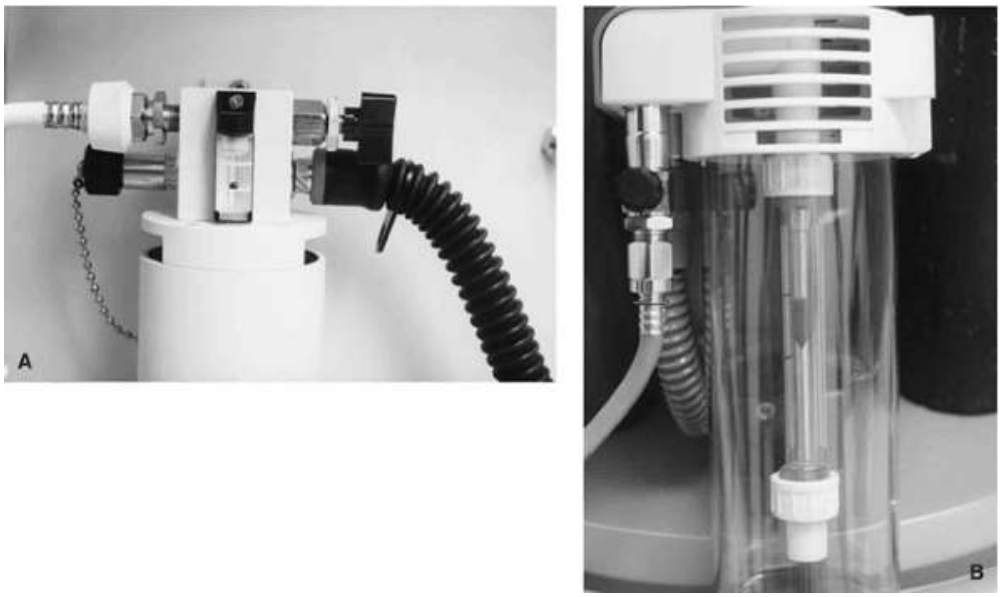

Figure 13.5 Open interfaces. The open ports at the top of the canister provide positive and negative pressure relief. The flow control valve is used to regulate the scavenging flow. The flowmeter indicates whether or not the flow is within the range recommended by the manufacturer. The float should be between the two markings on the flowmeter. Inside the canister, one tube conducts waste gases to the bottom. The other tube conducts gases from the bottom to the disposal system.

Open interface are shown in Figs. 13.4A, and 13.5. Anesthetic gases from the transfer means enter at the top and are conducted to the base where they are dispersed. A parallel tube is connected at the top to the reservoir. The space around both tubes acts as a reservoir. The holes at the top are open to atmosphere. A flowmeter measures the amount of vacuum that is applied to the interface by the active disposal system. It also provides a visual indication that the vacuum is turned ON. Usually, there are two marks between which the indicator should be located.

The open interface is simple but may pollute the atmosphere if the reservoir does not have sufficient volume to contain the boluses of waste gases. The active disposal system must supply adequate flow to remove the scavenged gases from the interface. Turbulence will increase the volume of air contaminated with anesthetic gases (242). Turbulence is greatest when gases from the breathing system flow against the disposal system flow and least when flow is in the same direction.

Closed Interfaces

A closed interface (Fig. 13.4B,C) makes its connection(s) to atmosphere through valve(s). A positive pressure relief valve is always required to allow gases to be released into the room if there is obstruction of the scavenging system downstream of the interface. If an active disposal system is to be used, a negative pressure relief (pop-in, inlet relief) valve is necessary to allow air to be entrained when the pressure in the reservoir falls below atmospheric.

A reservoir is not required with a closed interface and should not be used unless an active disposal system is used. If an active disposable system is used, a distensible bag is useful for monitoring scavenging system function.

Positive Pressure Relief Only

A closed interface with only positive pressure relief should be used only with a passive disposal system. An example is shown in Figure 13.4C. The positive pressure relief valve remains closed unless there is a problem downstream of the interface. The relief device may be spring loaded or work by gravity.

Positive and Negative Pressure Relief

If an active disposal system is used, a negative pressure relief valve must also be present. Subatmospheric pressures greater than -0.5 cm H_2O can raise or lower the opening pressure of some APL valves (248).

Examples of the closed interfaces are shown in Figures 13.4B and C and Figure 13.6. When a passive disposal system is used, the negative pressure relief will

remain closed at all times. If an active disposal system is used, it should close during high peak flow rates from the gas-collecting assembly and open when the gas-disposal assembly flow is greater than the flow of gases entering the gas-collecting assembly from the breathing system.

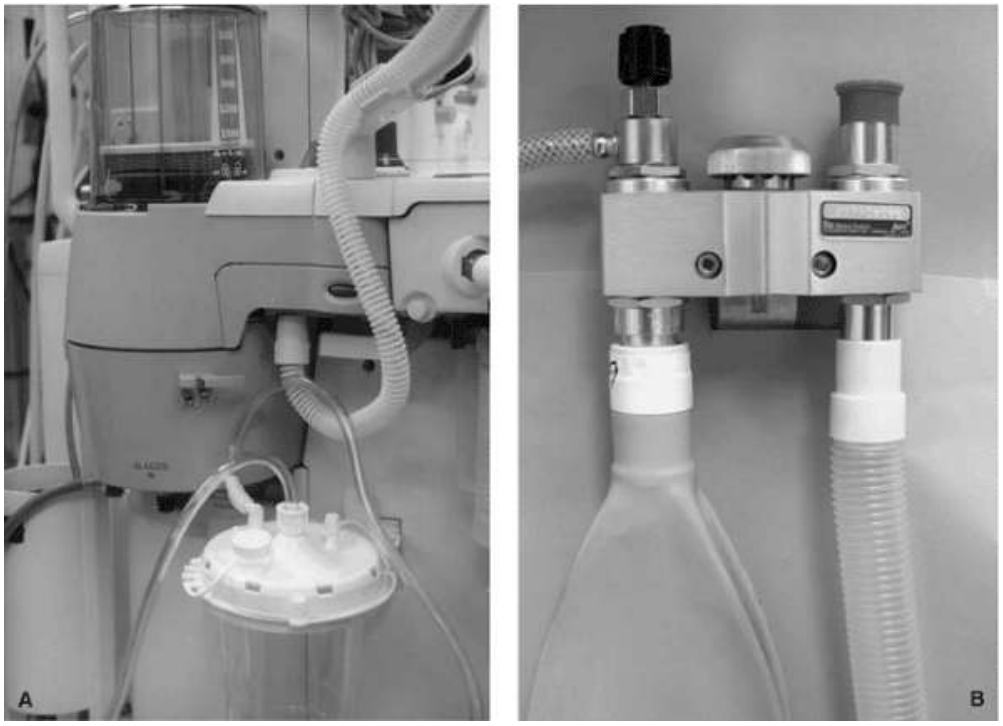

Figure 13.6 Closed interfaces. Note the wide-bore flexible transfer tubing that is different in appearance from the breathing system tubes.

The rate of flow into the gas-disposal assembly should be adjusted to the optimal level by observing the bag (if present) and the positive and negative relief valves. In an optimally adjusted system, the bag expands and deflates but never becomes overextended or completely deflated (249,250,251). If the bag is continually collapsed or the negative pressure relief valve opens frequently, the flow should be lowered. If the bag becomes distended or the positive pressure relief valve opens frequently, flow should be increased.

A closed interface can be used with any type of disposal system, but valves add to the complexity. They must be designed so that they do not stick or leak. Interfaces with two negative pressure relief valves are available and add a margin of safety.

Gas-disposal Tubing

The gas-disposal tubing (receiving hose, disposal tubing) connects the interface to the disposal system (Fig. 13.1). To avoid misconnections, it should be different in size and appearance from the breathing system hoses. It should be

resistant to collapse and free of leaks. With a passive gas-disposal system, it is important that the hose be as short and wide as practical to minimize resistance.

Ideally, the gas-disposal tubing should be run overhead to minimize the risk of occlusion and to avoid the dangers of personnel tripping over it or other apparatus becoming entangled in it. It may be hidden in a false ceiling. If the tubing must be run across the floor, it should be routed where it is least likely to be stepped on or have equipment rolled over it. If it must pass a doorway, it should follow the door frame.

Gas-disposal System

The gas-disposal system (elimination system or route, disposal-exhaust route, disposal assembly) removes waste gases from the anesthetizing location. The gases must be vented at a point that is isolated from personnel and any air intakes.

Gas-disposal systems are of two types: active, in which a flow-inducing device moves the gases, and passive, in which the pressure is raised above atmospheric by the patient exhaling, by manually squeezing the reservoir bag, or by a ventilator. With an active system, there

will be negative pressure in the gas-disposal tubing. With a passive system, the pressure will be positive.

Active systems are usually more effective at keeping pollution levels low, because most leaks will be inward (182,252,253). They allow small-bore tubing to be used, and excessive resistance is not a problem. They also aid room air exchange. They are, however, expensive in terms of energy costs. They are not automatic and must be turned ON and OFF. If they are not turned ON, air pollution will occur; if they are not turned OFF, there will be needless waste of energy. Active systems are more complex than passive ones. Their use requires that the interface have negative pressure relief.

Passive systems are simpler but may not be as effective in lowering trace gas levels, because the positive pressure encourages outward leaks. They are less expensive to operate than active systems.

Passive Systems

Room Ventilation System

Ventilation systems in operating rooms are of two types:

nonrecirculating (one pass, single pass, 100% fresh air) and recirculating (187). A nonrecirculating system takes in exterior air and processes it by filtering and adjusting the humidity and temperature. The processed air is circulated through the room and then all of it is exhausted to atmosphere. This type of ventilation system can be used for waste gas disposal by securing the disposal tubing to a convenient exhaust grille. Air flowing into the grille will remove the gases from the room.

Economic concerns has led to increased use of ventilation systems that recirculate air. With this type of system, a small amount of air is taken in from the atmosphere, while the remaining air is recirculated. Most of the gases exhausted from the room are shunted back into the intake and recirculated, while a volume equal to the fresh air admitted is exhausted. With this type of system, waste gases must be vented beyond the point of recirculation.

The health care facility engineer should know which type of ventilation system is present. If not, absence of recirculation can be determined by sampling the room air inlet to see if it is free of trace gases after they have been released in another room.

An important consideration when using the room ventilation system for waste gas disposal is the negative pressure in the exhaust duct. If waste gases are introduced at the grille, the negative pressure is usually minimal and its effect negligible (246). If they are introduced at a distance downstream in the duct (as they must be with a recirculating system), negative pressure relief must be provided in the interface.

In many operating rooms, the exhaust grilles are not located close to the anesthesia machine, posing problems with tubing on the floor where it may be occluded. In some cases, the disposal tubing can be extended to a wall- or ceiling-mounted connection that leads to a pipe in the wall (187). The pipe then connects to the exhaust duct.

Piping Direct to Atmosphere

Piping direct to the atmosphere is also known as a direct duct or vent, specialized duct system, direct disposal line, or through-the-wall system (252,253,254,255). Excess gases are vented through the wall, window, ceiling, or floor to the outside, using only the slight pressure of the gases and leaving the gas-collecting assembly to provide the flow. This type of system is not suitable for an operating room that is far from an outside wall (246).

To prevent cross flow between rooms, each room should have its own duct. The inlet to the duct should be close to the anesthesia machine. There should be a means to cap the opening to the duct when it is not connected to the gas-disposal tubing. The duct should be short with a large diameter to avoid excessive back pressure. A unidirectional valve may be placed in the duct to prevent outside air from entering the operating room and to minimize the effects of wind pressure on the disposal system (254).

The discharge point on the outside should be selected so that it is away from wind pressures, ignition hazards, windows, and the inlets for the ventilation system. It may be advantageous to attach a short T-piece as a terminal (256). The open end(s) should point downward to prevent water and dirt from entering and be fitted with netting to prevent insects, rodents, and foreign matter from entering the pipe.

The direct piping disposal system is easy to use but requires a special installation. In redesigning an existing operating room or designing a new room, construction of such a system should be considered. If the operating rooms are not near the outside of the building, this type of disposal assembly may not be practical.

Problems that can occur with the direct disposal system include both positive and negative pressure caused by wind currents, obstruction from ice buildup, and accumulation of foreign matter at the outlet (255,257). There needs to be a means to determine system patency. It is important to do trace gas monitoring with the system in use in order to make certain a flow-inducing device is not needed. A study of this type of system found that it worked efficiently and had low maintenance costs (258).

Adsorption Device

An adsorption device removes some or all excess anesthetic agents by adsorbing them or converting them to harmless substances (185,255,259,260,261,262,263,264). Canisters of varying shape and capacity that are filled with activated charcoal have been used for waste gas disposal. Some can be regenerated by autoclaving (265). Different volatile agents are adsorbed with varying efficiency. The efficiency of adsorption also

depends on the flow rate through the canister (266). Moisture may reduce the efficiency (267).

Adsorption devices are simple and portable and do not require expensive installation or maintenance. An additional advantage

is that halogenated anesthetic vapors are not released to the ozone layer (266). An activated charcoal filter has been used successfully to scavenge nitric oxide and nitrogen dioxide (268).

Adsorption devices have a number of disadvantages. At present, there is no adsorption device for nitrous oxide. They are fairly expensive and are effective for only short periods of time. They must be replaced regularly and pose storage and disposal problems. In order to determine whether or not the adsorber is saturated requires monitoring or weighing. Finally, a large canister may impose significant resistance (259). It is recommended that adsorption devices be limited to situations where nitrous oxide is not being employed and no other means of eliminating waste gases is available.

Concerns about the release of anesthetic waste gases into the atmosphere and their contribution to global warming and ozone depletion have been voiced (255,269,270,271). Zeolites may be used to adsorb halogenated agents from the outlet of the scavenging system, thereby reducing atmospheric pollution (269,272,273).

Catalytic Decomposition

Catalytic decomposition can be used to convert nitrous oxide to nitrogen and oxygen, reducing its contribution to the greenhouse effect (274,275).

Active Systems

Piped Vacuum

The central vacuum system is a popular method of gas disposal (276,277,278). The system should be capable of providing high volume (30 L/minute) flow, but only slight negative pressure is needed. There should be a means to allow the user to control the flow. This will conserve energy, reduce the load on the central pumps, and reduce the noise level. For some units, this is done by observing the bag and the positive and negative pressure relief valves. Others have a means to allow the user to adjust the flow to that recommended by the manufacturer (Figs. 13.5, 13.6). A restrictive orifice may be placed in the vacuum nipple to limit the flow (279).

There are a number of problems associated with using a central piped vacuum system for scavenging.

Inadequate Number of Vacuum Outlets

Many operating rooms have only two vacuum outlets. This is

barely enough for some surgical procedures, let alone anesthesia use. Ideally, anesthesia personnel should have two vacuum outlets available, one for suctioning the airway and one for scavenging waste gases.

If there are not enough outlets, a Y may be inserted into the vacuum line to create two lines. Unfortunately, this may reduce the flow so that it becomes inadequate for either purpose.

Some anesthesia providers use a single vacuum line for scavenging and patient suctioning. The vacuum line remains attached to the interface most of the time and is detached when needed for patient suctioning. If the flow of anesthesia gases is not turned OFF, there will be escape of anesthetic gases into the room air.

Inconvenient Outlets

If a suction outlet is not near the anesthesia machine, long tubings must reach across the floor, with the hazards of occlusion, tripping, and entanglement with other apparatus.

System Overload

Because scavenging requires high flows, the central vacuum system may become overloaded if too many devices are in use at the same time. Overcoming this problem may require a major renovation of the system. System overload can be reduced if anesthesia personnel adjust the flow to that necessary to prevent gases from being spilled into room air and turn off the flow after use.

Damage to the Vacuum System

Wear and tear on the vacuum pump can be expected to increase if the central vacuum system is used for disposal of waste gases. Vacuum pump failure and pump fires have been reported (280).

Personnel Exposure

If the exhaust from the central vacuum pump goes to an area frequented by personnel or is situated near an air intake, open window, or door, this will result in additional exposure of personnel to waste gases. It may be necessary to relocate the pump exhaust.

Inconvenience

To conserve energy, the vacuum system should be turned ON

just before anesthesia is begun and turned OFF at the termination of a procedure. For further energy conservation, the anesthesia provider should adjust the vacuum flow according to the volume of waste gases. If these duties are neglected, there will be either wasted energy or operating room pollution.

Active Duct System

The other type of active disposal assembly is a dedicated evacuation system that leads to the outside and employs flow-inducing devices (fans, pumps, blowers, etc.) that can move large volumes of gas at low pressures (246,252,278,281,282,283,284) (Fig. 13.7). It has been recommended that two flow-inducing devices be provided and arranged so that if one fails, the second one will run. Several ducts may be connected together to a common duct that leads outside. The flow-inducing device is located in the common duct and provides movement of gases at a low negative pressure. Balancing dampers should be provided to prevent pressure imbalances from developing between the operating rooms that are connected to the system (248,278). The

negative pressure helps to ensure that cross contamination between operating rooms will not occur and prevents atmospheric conditions from affecting the outflow from the system. The outlet to atmosphere should be away from windows and ventilation intakes. A means to adjust the flow may be incorporated into the common duct.

Figure 13.7 Part of a piped anesthetic gas evacuation system with a shut-off valve. The gauge is at the right.

Each operating room is supplied with an evacuation inlet (Fig. 13.8). It should not be interchangeable with other systems, including the piped vacuum system. It is recommended that there be a means to indicate to the user that the scavenging system is operational.

The advantages of the active duct system are that resistance is not a problem, and wind currents do not affect the system. Disadvantages include those of any active system: added complexity and the need for negative pressure relief and reservoir capacity in the interface. It requires a special installation, which should be considered during renovation or when a new anesthetizing location is being designed. The flow-inducing device means added energy consumption and requires regular maintenance.

Alterations in Work Practices

A number of work practices allow anesthetic gases to enter room air (285,286,287,288). Adhering to the following practices will significantly reduce contamination. Most can be followed without compromising safety, and some of them are beneficial to the patient. Trace gas monitoring can be used to demonstrate to personnel the techniques needed to avoid polluting room air.

Adhering to good work practices should not distract from patient comfort and safety. For example, in pediatric anesthesia, use of uncuffed tracheal tubes may necessary, and holding the mask tightly against the face may be frightening to a child.

Checking Equipment Before Use

Before starting an anesthetic, all components of the scavenging system should be securely connected and patent.

If an active gas disposal assembly is to be used, the flow should be turned ON.

Figure 13.8 Inlet for anesthetic gas evacuation (at right). A probe attached to the gas transfer disposal tubing is inserted into this.

Leaks in the anesthesia machine and breathing system can contribute to operating room contamination. The preuse checkout (Chapter 33) should reveal these leaks so that they can be corrected (289).

Nitrous oxide should be turned ON only momentarily during the preuse equipment checkout. Most tests should be conducted by using oxygen or air.

Using Scavenging Equipment

Failure to use available scavenging equipment correctly is common (290,291). In some cases, the reasons relate to equipment design and specific circumstances. More frequently, however, lack of concern is the problem.

Proper Mask Fit

Obtaining a good mask fit requires skill but is critical to maintain the lowest possible levels of anesthetic gases in the room. Mask fit is especially important during assisted or controlled ventilation, when higher pressures will magnify the leak between the patient and the mask. Anesthesia by face mask causes the highest levels of pollution (234,240,289,292,293,294,295). Pollution is also a problem with supraglottic airway devices, although lower levels of anesthetic gases are found with these devices than with face masks (234,292,293,296,297). An active

scavenging device near the mask (210,241,298) or the use of a double mask can reduce room pollution from a poor mask fit (299,300).

Preventing Anesthetic Gas Flow Directly into the Room

Nitrous oxide and other agents should not be turned ON until the mask is fitted to the patient's face. Turning the gas flow (but not the vaporizer) OFF during intubation is also good practice (301,302,303,304,305,306). This maintains postintubation concentrations close to preintubation levels and decreases operating room pollution.

The patient connection port on the breathing system can be blocked during intubation (307,308,309,310), but care should be taken that part of the blocking device does not become dislodged and enter the breathing system (311). The fresh gas flow should be turned OFF or the APL valve opened to prevent the bag from overfilling.

Disconnections can be prevented by making certain that all connections are tight before use. Disconnections for activities such as taping the tracheal tube or positioning the patient should be kept to a minimum. If it is necessary to make a disconnection, release of anesthetic gases into the room can be minimized if the reservoir bag is first gradually emptied into the scavenging system and the fresh gas flow is turned OFF. Alternately, the patient port can be occluded and the APL valve opened so that the gases will enter the scavenging system. If a ventilator (which has its own spill valve) is being used, the APL valve does not need to be opened.

Washout of Anesthetic Gases at the End of a Case

At the end of a case, 100% oxygen should be administered before extubation or the face mask or supraglottic device is removed to flush most of the anesthetic gases into the scavenging system.

Preventing Liquid Agent Spills

It is easy to spill liquid agent when filling a vaporizer, so care should be exercised. The use of an agent-specific filling device (Chapter 6) will reduce spillage. Devices that reduce spillage when using funnel-fill vaporizers are available.

Using local scavenging will reduce contamination associated with filling and draining vaporizers (176,240). A portable vaporizer

may be filled in a hood with gas extraction.

The connections for filling and draining a vaporizer should be kept tight. If one of these connections is loose, agent may escape (312).

Avoiding Certain Techniques

Insufflation techniques in which an anesthetic mixture is introduced into the patient's respiratory system during inhalation are sometimes used for laryngoscopy and bronchoscopy. These techniques result in flooding the air around the face with anesthetic agents. High flow rates are required to avoid dilution with room air and result in a cloud of anesthetic gases escaping into the room air. Local scavenging should be used to remove the anesthetic gases if an insufflation technique is used.

Proper Use of Airway Devices

The use of cuffed tracheal tubes will reduce environmental contamination from waste anesthetic gases (313). Only small leaks should be permitted around uncuffed tubes in pediatric patients. When using an uncuffed tube, contamination can be reduced by placing a suction catheter in the mouth (314) and using a throat pack (176).

Supraglottic airway devices usually have a greater leak than cuffed tracheal tubes but contribute less to trace gas contamination than anesthesia conducted with a mask (234,292,293,296,297).

Where it is not possible to use a leak-tight device, a hood can be placed around the head and suction used to remove the trace gases (313,315,316).

Disconnecting Nitrous Oxide Sources

Nitrous oxide and oxygen pipeline hoses leading to the machine should be disconnected at the end of the operating schedule. The disconnection should be made as

close to the terminal unit as possible and not at the back of the anesthesia machine so that if there is a leak in the hose, no gases will escape to room air while the hose is disconnected. This will result in lower levels of nitrous oxide in the operating room and conserve gases.

When cylinders are used, the cylinder valve should be closed at the end of the operating schedule. Gas remaining in the machine should be ‘€bled out‘€ and evacuated through the scavenging

system.

Using Low Fresh Gas Flows

Using low fresh gas flows will reduce the pollution resulting from disconnections in the breathing system and from inefficient scavenging (317,318,319). It also allows low removal flows to be used with active disposal assemblies, resulting in energy conservation and reduced wear and tear on the disposal device. The use of a trace gas monitor may lead to use of lower fresh gas flows (320). Using low gas flows does not make scavenging unnecessary, because high flows must still be used at times.

Using Intravenous Agents and Regional Anesthesia

Using intravenous induction techniques significantly reduces trace gas exposure (321).

Keeping Scavenging Hoses off the Floor

A scavenging hose on the floor can be obstructed or damaged by equipment rolling over it, reducing scavenging.

Leak Control

Some leaks are unavoidable, but they should be minimized (14,25,198,287,288,322,323). Leak control may require replacement of equipment that cannot be made gas tight.

Most anesthesia machines are serviced at regular intervals. Unfortunately, this servicing does not always identify or correct all leak points. In addition, leaks in some equipment develop fairly frequently, so quarterly servicing is not sufficient. In-house monitoring and maintenance are necessary to minimize leakage.

Pressure Terminology

Some literature on scavenging has referred to all equipment upstream of the flow control valves as the high-pressure system and all equipment between the flow control valves and the patient plus the scavenging equipment as the low-pressure system (287). In this book, the high-pressure system refers to those components that contain gas whose pressure is normally above 50 psig (340 kPa). This includes the components between the cylinder and the regulator. The intermediate-pressure system includes components normally subjected to a pressure between 50 and 55 psig. This includes the pipeline hoses and the components of the machine between the pressure regulators or pipeline inlets and the flow control valves. The low-pressure

system consists of components downstream of the flow control valves to the patient, plus the scavenging system.

Identifying Leak Sites

There are several techniques for locating leak sites (234). A continuous infrared nitrous oxide analyzer can be used. The equipment under test is pressurized with nitrous oxide and the sampling probe directed at suspected leak sites. The meter reading indicates the presence or absence of leaks. This will identify most leaks. An exception would be leakage into a vaporizer.

Some leak sites can be identified by application of a solution of 50% liquid soap and 50% water or a commercial leak test solution. Another method is to put alcohol on one's hands and move the hands over the equipment. A leak will cause cooling.

Leakage can be assessed by testing the capacity of the equipment to sustain pressurization. The total leak rate is determined, after which a component is excluded and the leak rate determined again. The difference is the leak rate for that component.

High-pressure System

To test for leaks in the high-pressure system, the pipeline hoses should be disconnected and the flow control valves closed. The valve on a nitrous oxide cylinder should be opened fully, the pressure recorded, and the cylinder valve closed. The pressure should be recorded again 1 hour later. If little or no pressure drop has occurred, there is no significant leakage. If it falls, the high-pressure system is not tight. The test should be repeated with the other nitrous oxide cylinder if there is a double yoke.

If a significant leak is found, the most common site is the yoke, and application of a leak test solution will demonstrate a poor seal. Tightening the cylinder in its yoke will often seal the leak. Other easily correctable causes include double, absent, or deformed washers. If damaged parts are found, they should be replaced. If fixing these problems does not cause the pressure to hold, the leak is inside the machine and must be corrected by the manufacturer's service representative.

Because leakage in this area does not occur often, checking every 2 to 4 months as well as after a cylinder has been changed should be sufficient (202,285,287).

Intermediate-pressure System

Leaks in the intermediate-pressure system components can be determined by measuring the nitrous oxide concentrations in the operating room when no anesthesia is being administered (287). The survey should begin at least 1 hour after administration of anesthesia has been discontinued. If a

recirculating air conditioning system is in use, a longer period may be required. The early morning is an excellent time to perform this test.

Flow control valves should be closed, pipeline hoses connected, and cylinder valves closed. Room air should be sampled at the anesthesia breathing zone (4 to 5 feet above the floor within 3 feet of the front of the anesthesia machine) and the room air intake and outlet. Nitrous oxide concentrations should be less than 5 ppm (153,230). If a higher level is found, the pipeline hoses should be disconnected and the measurements repeated after a period of time. If a high level is still present, this indicates a leak in the nitrous oxide pipe leading into the room or the station outlet and should be reported to the health care facility engineer. If the level falls, this indicates a leak in the pipeline hose or the anesthesia machine.

Common problems with pipeline hoses include worn or leaking connections (especially quick connects), deformed compression fittings, and holes. These should be corrected or the hoses replaced. Leaks inside the anesthesia machine require correction by a service representative.

Once leaks are corrected, it is suggested that testing of the intermediate system be performed every 2 to 4 months (198,230,285,287).

Low-pressure System

The low-pressure portion of the system develops leaks more frequently than other parts. The preuse test for leaks in the breathing system (Chapter 33) is sufficient for the safe conduct of anesthesia, yet can miss leaks that emit large amounts of anesthetic gases into room air.

One way to quantify leakage in most of the low-pressure system is shown in Figure 13.9. The breathing system is assembled for use. All components that are normally used should be present in their usual positions. The patient port is occluded. The bag is removed and the bag mount occluded. This is necessary because the bag's compliance makes it hard to quantitate low leak rates. The bag should be tested separately for leaks. A vaporizer on the anesthesia machine should be turned ON. The APL valve

should be fully open and the scavenging system occluded upstream of the interface. The oxygen flow control valve is now opened sufficiently to establish and maintain a steady pressure of 30 cm H_2O on the pressure gauge in the breathing system.

The flow on the oxygen flowmeter is the leak rate and should be less than 1,000 mL/minute. Leakage of 1,000 mL/minute of nitrous oxide would result in a mean concentration of only 30 ppm in a 4,000 cubic foot room with 15 air changes per hour (248). The leakage test should be repeated with the other vaporizers turned ON.

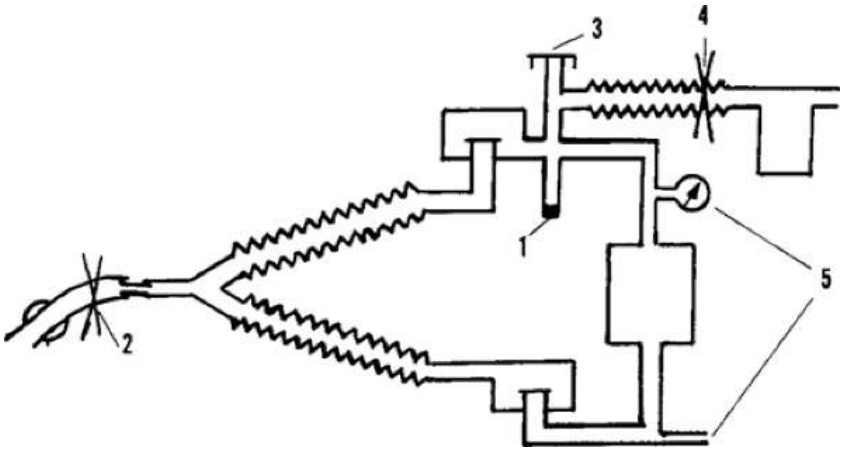

Figure 13.9 Test for quantifying low-pressure leakage. *(1)* The reservoir bag is removed, and the bag mount is occluded. *(2)* The patient port is occluded. *(3)* The APL valve is opened fully. *(4)* The transfer means is occluded just upstream of the interface. *(5)* Oxygen flow is turned on and adjusted to maintain a pressure of 30 cm H_2O on the pressure gauge in the breathing system.

If the leak rate exceeds 1,000 mL/minute, the APL valve should be closed and the leak rate again determined. The difference is the leak rate in the scavenging system. The remaining leakage can be divided into that associated with the machine and that associated with the breathing system by attaching a sphygmomanometer bulb to the anesthesia machine common gas outlet and determining the oxygen flow necessary to achieve and maintain a pressure of 22 mm Hg. This is the portion of the low-pressure leakage associated with the machine. The machine leak site can be further refined by turning the vaporizer OFF and again determining the leak rate.

Problems in the scavenging system may be as simple as a crack in a tubing (especially where it becomes kinked) or a poor connection.

The breathing system is the most common location for significant low-pressure leaks, and the most common site is the absorber. Common problems include defective gaskets or seals, improper closure, inadequate tightening, and open or leaking drain cocks. Absorbent granules on the gaskets can prevent a tight seal. Disposable canisters may be cracked during transit and leak after being installed. Most of these problems are easily corrected. Complicated repairs should be done only by the service representative.

The above test does not check for leaks in the ventilator. The ventilator and the low-pressure system can be tested by using an infrared nitrous oxide analyzer. The anesthesia machine and breathing system are set up for clinical use. The patient port outlet is occluded and the bag/ventilator selector switch put in the bag mode. The APL valve is closed. Using the flowmeters, the breathing system is pressurized to 30 cm H_2O with a 50% mixture of nitrous oxide and oxygen. The machine and breathing system are scanned for nitrous oxide leaks. The selector valve is then put in the ventilator mode and the flowmeters set to deliver 2 L/minute oxygen and 2 L/minute nitrous oxide. The ventilator is turned ON and set to a

tidal volume such that a peak pressure of 30 cm H_2O is reached. The scavenger system is activated. The machine, ventilator, breathing system, and scavenging system are scanned. Readings should not be greater than 25 ppm nitrous oxide.

A ventilator with a standing bellows can be checked for leaks by filling the bellows with gas, then switching the bag/ventilator selector switch to the bag position. The bellows should remain fully inflated. A hanging bellows can be tested for leaks by stopping it during inspiration and placing the bag/ventilator selector switch in the bag position. The bellows should remain compressed.

It is controversial as to how often the low-pressure system should be tested for leakage. Suggested intervals vary from daily (230,285) to every other week (287) to monthly (198). It should be repeated with new equipment and when the absorbent is changed.

Room Ventilation System

The room ventilation system serves as an important adjunct to trace gas control by diluting and removing anesthetic gases resulting from leaks, errors in technique, and scavenging system malfunctions (324,325,326,327,328). Recirculating systems are less effective at removing trace gases than nonrecirculating systems. A downward displacement ventilation system is more effective than a turbulent flow system (183). A turnover rate of 20 exchanges per hour is considered necessary to prevent bacteria from settling (329).

The anesthesia machine should be placed as close to the exhaust grille as possible. This will ensure maximum gas removal by the ventilation system and make it easy to use the ventilation system as the gas-disposal system. This should be taken into consideration when constructing a new operating room or renovating an older one.

Online ambient air control has been proposed (10,330). This would permit the room ventilation to be matched to the actual contamination level.

Hazards of Scavenging Equipment

Misassembly

Misconnections involving the scavenging system are not uncommon (331,332). Most scavenging components have 19- or 30-mm connections rather than the 15- and 22-mm sizes found in breathing systems. This will not completely prevent misconnections, because there may be other apparatus in the room that will accept 19- or 30-mm connections (325,325A), and sometimes a 19- or 30-mm connector can be fitted onto a 22-mm one (333,334). The safety provided by 19- and 30-mm connectors can be bypassed by using cheater adapters or tape for making connections.

A circle system hose may be connected to the outlet of the APL valve collecting assembly (194,195,335,336). Measures to prevent this include turning the exhaust port of the gas-collecting assembly so that it points in the opposite direction from the breathing system ports, use of transfer and gas-disposal tubings of different colors and/or configurations from breathing system tubes, and using 30-mm connections in the scavenging system.

Pressure Alterations in the Breathing System

The scavenging system extends the breathing system all the way to the gas-disposal point. When a scavenging system

malfunctions or is misused, positive or negative pressure can be transmitted to the breathing system. This is more likely to occur with closed interfaces.

Measures to prevent these untoward incidents include employing collapse-resistant material in all disposal lines, making the transfer means easy to disconnect, using scavenging tubing that has a distinctive appearance, incorporating positive and negative pressure relief valves in the interface, regularly checking the valves for proper functioning, using an open interface, and using airway pressure monitors (Chapter 23).

Positive Pressure

Positive pressure in the scavenging system can result from an occluded transfer or gas-disposal tubing. This can be caused by the wheel of an anesthesia machine or other equipment rolling onto the tubing (195,337,338,339,340), ice (257), insects, water, or other foreign matter. Another cause is defective components (341). Misassembly of the connection to the exhaust grille (342) and failure to include an opening between the inner and outer tubes of a tube-within-a-tube interface (343) have been reported.

These malfunctions may not result in a pressure buildup when a positive pressure relief mechanism is incorporated into the interface. The positive pressure relief mechanism may be incorrectly assembled, may not open at a low enough pressure, or may be blocked (344). Obstruction or misconnection of the transfer tubing may occur (334,345,346,347,348,349). Because these problems are on the patient side of the interface, disconnecting the transfer means from the gas-collecting assembly may be necessary to prevent a dangerous increase in pressure. In one reported case, the transfer tubing was kinked, causing back pressure to develop in the gas jacket of an extracorporeal oxygenator. This resulted in gas being forced into the blood (350). All tubings that conduct scavenged gas should be off the floor or protected so that they cannot become obstructed (339).

With some older APL valves, subatmospheric pressure can result in obstruction and a buildup of positive

pressure in the breathing system (343,351). In one reported case, subatmospheric pressure in the scavenging system drew a ventilator relief valve diaphragm onto its seat and closed the valve, resulting in a pressure increase in the system (352).

In another reported case, low scavenging flow resulted in an

increase in pressure in the bag at the interface. This caused the ventilator to fail, and there was sustained positive pressure in the patient circuit (353). On newer models, only full flow can be used for scavenging.

Negative Pressure

If an active disposal system is in use and the APL valve is fully open, there is danger that subambient pressure will be applied to the breathing system. Monitoring expired volume (but not airway pressure) may fail to detect a disconnection in the breathing system because the scavenging system may draw a considerable flow of room air through the expiratory pathway (354,355,367).

Gas may be evacuated from the breathing system if the APL valve allows gas to be drawn through it and into the scavenging system at a pressure less than that needed to open the negative pressure valve on the interface (356,357). This problem can be corrected by partially closing the APL valve (358), increasing the fresh gas flow, or lowering the flow in the gas disposal system.

The negative pressure relief mechanism may malfunction (344,359,360,361,362,363). Another problem is using an interface designed for a passive system (which has no means to prevent a subatmospheric pressure) in an active scavenging system (346). In some scavenging systems that use the central vacuum system, a restrictive orifice is incorporated into the vacuum hose fitting to limit gas evacuation, regardless of the pressure applied by the central vacuum source (279). If this orifice is omitted or becomes damaged, excessive vacuum will be applied to the interface and the capacity of the negative pressure relief mechanism may be exceeded.

Ways to prevent negative pressure from being transmitted to the breathing system include provision of one or more negative relief mechanisms in the interface with an active disposal system (364), adjusting the flow through the gas disposal system to the minimum necessary, and protecting the openings to atmosphere from accidental occlusion.

Loss of Monitoring Input

A scavenging system may mask the strong odor of a volatile anesthetic agent, delaying recognition of an overdose (345,365). Use of anesthetic agent monitoring (Chapter 22) should largely eliminate this problem.

Alarm Failure

A case has been reported in which negative pressure from the

scavenging system interface prevented the ventilator bellows from collapsing when a disconnection in the breathing system occurred (366). The low airway pressure alarm in the ventilator was not activated. In another case, room air was drawn into the breathing system through a disconnection, preventing the low minute volume alarm from sounding (367).

Monitoring Trace Gases

Rationale

Air monitoring is the best indicator of the success of a waste gas control program. It reflects how well leaks and errors in technique are being controlled as well as the efficiency of the scavenging and room ventilation systems and documents that low trace levels are being maintained. Some anesthetic departments do not monitor trace gas levels in the belief that scavenging devices have solved the problem (368).

Monitoring is necessary because a scavenging system that appears adequate in design may perform inefficiently in use. Sites where gas can leak are diverse, frequently obscure, and sometimes inaccessible. Even relatively large leaks may be inaudible. Nitrous oxide is odorless, and the threshold for smelling halogenated agents may be as high as 300 ppm (369). Without monitoring, operating room personnel may be unaware that atmospheric contamination is at unacceptable levels. A properly conducted monitoring program can provide a constructive method of reminding anesthesia personnel to avoid careless work habits. Another advantage of monitoring is that it can detect problems with gas delivery to equipment (370).

Although such a program will increase a health care facility's operating expense, it will help to reduce the institution's liability to claims by employees alleging that exposure to waste gases contributed to a spontaneous abortion or other medical problems. Correcting certain leaks such as those associated with the pipeline or pipeline hose can result in a savings to the facility.

In-house versus Commercial Laboratory

The monitoring program should be directed by an interested and qualified person, preferably from the anesthesia department. Samples may be analyzed by either facility-based personnel or outside commercial laboratories. The use of an outside laboratory avoids the cost of purchasing, operating, maintaining, and calibrating a gas analyzer. The responsibility for record keeping is shared.

The chief disadvantage is the delay in reporting results. The precise circumstances at the time the samples were taken are likely to have been forgotten, and the effect of corrective measures cannot be immediately assessed. In addition, analysis of a large number of samples is expensive.

Advantages of in-house analysis include a virtually unlimited number of analyses at modest cost and immediate on-site reporting. Leaks can be found quickly and the effectiveness of the correction assessed immediately. An on-site continuous monitor is useful for demonstrating the effects of technique errors on trace gas levels and the results of corrections.

A small facility might periodically lease an instrument or share one with other health care facilities in the area rather than purchase its own.

Equipment for Determining Trace Gas Concentrations

Infrared Analyzers

Infrared gas analyzers were discussed in Chapter 22. These monitors are the most practical for the average health care institution because they are reliable, relatively inexpensive, and easy to use (371). They are useful for locating leaks, especially those in unusual locations. They give continuous measurements so that exposed personnel and those responsible for air monitoring are given an immediate reading. When operated on battery power, a number of locations can be sampled quickly. A recording attachment may be helpful.

These instruments are most often used for monitoring nitrous oxide. Unfortunately, carbon dioxide and water vapor in high concentrations will interfere with the analysis. This can be avoided by sampling at least 6 to 10 inches away from personnel. Analyzers capable of measuring halogenated anesthetics are available but have many technical difficulties; alcohols and other substances in the operating room cause interference (66,371,372).

Proton Transfer Reaction Mass Spectrometry

Proton transfer reaction mass spectrometry allows measurement of trace gases in parts per billion (373). It has been used to measure trace gases both in ambient air and exhaled gases (10,296,374). This technology is not available for in-house use.

Dosimeters

Passive dosimeters measure the amount of nitrous oxide that diffuses into a molecular sieve (375). Analysis (usually by the manufacturer) requires extraction of the nitrous oxide.

Passive dosimeters have many advantages. They can give a time-weighted average (TWA) concentration for as long as a month. They are convenient to use. They can be made lightweight and compact so that they can be worn for personal sampling.

A variant of the passive dosimeter is the gas cartridge sampler, which is a small container that is filled with a sample of operating room air and then sent to the laboratory for analysis.

Active dosimeters depend on energy outside of the absorbing medium to obtain the sample. A pump is used to take in gases that are then stored in a gas-tight bag in an absorbing medium. The samples are aspirated into an analyzer.

Ionizing Leak Detector

The ionizing leak detector (leak meter) consists of three components: an electron capture detector housed within a hand piece and fitted with a probe, a control unit that processes the signal from the detector and displays the output on a meter, and a carrier gas supply (198,376). The instrument is compact, relatively inexpensive, portable, and can be operated on batteries.

The ionizing leak detector is suitable for measuring low concentrations of halogenated agents. However, there may be interference from other halogenated agents in the area, including antibiotic and skin-protection sprays. It is not useful for nitrous oxide detection. It is somewhat unstable in use, requiring frequent zeroing and recalibration (198,324).

Oxygen Analyzer

An oxygen monitor can be used to check the scavenging system. Using 100% oxygen, the sensor is positioned at the interface where overflow would exit into the room. Any increase in oxygen indicates that anesthetic gas will be released during normal use.

Carbon Dioxide Analyzer

The efficacy of scavenging with an open interface can be checked by analyzing the open end of the reservoir for carbon dioxide (243). If any of the patient's expired gases overflow,

carbon dioxide will be detected.

Sampling Methods

Instantaneous Sampling

Instantaneous (grab, single-shot, periodic, snatch) sampling is performed by drawing a sample of air into a container and subsequently measuring the trace gas concentration. The container must not adsorb or absorb the contaminant or leak. Nylon bags are the preferred storage container when nitrous oxide levels are measured (176,377).

When an instantaneous sample is taken, it is important to record the date and time of collection, the work practices, anesthesia machine, breathing system, fresh

gas flow, airway device (face mask, supraglottic airway device or tracheal tube), type of ventilation, ventilator, anesthetic agents used, location of sampling site, and the person administering anesthesia.

This method is relatively inexpensive, quick, and simple to perform and does not involve taking bulky equipment into the operating room. There are some serious disadvantages. A long interval between sampling and reporting makes it difficult to remember the precise circumstances under which the sample was taken. The effect of corrective measures cannot be immediately assessed. It is of limited value in determining leak sites and assessing leak correction. Another serious disadvantage is that each sample represents the level at one location in a relatively small volume and over a very short time period. Failure to sample in the right place at the right time can produce results that are misleading (14). One investigation concluded that gradients in operating rooms were sufficiently large to invalidate estimation of personnel exposure from instantaneous samples (378). This disadvantage can be decreased by taking multiple samples, but this increases the expense.

The instantaneous sample is probably best employed for analysis of steady-state contamination, that is, sampling before starting anesthesia for intermediate pressure leaks or when equilibrium has been achieved. If good techniques are employed and leaks have been corrected, trace gas levels tend to rise in a fluctuating pattern during the early part of an anesthetic and then roughly equilibrate, reaching a level that represents the net effects of leaks, air conditioning, inflowing gas, scavenging

efficiency, and personnel movement (378). Under these circumstances, an instantaneous sample 30 to 45 minutes after induction is probably a good index of the average trace gas levels (230,378). If poor techniques are employed and/or no attempt has been made to eliminate leaks, pollution levels will vary markedly and instantaneous samples may be quite misleading. If unacceptably high levels are found, one cannot be sure whether the cause is a leak, poor technique, or a fault in the scavenging system.

Sampling at the Air Conditioning Exhaust

Samples may be taken at the air conditioning exhaust grille (289,379). This location gives a general indication of the overall leakage into the room but not of individuals' exposure to trace gases.

Time-weighted Average Sampling

The toxicity of anesthetics is probably a function of both dose and exposure time. Hence, a method that gives an average exposure level during a period of time (an integrated sample) is of interest. TWA sampling is also known as integrated or time-integrated sampling.

TWA samples can be obtained by using active dosimetry in which gases are pumped continuously over a period of time into an inert container (372,380,381) or a device containing an adsorbent material (176,382,383,384,385,386).

Passive dosimetry, which depends on gas diffusion into a molecular sieve, can be used to obtain TWAs (387). Small, rugged, lightweight dosimeters (diffusive samplers) are available (318,387,388,389). They are unobtrusive, easily attached, and require a minimum of maintenance (182). They can be used either as personal or area monitors for up to 40 hours (388). They have been found to be quite accurate (387,388). Separate sampling media have to be used for nitrous oxide and the halogenated agents (2). However, more than one halogenated agent can be measured from one sampler.

Other ways of obtaining a TWA are to average the results of many instantaneous samples, average the concentrations measured at equal time intervals throughout the recorded tracing of a continuous analyzer, or integrate the output of a continuous analyzer (390).

By eliminating errors due to temporal fluctuations, TWA sampling reflects personnel exposure better than instantaneous sampling.

It requires only a modest capital investment, and there is considerable time and labor savings compared with taking and analyzing multiple instantaneous samples.

There are several disadvantages to time-weighted sampling. It does not help with detecting leaks or improving work techniques. Delayed results make it difficult to correlate with activities at the time of collection. If concentrations in excess of those recommended are found, one cannot tell whether the problem is technique errors, leaks, or inadequate scavenging.

Continuous Sampling

Continuous (direct-reading, real time) monitoring is carried out by using an infrared analyzer, leak meter, or proton transfer reaction mass spectrometry. The use of a battery-powered instrument allows for easy movement within and between rooms. If a writer is attached and the analyzer is run over a period of time, a TWA sample is obtained (176,390).

Continuous monitoring can be used to detect leaks and to determine if a leak has been reduced or eliminated. A continuous analyzer operated while anesthesia is being administered can be used to demonstrate the effects of improper work practices on trace levels and the improvement from modifying those practices.

The convenience and immediate feedback of continuous monitoring are distinct advantages over instantaneous or TWA sampling. When high readings are obtained, the causes can usually be determined immediately and corrective measures taken.

A disadvantage of continuous monitors is that the time and expense required to maintain the instrument

may make it unsatisfactory for a small facility. In such circumstances, several facilities might consider sharing an instrument, or a manufacturer's service representative might use one during routine quarterly maintenance calls. This method tends to disrupt the operating room routine more than instantaneous or TWA sampling. Finally, rapidly changing concentrations are difficult to interpret in terms of personnel exposure unless integration over time is employed.

Personnel Sampling

End-tidal samples of gases may be taken from exposed personnel after a period of exposure (8,186,374,378,391,392,393,394,395,396). This method is most

suitable for potent halogenated agents. Nitrous oxide is so rapidly absorbed and excreted that its level in end-tidal gas reflects only the most recent exposure.

Blood samples can be drawn from personnel at the end of an exposure period and analyzed (183,391,393,397). Urinary concentrations of anesthetic agents show a significant correlation with environmental exposure (395,398,399,400,401,402,403,404).

Agents to Be Monitored

Ideally, all gases employed in the conduct of anesthesia with the exception of oxygen should be measured. Analyzers that can scan the infrared spectrum and can be programmed to distinguish individual inhalational agents are available. Likewise, mass spectrometry and gas chromatography can measure all agents. However, it is simpler to monitor a single gas. The NIOSH criteria document (285) does not recommend monitoring of all anesthetic agents but only the one most frequently used.

Nitrous Oxide

Many people believe that nitrous oxide is the most logical agent to monitor because it is administered in higher concentrations than other agents, is easy to measure, and is more likely to be subject to occult leakage than volatile liquid agents.

Because nitrous oxide and other agents are not separated by buoyancy effects (198,324), they will be present in a room in the same ratio in which they are introduced. Because of this, many people contend that nitrous oxide can serve as a tracer for other agents administered with it to a degree of accuracy sufficient to assess occupational exposure. This tracer concept works best under steady-state conditions and low equipment leakage. It does not work well when a vaporizer is being filled or drained, during cardiopulmonary bypass, during induction or recovery from anesthesia, or when there is a large nitrous oxide leak or a leak in a vaporizer.

Volatile Agents

Monitoring agents other than nitrous oxide can be worthwhile (405,406). Volatile agents can leak independently of nitrous oxide. Analyzers that measure potent agents are more expensive than those that measure only nitrous oxide.

Sites to Be Monitored

Monitoring should be scheduled so that the work of each

anesthesia provider and of each operating room is checked while using a mask, supraglottic device, and tracheal tube. Monitoring should be performed during spontaneous, manually assisted, and manually controlled and automatic ventilation. The results of the monitoring should be analyzed and discussed with all parties concerned.

Personal Monitoring

When monitoring worker exposure to waste anesthetic gas levels, the Occupational and Safety Health Organization (OSHA) mandates that sampling be performed in the worker's breathing zone (407). Anesthesia personnel are considered the most important to monitor, because they usually are exposed to higher concentrations than other operating room personnel (389) and are more likely to remain in the room for the entire duration of anesthesia administration.

Passive dosimeters can be attached to the person's clothing and worn for prolonged periods. Sampling directly in the subject's expiratory pathway must be avoided if measurement of nitrous oxide by infrared analysis is used.

Area (Room) Sampling

The exhaust grille of the air conditioning system or the open door will be representative of average personnel exposure if gases are evenly distributed in the room. Fifteen or more air exchanges per hour are sufficient to produce near homogeneity of anesthetic concentrations in all locations except those close to the leak (66,82,324). With lower exchange rates, mixing may not be complete, and localized areas of high (hot spots) or low (cold spots) concentration may occur. Area sampling may be less disruptive to the operating room routine than personal monitoring.

Monitoring Frequency

At the initiation of a waste gas control program, frequent monitoring under actual working conditions will be necessary. As experience is gained and equipment is maintained leak tight, the frequency can be decreased. Whenever higher-than-acceptable concentrations are found,

new equipment is installed, or old equipment is modified, monitoring should be repeated.

The following schedule has been suggested (14):

1. An annual comprehensive survey in which exposure levels are measured, leaks detected and corrected, and TWA exposure levels are calculated or measured.
2. Quarterly follow-up with a less-detailed survey; if there appears to be a problem, a comprehensive survey should be performed to determine causes and assess corrective actions.
3. A repeat comprehensive survey in the event of major changes to the ventilation system, anesthesia equipment, or scavenging systems.
4. TWA monitoring of each member of the staff for a short period, such as a week, repeated on a 6-month basis also has been suggested (372).

Role of the Federal Government

In 1970, the U.S. Congress passed the Occupational Safety and Health (OSHA) Act (14,408,409). It created two separate executive-branch agencies to carry out the provisions of the act: the National Institute of Safety and Health (NIOSH), an agency with the Centers for Disease Control and Prevention under the Department of Health and Human Services, and OSHA, under the Department of Labor (176).

NIOSH is responsible for conducting and funding research and education and for preparing criteria documents to be used to develop standards. Criteria documents prepared by NIOSH are transmitted to the secretary of labor for review by the OSHA staff.

OSHA is responsible for enacting job safety and health standards, establishing reporting and recordkeeping procedures, inspecting workplaces, and enforcing the requirements of the act by using citations and fines (176).

A criteria document on trace gases was published and transmitted to OSHA in 1977 (285). It included the following provisions.

1. Although a safe level of exposure to trace anesthetic gases could not be defined, maximum concentrations to which a worker in the operating room should be exposed were recommended. For nitrous oxide alone, a TWA exposure limit of 25 ppm was recommended. For halogenated agents used alone, the limit was 2 ppm TWA. When halogenated agents are used in combination with nitrous oxide, the

recommended limits were 25 ppm nitrous oxide and 0.5 ppm of the halogenated agent. For dental facilities, a level of 50 ppm nitrous oxide was recommended. These were arbitrary levels and were not based on toxic effects. Isoflurane, desflurane, and sevoflurane were not included in the recommended exposure limits because they were not in clinical use in 1977. Higher limits are recommended in other countries (255,294,410,411).

Isoflurane and desflurane levels can be kept below the NIOSH levels relatively easily (409,410,412,413,414). Except during a mask induction, levels of sevoflurane can also be kept under 2 ppm (415,416,417,418). However, it may be difficult to achieve this level when using a face mask (418,419). One study determined that sevoflurane in combination with nitrous oxide commonly exceeded the recommended limit (416).

2. Monitoring exposure levels is recommended in all areas with potential for worker exposure on a quarterly basis and following changes to ventilation systems, anesthetic equipment, or scavenging techniques. Breathing zone or work area samples are most desirable. Results of monitoring and corrective measures are to be maintained and retained for 20 years (176).
3. Recommendations were made regarding scavenging, ventilation systems, leak testing, and work practices aimed at minimizing employee exposure (176).
4. Medical surveillance, including comprehensive employee preplacement medical and occupational histories, annual updating of employee medical histories, and preplacement and annual physical examinations of employees exposed to waste anesthetic gases were recommended.
5. Employees were to be informed on assignment and at least yearly thereafter of the possible health effects of exposure to trace anesthetics, especially possible effects on reproduction. Appropriate signs and labeling were recommended.

NIOSH participation came to a halt after this criteria document on trace gases was transmitted to OSHA. To promulgate this as a standard, OSHA would have to go through an extensive rule-making procedure, including a public comment period. This has not occurred to date.

Medicolegal Considerations

Because the NIOSH document does not constitute a promulgated OSHA standard, employers are not obligated to comply with its recommendations. However, the general duty clause of the 1970 act gives OSHA the authority to inspect workplaces to determine whether employers are providing a workplace free from hazards, even in the absence of a relevant standard.

The act gives each employee the right to request an OSHA inspection if an employee believes that he or she is in imminent danger from a hazard or if OSHA standards are being violated. Several inspections in response to employee complaints were carried out in the 1970s. Fines and citations were issued because employees were exposed to concentrations of nitrous oxide in excess

of the NIOSH recommended levels or because exposure was not reduced to the lowest feasible level (406,409).

The American Society of Anesthesiologists (ASA) legal counsel has advised that it is within the right of an employer to refuse to permit an OSHA representative to enter the facility unless that individual has either a search warrant or a court order compelling the inspection. OSHA would need to seek a search warrant from a federal court and show probable cause for making an inspection (406). If faced with a visit from an OSHA representative, obtaining legal counsel is advisable. Failure to demand a search warrant or court order normally would constitute a waiver of any later right to object to the validity of an inspection.

All states have workers' compensation laws so that individuals suffering from occupational diseases can collect benefits, irrespective of whether or not the employer's negligence caused the disease. It is possible that a workers' compensation case could arise from an operating room employee suffering from one of the problems described in the first section of this chapter, provided the employee could show that the illness was work connected and that employment in the operating room subjected him or her to special risk in excess of those experienced by the general public.

In most states, workers' compensation laws preclude private lawsuits by an employee against his or her employer. However, in addition to making a claim for workers' compensation, an employee can bring a civil suit for damages against a third party (such as an anesthesia provider) whom the employee claims caused injury.

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Questions

For the following questions, select the correct answer

1. Trace amounts of the following anesthetic agent have been shown to have an effect on anesthesia personnel performance in the operating room?

Halothane

Nitrous oxide

Enflurane

Isoflurane

None of these

View Answer

2. Which of the following anesthetic agents is most likely to be associated with spontaneous abortions in animals?

Halothane

Nitrous oxide

Enflurane

Isoflurane

Sevoflurane

View Answer

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

3. The following measures are necessary to minimize trace gas concentrations in the operating room:

A scavenging system

Changing work techniques

Elimination of leaks

The room air conditioning system

View Answer

4. Gas-collecting devices need to be attached to

Anesthesia breathing systems

Pump oxygenators

Anesthesia agent monitors

Ventilators

View Answer

5. Parts of the scavenging system connected by the transfer tubing include

The interface and an adsorption device

The interface and ventilator

The interface and the room ventilation system

The interface and the APL valve

View Answer

6. Passive disposal assemblies include

The room ventilation system.

Piped vacuum system

Piping directly to atmosphere

Duct system with a fan

View Answer

7. Possible problems associated with the use of piped suction systems for gas disposal include

Inadequate number of outlets

Damage to the suction pump

Vacuum system overload

Exposure of personnel in other parts of the facility

View Answer

8. Components connected by the gas disposal tubing include

The interface and an adsorption device

The interface and the suction system

The interface and the ventilation system

The interface and the APL valve

View Answer

9. The following will reduce exposure of operating room personnel to trace anesthetic gases:

- Use of cuffed tracheal tubes
- Use of high fresh gas flows
- Disconnection of the nitrous oxide pipeline hose when the machine is not in use
- Use of insufflation techniques

View Answer

10. The maximum time-weighted average concentrations to which a worker in the operating room should be exposed according to the Occupational Safety and Health Administration include

- 5 ppm for halogenated agents
- 2 ppm for halogenated agents
- 180 ppm for nitrous oxide
- 25 ppm for nitrous oxide

View Answer

11. Hazards associated with scavenging equipment include

- Negative pressure in the breathing system
- Misconnections
- Barotrauma
- Ventilator malfunction

View Answer

12. Sampling methods for determining trace gas concentrations include

- Single shot
- Time-weighted average
- End-tidal sampling
- Urine sampling

View Answer

13. Size(s) of the inlet and outlet fittings of the transfer tubing include

- 15 mm

19 mm

22 mm

30 mm

View Answer

14. Ways in which leak sites can be identified include

Application of a 50% soap solution to a component

Testing the capacity of the machine to sustain pressure

Using a nitrous oxide analyzer to check suspected sites

Opening the nitrous oxide cylinder and watching the pressure drop

View Answer

15. When the low pressure system is checked for leaks,

The preuse machine checkout will reveal even small leaks

The bag port and the Y-piece should be occluded

The vaporizers should be in the OFF position

The leak rate should be less than 1 L/minute

View Answer

16. Concerning the room air conditioning system,

Air exchanges should be 25 to 35 per hour

Recirculating systems are less effective than nonrecirculating systems

The flow should be upward rather than downward

The anesthesia machine should be placed near the exhaust grille

View Answer

17. Problems that could cause positive pressure in the breathing system include

Occlusion of the gas disposal assembly

Missassembly of the connection to the gas-disposal system

Incorrect assembly of the positive pressure relief valve

Application of subambient pressure to the APL valve

View Answer

18. Concerning monitors that can be used for detection of trace gases,

Infrared analyzers are most often used to measure volatile agents

A carbon dioxide analyzer can be used to check the efficiency of scavenging with an open interface

The ionizing leak detector is best suited to measure nitrous oxide

An oxygen analyzer can be used to monitor the scavenging system interface

View Answer

19. Which factor(s) affect trace gas concentrations in the operating room?

Room ventilation system

Duration of the anesthetic

Fresh gas flow

The type of surgery being performed

View Answer

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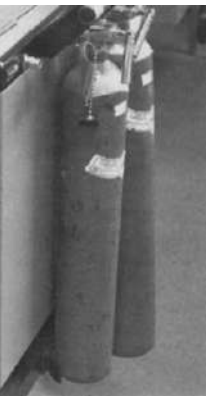

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s point for
reathing system.
d to ‾€break
Adhesive tape
nfortunately, tape
inhibit

res that the
tivated in the
ng system.
ent include a low
xide alarm, and
ed in Chapters 22
ent of the
urs (339).

eathing

face or the
omes blocked or
ure may be
eathing system

fiberscope
has entered the
gases will be
stem

is used, gas is
s a closed
aced from the
ed from the
g may find it
e patient and
lation can occur

atory

em can result in
be detected
esia provider or
ack of obstruction
rvoir bag
ll equipment that
the system when
ipment may

manufacturing
s, tape);
lems
6,357,358,359,360,361,362,363,364,365,366,367,368,369,370,371,372,373,374,375,376,377,378,379,380,381,382,383,384,385,386,387,388,389,390,391,392,393,394,395,396,397,398
le absorbent
e holes in the top
t

may stick in the
w-direction-
umidifier in
8). If the
position when
uction to gas
structed

king or twisting

cause the tubing
).

ner. Failure
ottom will
bsorber.

s is discussed in
s of driving or
d the ventilator
urned OFF and
to settings that

lude airway
e monitors.
oxygen analyzer
but should not
ited set of
heated
athing system
nay fail to detect

ng system are
efore it is used
place. The

ventilation, the
on
then determine
compliance is
ning system. If
patient
ventilator or
osed or
tinued or a

ation, the next
y device (mask,
ns difficult to
h the airway
to supraglottic
apters 17 and 19.

v into the
late the patient
. If increasing
on, a

g a resuscitation
to the anesthesia
ing should be
resuscitation bag
r room air. If the
achine outlet or
source of oxygen

using

g to become
he neck to prevent

have been
vestigated. A
and serious
sthesia machine,
oblem can be
y.

difier can
me

, which was
ll be zero if
Other causes of
h an increased

ministration

carbon dioxide
y be accidentally
ndicator is at the
eter may leak

connected to the
ay be mistakenly

oxide

bsorbent

rbon dioxide in
new machines
older machines.
s to bypass the

haled gases to

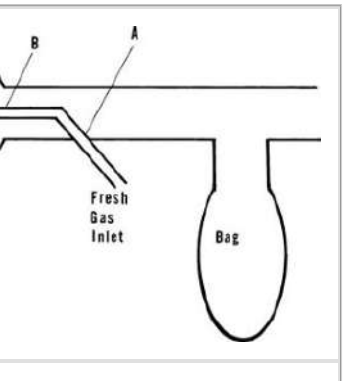
orber may be

n the absorbent
hat have small
ithout the
s possible that
nister is loose or
y remove the
e breathing
ticed by the next

ve leaflet.

epends on
y do not close
ecome displaced,
roperly
3,454,455,456,457,458,459)
removal for
may become

preoperatively
33). Problems
by a respirometer
he inspired
onogram with a
me loops



inner tube of the Bain system
gas supply tube can become
kinked or develop a leak *(B)*,
patient port *(C)*.

alves

valves can result
more fully in

Mapleson

low fresh gas
er 8). Reported
low; a leak or
fresh gas supply
62,463,464,465).

re delivered to
breathing will
ked, or omitted;
nd to the patient
4,475,476) (Fig.

placed or
dioxide will be
d without carbon

ning. This
s (478). An HME
thing system.
one is used on a
reathing may

port of the
eathing system

ust be used with

een the

ult in serious
ntaneously

h as under a
breathing,
mulate in that
rise (339).

Inspired carbon
rly functioning
hypoventilation
rcarbia is not
lt of
ill reduce the
rbon dioxide
g properly,
on dioxide levels
Mapleson system
creasing the
xide level.
and circle
f carbon dioxide

e inadvertent
ected by an
driving gas (or
sed ventilation
tidal carbon
ers 22 and 23.

pressure can
rdiovascular
e been reported
th surgery (483).

portant and will
reservoir bag;
esh gas flow;
ce mask, or

y limited to 50
ay allow slightly
ilator is in use,
bag or bellows is
y is removed and
idly if there is
from, or high
ommonly caused
bag. The bag
4.9).
a reservoir bag
re is a leak in
ttempt to
xygen flush can
ngerous levels

at there be a
em to 125 cm
). In addition,
he pressure in
t activates a
athing system
essure.

ntrolled
er than when
e ventilators
expiratory phase
488).

ure rise is an
h the cuff is not
ure to 34 cm H_2O
xcessive

provide a means

mponents cannot
the pressures
hose that cause

essure

n, 35 to 75
sh valves on
cally but can fail
cidentally
ent may cause
93,494,495). If
ation when a
me of gas will
n a greatly
m configurations
ction, resulting in

ab

breathing
s, breathing
cularly
bag. The
bodies
ape, and caps)
nt defects or

,512,513,514,515,516,517,518).

come obstructed
on, misassembly,

hat has the fresh

ſ€low dead
supply tube may
nd of the
on of the
oblem has been

ressure in the
). The exit of
cked (535).

essure-

ay occur
may fail to open
taneous
excluded from
on and
eous ventilation.
m an active
, preventing

ystem

on of the
ing system
be affected.
PL valve in the
e ventilator and
reathing system
er tubing may be

avenging
ositive pressure
ted case, a valve
one for positive

alves in

or bump on the
sufficient
inspiratory
e in pressure.
unction may
560).

dwelling tracheal
ce without
sastrous results
4.14). Another
T-piece with a

atory

it and not be
in the ON

the next user
tems, the airway
of the
rved on the
measure the
l valve.

is condensed in

g in the bag of a

ached to the mask. **B:** The
ask and is attached to the
for the gas to escape.

tial that the
ystem pressure
respirometer,
rving the airway
e problems.
eful. The

ns. A continuing
rator to this
an ascending

ected by

omeone breathe
edure for preuse

P. **B:** Same valve
nce.

sconnection
ube connector
roblem may

scitation bag until

es

more risk than
the patient's

m, laryngospasm,
patient's face
at the patient
APL valve when
ove dust before
nisters

water, oil,
tallic fragments
90,591).
d air

onents
k and become
f the sampling
APL valve, an

ome
onents with

nd in breathing

,606,607,608,609).

hydroxide can

scussed in detail

re
ore complete
function.

itated, a very
aporizer is
Ī€travelĪ€
n the rest of the
e anesthesia

vertently

rvice technician
in the ON
ve the machine
ON. Inadvertent
from the main
gen (614).

esigned for an
er minimum
sly high
8). An example
designed for

h gas flows is
anesthesia
a higher-than-
e oxygen flush is
iderably higher-

gas flow is
ncentration

cannot be
event overfilling
nside of the
n be overridden
ning the
). A drain has
nt overfilling.

ure

ble to turn on

concentration of
overdose of
d be
tilated by using
than the

elivery

serious
the surgical

leaks, a frozen
e system supply,
,631,632,633).
leak in the
s oxide flow
using air

centration

xygen sources
esthesia
n that of nitrous
e (636,637).

cur
he oxygen flush
nt awareness
e can cause it to

m will cause it to
is delivered

ent can cause

or interlock

,656,657,658,659,660,661,662,663,664).
izer is turned
ecking procedure
d ON (Chapter

associated with a
reported case
65).

at runs empty
id level was
vaporizer was
obstructed the
dicator, showing
(667). Some
the liquid level

hly volatile agent
t will fail to
n example is
for isoflurane.

anesthetic
equently during a
erator's
ON a vaporizer
ne is turned OFF
may default to

nts and
ensive that it is
ntration. If there
tting and the
breakdown

e Agents

malignant
s of agent
if the vaporizers
674). When a
e entities must
be prepared for
Other necessary
g the fresh gas
shing with a

cur during
has a machine
hat has been
e substituted for
ould be used. If
he following
concentration of

ag.

ort of the

ssible.

r if the
a patient
gas delivery port
ed to deliver
vertently turned
anesthetized with
oided by using
ne, an oxygen
cylinder as the

t added to the
ne becoming top
n or other
loor or
ve a generally
onitoring devices
es, it is still

presence of wires
ely that the
oment to the

oses, tubings,
e been
machine wheels
a machine can
er (687).

go over the hose, the machine
is device allows easier
se out of the way. (Picture

ess radio
has increased
uter networks,
hones, and other
gnetic energy,
In the future, it
connected to the
nnection. These
e device is in
o the base

emits radio
nic medical
. The extent of
ndicate that
reported being
sion pumps. The
wer and
unity

devices used in
ons difficult to
ritical care
onic medical
Diagnostic,
rectly attached to

manufactured to
external sources
nd newer
revent
quipment is of
signed to be
netic environment

eases with
he separation
the lower the RF
tial for EMI.

the risks and
nd health care
fely and
d for immunity to
ch devices may
transmission

oduced, health
a prudent policy
have banned the
hers allow them
their use in
dical equipment

testing for

ment, they
problems. Under

if the device
direct or close
s communication
ublic areas do
esting of
ment will be

equipment
the apparatus
ved

care facility
cted at once to
lished protocol
ortant areas are
n the incident
he event while
be a simple
sality or

n?

s a problem?

ny alarms

hibit?

the electrical

ident?

ea on that day?

ases performed
day?

er areas on that

area recently?
n where it was

were made?

nesia machine?

machine, were
ing spilled into

ad occurred,

e line, on which

. This will help
of missing data.
t system can

rea from various
at the time of
photographed

equipment
equestered in a
B.Ĩ€ Settings
rmation such as
should be

e that the
blem, a thorough
ird party in the
nsurance carrier,
entative, and
The investigation
equipment
rlier in this
ecked to
on. An analysis
ecessary.
nade, detailing

empt should be
done without
ain be locked up
reveals no
vice with the

Radiological
tion (FDA)
itted by

erious injury, or
FDA analyzes
c health and
th care
FDA's name for
road program
reporting for

medical device
ributed to death,
or injury is
nent impairment
dy structure or
intervention to

an 10 days after
y and in a timely
es. Problems
FDA and to the
y events are

urer is not
sponsibility to
rt the incident to
ch a device
t in a death or
hrough the FDA's

therwise used in
king the report
number of ways
luding the
ible that this
8).

ndling adverse
rted in a timely
he health care
cal department,
he report.

Preventable

ysis of major
anagement.
Anesthesiology

c
6.

tic critical
Care

the causation
from the
he Boston

nalysis of
quality
hesia.

incident
assurance

during
J Anaesth

equipment

al.
m a critical
96;51:615Ĩ

Adverse
equipment. A
7: 741Ĩ€“748.

poxia from an
sthesiology

ng gasĨ€
:26.

ypoxia from
alg

njury from
August 9,

amination of
2:1098Ĩ€“1102.

e into deaths
23Ĩ€“124.

ses three
983;13:88Ĩ

ls two. Biomed

emergency
ror. Aust Dent

nese

Technol

O.R. death.

thesiology

of oxygen
ypoxia.

disaster from

ts associated
680Ì€“682.

the oxygen

es cause
26:1009Ì

R, et al.
condition
2;47:500Ì

contamination
ventilators.

rtioners.

ontamination
al engineering
Ì€“300.

ld be the
14.

identity
as system of a
Ì€“209.

Technol

gas outlets.

cal gas

ed for
1992;22:14.

es. South Afr

tion of a new
Anesthesiology

from
Anesthesiology

eading to
ia during
Ī€“441.

O_2 outlet
92Ī€“93.

cal gas
67Ī€“58.

death caused
erts 2005;29:3.

avoid making
cation

(accessed).

Schraeder

naesthetic

medical gas

and nitrous
Anesthesiology

cet

blems. Eng

two intensive
hesiology

meter-indexed
319.

f oxygen:
01;21:97Ī€“98.

sth 1991;12:7Ĩ

er confusion.

s Care

y an
t. Br J

f cylinders.

s Care

ders.

er Ĩ€wrong
1991;6:9.

gas machines
roblems with
Int Anesth

n/oxygen.

sthesia

sia

ulator to
Safe Stand

n of gas
:2.

xygen pin-

's lawĨ€"mix
164.

sth Intens Care

labels! They're
s. Technol

of an
ces

tient simulator
11:394â€“395.

sthesia

ol Anesth

. Anaesth

eable oxygen
â€“1206.

eable oxygen
sthesia

pin index
sia

ing failure.

unscrewed

nnexion of
achine.

ction. Anaesth

flow control

ter failure on
sthesia

$2.5 million
3.

ard. Can

Can Anaesth

Anaesth Intens

esthetic
ce. BMJ

gen
997Ł€“999.

rgen
397Ł€“398.

410 machine.

cel 210

tic gas flow
stem of
672.

10 anaesthesia

in-link
sia machine.

210 SE
3Ł€“439.

chain-link
tic machine.

ngerous
7;52:283Ł

. Failure of the
re on a
siology

thesia
y

otential hazard
06Ł€“607.

oxide by Ulco
Care

% nitrous oxide
. Anaesth

netic machines.

flowmeter.

tubes.

lowmeters. Br

ibrated
970;33:467

oes. Anaesth

sth Analg

against

xic gas
quipped with a
Soc J

tameter. Br J

gen leak.

meda Excel

r. Br J Anaesth

ntiflex
y. Anaesth

d with removal
)88;43:892Ĩ

ks from
308Ĩ€“1312.

leak. A
a

s Care

akage of fresh
sth

leaks.

with Ohio
1986;64:266Ĩ

case report of
62:696Ĩ€“697.

sia delivery
6, New

system.

anaesthesia
.

xia risk with
s. Anaesth

etic gases by a
ology

circuit
ms.

s. Anaesth

dental
ology

anaesthesia
979;34:678Ĩ

se in inspired
or bellows. Can

tilator causing
th Intens Care

unction
1981;9:395.

n Ĩ€trunkĨ€
esth

e use of high
duction of new
004;99:1737Ĩ

rkstation.

dition: safety
onse. APSF

sth Intens

us mother

quipment
Anaesth Intens

he hospital
Care

ne failure.

ruption of the
thesia

. Biomed Safe

al oxygen
Stand

cause patient
.

failure.

d could fail.

en failure.

pipeline
an Anaesth

pipeline.

ureÎ€”cause for

n of gas flow
Anaesth Soc J

peline supply
:39Î€“41.

e supply.

ld have gas-
1.

associated
cylinders. J

ittent oxygen
hine due to a
halg

flow reduction
ter. Anesth

al. Potential
v.

oxygen

al. Physical
ia: an analysis
1993;21:659Î

f medical gas
J

an imperfect

associated
cylinders. J

anagement of
o in

needle valve.

other machine

sthetic gas

705
thesiology

ute failure of
Î€“1039.

he Blease
hesia

ease Frontline
esia

me to recheck

naesthetic

ailure in an
63:335Î€“336.

machine

as line
.

ailure.

A possible
Anesth Analg

r leak.

oss from Ohio
esth Analg

a selectatec.

f free-standing

oblem.

es
2;47:359.

oyle vaporizer.

c block.

Anaesthesia

ases due to
3;62:369Ĩ

use (and cure)
42Ĩ€“843.

s anesthesia

associated
a

k. Anaesth

use (and cure)
42.

ine checks

Technol Anesth

y 1978;49:302.

naesthesia

eak through a
58:239Ì€“240.

s Care

ng of the
esth Analg

an anesthesia

achine

Anaesth

naesthetic

naesthetic
sthesia

989;44:703Ì

mmon gas
rean section.

neous
esia circuit.

nes. Can J

esia. Anesth

ece. An
e learned.

se of failure of
esth Analg

s & fresh gas
9.

esh gas flow in
3:535Ī€“536.

the operating
truction.

cause of
sthesiology

breathing

raeger Cato

from
J

structions.

Anaesth

ing circuit. Can

leads to

rn leads to
004;19:34.

on dioxide
circuit.

et al. Problems
eports.

ia

t to do a
ine. Anesth

1998;80:878Ł

leak. J Clin

anesthesia
.

alerted to
Stand

eal after
9;1:474Ł€“476.

th Intens Care

recall
7:164Ł€“166.

leak possible.

Technol Anesth

athing circuits
Health Devices

el leak from an
:975Ł€“976.

respiratory
763.

al. A cause of
esthesia.

ing circuit
Anesthesiology

source of leak
;62:208Ł€“209.

ns Care

aks. Anaesth

olumeŁ€
: an unusual
Clin Anesth

transducer gas
99;89:1587.

single-use in-
sia

al. A cause of
esthesia.

er fifty percent
;70:S194.

it leak from
an Anaesth

1981;60:121Ł

hose causes
alg

ak. Anesth

d to the use of
y 1990;72:958.

humidifier.

rce of a major

a leak in a
989;71:806.

posal for
1;72:130โ

leak. Anesth

use of tape.

e of breathing
8.

cuit
450.

aesth Intens

esia

mpling set for
47:173.

anaesthetic gas

ve of a Y-
ntial foreign
"1170.

e of air leak in
h Analg

orrugated
esthesiology

breathing

of disposable
"115.

he circle

ng circuit
1994;24:124โ

els. Anaesth

1996;51:406Ì

aesthesia

esthetic

. Occult leak in
assessment.

of a reservoir
ilure.

nction of age?

unt: now you
9Ì€“700.

r recalled: port
€“118.

trophic failure
ology

d instant

d instant

of heated wire

of heated wire
72.

rcuit tubing
86;65:1247.

el heater-wire
alth Devices

lt involving an
re

ure of Bain
;55:716Ī€“717.

stem. A

of the
a 1990;45:992.

djustable
788Ī€“789.

sive in
“74.

circuit. A

f the Cape-

an Ohio
42.

h Intens Care

leak. Can

cause of
ogy

hazard of an
1986;65:126Ī

e malfunction.

r
r. J Clin

al.
ture. Anesth

al. Flapper
g system.

ack of
nes. Technol

s with
990;18:560ĩ

silicone
.

tation kits may

disposable

ows ventilators
;58:486.

n be lethal.

ons. Br J

ipment.

: averting
3.

victed of
2.

Canadian
sthetic
“473.

associated
s. Their effect
and airway

ctor from
“1052.

y of
Anaesth Soc J

aks could be
95;10:20.

Anaesthesia

better than to

ls. Particular
their
hocken, PA:

t. Can J

naesthetic gas
89;36:204Ĩ

hazard in the
977;47:302Ĩ

piratory
37:468Ĩ€“469.

the Drager
Analg

m an
1.

persistent leak.

ilure induced
9:161Ĩ€“162.

-failure of
dobronchial
25:851Ĩ€“853.

ld have
ogy

circuit
Care

RA. Unusual
ackaging

chanical
mimicking
92Ĩ€“994.

f difficulty in
7Ĩ€“139.

eathing circuit

de absorbents.

xchange.

ion in

echnol Anesth

echnol Anesth

zard. Anaesth

nt and the
GBAT).

esthesia

circle

tsâ€”Gilbeck

blocked by
1:91.

ory pressure.

. Technol

5188 heated
ealth Devices

s Care

uit occlusion
J Anaesth

Anaesthesia

an anesthetic

onโ€”another

A hazardous
12.

and moisture

tion of a
.

y serious
y 1986;65:563.

. Anesth Analg

to ventilate
breathing

elopment of
CO_2 cap in the
04โ€“213.

al breathing

rway.

eign body. Can

ght the need
cuits. Health

r J Anaesth

ere a foolproof

obstruction
9:35.

cked
33.

d instant

g circuits:
lerts

Technol Anesth

C, et al.
ivel port

eathing circuit
onnector by a
e 1999;27:73[

expiration.

use of total
10.

xial breathing
st come out.

struction from
2;57:505.

Anaesthesia

ly.

ed by plastic

aesth Intens

e of circuit

cuit.

d instant

struction to an
€“111.

G. Acute
y an end-tidal
1999;89:804Ī

rm air blanket
sthesiology

parts recalled
tand

ow circuits
Safe Stand

airway

ht the need
cuits. Technol

kaging hazard.

rption

isory.
92.

Obstruction
ter wrapping.

e to retained
nesth Analg

EP valve.

swivel

f coaxial

thetic

6.

mplete
er by
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xchange.

al. Root-cause
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erative
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rcuit. Anaesth

struction.

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nctionÎ€”a
Analg

ty warning with
esign. Anaesth

s can detect
65.

in the
984;61:374.

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re to detect
89;44:79.

ure alarm
nesiology

ponse
. Anesth Analg

the breathing
nesthesiol

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. Anesth Analg

dition: safety
onse. APSF

stration of
4.

ia during

naesthetic
€“912.

hypercarbia
30;53:248Ī

ommonly used
44:535Ī€“537.

ers. Anaesth

xpiratory valve.

g flutter valve.

e failure.

eck valves may
56.

ypercarbia by

tory valve
circuitĪ
veform. Anesth

mpetency of
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alve
ns Care

l valves of
bers. Can J

A defective
during normal

spiration of

et al. An
n a circle
€“1028.

due to a
0:823Ł€“824.

mal looking
2002;57:929Ł

w leak test for
nhalation

al expiratory
2003;58:1239Ł

rcle system
8.

islodge in
20:108.

An unusual
esiology

disconnection
1987;34:622Ł

Can Anaesth

leak from an
5;50:266Ł

th Soc J

ected with re-
naesth Soc J

aesth

Soc J

the Bain
naesth Soc J

of inner tube
;53:1106Ī

e. Anaesthesia

the Kendall Ī
510.

misused co-

tion?

a and
a report of two

apnia related
sth Analg

tric breathing

Anaesthesia

Effects of
n. Anesth Analg

ently opposed

ateral
airway

ve airway
he Fraser
:41Î€“44.

rvoir bags:
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Chapter 15
Latex Allergy

Concern about latex allergy in the medical community has increased as health care personnel have seen an increase in reactions among both patients and themselves. Latex is the second most common cause of intraoperative anaphylaxis, preceded only by muscle relaxants (1).

Origin of Sensitivity

Natural latex is obtained from the sap of a rubber tree. During the manufacturing process, many chemicals are added to the latex, depending on the design and technical requirements of the finished product. These substances may also be allergenic. There may be as many as 240 potentially allergenic substances in processed latex products (2).

The increased incidence of latex allergy is believed to be due both to changes in the manufacturing processes and increased use of latex-containing products. Adoption of universal and standard precautions (Chapter 34) has greatly increased latex exposure.

Latex sensitization can occur as a result of contact via the skin or mucous membranes, inhalation, ingestion, parenteral injection, or wound inoculation.

Latex-containing Products

Latex is ubiquitous in the home, workplace, and health care setting but is not always obvious. In the operating room suite, it is found in gloves; tracheal tubes; Combitubes; face masks; mask straps; airways; wrappers on trays; laryngoscope bulb gaskets; skin temperature monitors; rubber suction catheters;

arm boards; bite blocks; teeth protectors; breathing tubes; oxygen tubing; reservoir bags; ventilator hoses and bellows; resuscitation bags (black or blue, reusable); blood pressure cuffs and tubing; stethoscope tubing; intravenous tubing injection ports; tourniquets; syringe plungers; rubber-shod clamps; intravenous bag and tubing ports; medication vial needle ports; tape and other adhesives (e.g., Esmarch bandages, adhesive bandages); dental dams; elastic bandages (Ace wraps); dressings (e.g., Coban, Moleskin, Micropore); rubber pads; protective sheets; drains; electrode pads; rubber aprons; circulating fluid warming blankets; some cast material; goggles; pulmonary artery catheter balloons; epidural catheter adapters; intravenous (IV) medication pump cassettes; electrocardiogram (ECG) electrodes and pads; finger cots; ostomy bags; intestinal and stomach tubes; rubber bands; chest tube drainage system tubing; condom urinals; urinary and nephrostomy catheters; gastrostomy tubes; bulb syringes; adhesive drapes; nipples; instrument mats; specimen traps; catheter bag straps; dilating catheters; and

the elastic in items ranging from surgical masks, head coverings, hats, and booties to diapers. Allergic reactions have been attributed to drugs that had been prepared in a latex-containing syringe for a considerable time before use or a bottle with a latex stopper between the drug and the diluent (3,4).

Products made of dry, molded, or extruded rubber such as wheelchair tires, tool handles, rubber seals, vial stoppers, and syringe plungers contain much less allergen than do items such as gloves, condoms, and balloons that are formed by dipping forms into liquid latex (5).

Well-washed rubber products such as ventilator bellows pose less risk than new items (2). There is a decrease in latex proteins in gloves that are autoclaved (6). Products that are sterilized by using ethylene oxide may increase the risk of latex sensitization (7).

Gloves have very high allergen levels compared with most other latex-containing medical products. Latex gloves are the biggest contributors to the aeroallergens inside the operating room. Many gloves contain powder. Latex proteins from the gloves bond with this powder. When a glove is put on or removed, the powder may spray into the air. It can then be inhaled by personnel, inoculate an open wound, and contaminate the instruments on the surgical field (8). The highest levels of airborne latex allergen are found in the operating rooms where powdered latex gloves are frequently donned and removed (9,10,11). The powder can remain suspended in the air for hours. Even in operating rooms where laminar airflow devices are used, latex aeroallergens are present in high quantities. Allergens are carried throughout the environment by ventilation air exchange systems as well as by settling on clothing and equipment. Switching to low-allergen gloves has been found to reduce the levels of these aeroallergens (12).

Latex is found in many products outside the health care setting. These include toys; condoms; expandable fabrics (waistbands); diaphragms; balloons; hot water bottles; erasers; rubber bands; shoe soles; motorcycle and bicycle handgrips; bathing suits, caps, and goggles; racquet handles; pacifiers; baby bottle nipples; bungee cords; chewing gum; cosmetic applicator sponges; fish tanks; bike helmets; automobile tires; raincoats; computer mouse pads; earphones; household rubber gloves; and carpet padding to name but a few (8,13).

Clinical Signs and Symptoms

Reactions to latex include a spectrum of non-immune and immune-mediated responses. Signs and symptoms may be local or systemic and vary widely in severity and the time of occurrence. Most adverse reactions to latex occur 30 to 60 minutes after induction (14,15). Symptoms can progress quickly from mild to severe. In some cases, life-threatening reactions are the first to appear.

There are three types of reactions to latex: irritant contact dermatitis, Type IV delayed hypersensitivity, and Type 1 immediate hypersensitivity (2,8,16).

Irritant Contact Dermatitis

This is the most common type of glove-related reaction. It results from the direct action of latex and other irritant chemicals and consists of itching, redness, scaling, drying, and skin cracking. The rash is usually limited to the exposed skin area. Soaps, mechanical irritation from scrubbing, and excessive sweating often exacerbate it. While this is not a true allergy, disruption in skin integrity may enhance absorption of latex allergens and accelerate the onset of allergic reactions.

Type IV Delayed Hypersensitivity

Hypersensitivity is an immune response that leads to tissue damage. Once sensitized, an individual's exposure to an antigen can cause a reaction. It may take several years for latex sensitivity to develop. When it does, most develop as a Type IV (delayed) reaction.

A Type IV reaction (allergic contact dermatitis, delayed hypersensitivity) is a T-cellâ€“mediated response characterized by a skin rash that appears up to 72 hours after initial contact and may progress to oozing skin blisters. Unlike irritant contact dermatitis, allergic contact dermatitis often spreads beyond the area of contact with the allergen. Flushing, itching, rhinitis, dizziness, sinus symptoms, conjunctivitis, and eyelid edema may also be present.

Not all individuals who develop Type IV hypersensitivity progress to Type I, but most individuals with Type I sensitivity have previously had Type IV symptoms (2,16,17).

Type I Immediate Hypersensitivity

This is the most severe reaction and may lead to significant

morbidity and mortality (18). Symptoms usually appear shortly after exposure but can occur hours later. They run the entire spectrum from mild (skin redness, hives, itching, rhinitis, scratchy throat, itchy or swollen eyes) to more severe (facial edema, faintness, nausea, abdominal cramps, diarrhea, cough, hoarse voice, chest tightness) to life threatening (laryngeal edema, bronchospasm, anaphylaxis). A survey of anaphylaxis during anesthesia showed that cardiovascular symptoms, cutaneous symptoms, and bronchospasm were the most common clinical features (19).

Anaphylaxis is an immediate, severe, life-threatening allergic response. There are a number of reports in the literature of anaphylactic reactions to latex (1,2,4,7,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34).

Latex allergy should be high on the list of possibilities when anaphylaxis occurs during anesthesia and surgery. It may not be apparent that latex is the causative factor. If medications have been injected in close proximity to the anaphylactic reaction, the anesthesia provider may suspect that medication caused the reaction (32). Failure to recognize latex allergy can delay removal of latex-containing products and delay effective treatment.

Individuals at Risk

Identifying patients at high risk for having an allergic latex reaction allows preventive measures to be targeted (17). High-risk groups can be identified by knowing the risk factors and appropriate questioning. Latex anaphylaxis may be decreased by identifying at-risk patients (19).

The reported prevalence of latex allergy varies greatly depending on the population studied and the methods used to detect sensitization. Anyone with frequent exposure to latex-containing materials is at increased risk of developing latex allergy. The greater the exposure to latex in a population, the

greater the number of sensitized individuals. Extended or massive exposure in and of itself is neither necessary nor sufficient to cause sensitization if the person is not genetically predisposed (35).

Children and younger adults are more likely to become latex sensitive than the general population. Some but not all studies have found that women and members of non-Caucasian races are more likely to have latex allergies (17,35,36,37,38).

The majority of latex-sensitive individuals have a history of atopy (predisposition to multiple allergic conditions) or positive tests in atopy screening (2,17,25,27,35,39,40,41,42,43). Many have a history of an anaphylactic reaction in the past (8,36,43). Some studies have found a connection between an allergy to an anesthesia-related agent and latex (43,44).

Many patients with Type I latex allergy have a history of allergy to certain foods, including bananas, mangoes, watermelons, avocados, peaches, figs, apples, chestnuts, pineapples, kiwi, passion fruit, apricots, nectarines, papaya, celery, peanuts, cherries, strawberries, plums, potatoes, and tomatoes (2,5,25,35,37,45,46). There may be cross sensitivity between latex and ficus, grasses, and ragweed (47). Patients with milk protein allergies may exhibit allergic reactions to latex products containing casein (48).

Individuals with hand dermatitis who wear latex gloves are at increased risk (35). A history of glove-related symptoms does not reliably indicate latex allergy; conversely, absence of symptoms does not rule out sensitization (42).

Many latex-sensitive individuals report swelling or itching on the hands or other areas after contact with rubber gloves, condoms, diaphragms, toys, or other rubber products. Other symptoms include swelling or itching at the lips or mouth from blowing up balloons or after dental examinations (2).

Latex allergy incidence is highest for patients requiring multiple

operations along with repetitive urinary catheterization. This includes patients with myelodysplasia, congenital orthopedic defects, and congenital genitourinary tract abnormalities (49). Spina bifida patients have a particularly high incidence. However, adults with spinal cord injuries have a low risk of latex sensitization (50). Other high risk groups include patients who undergo repeated esophageal dilations, patients who have frequent vaginal exams (particularly those going through an in vitro fertilization program) and are examined with a latex-covered ultrasound probe (51), and patients undergoing barium enema procedures with a latex balloon tip (17).

Other at-risk patients for latex allergy include those who use gloves in their daily activities: farmers, food-service workers, gardeners, painters, mortuary workers, auto technicians, law enforcement personnel, waste removal workers, hairdressers, individuals involved in the manufacture of latex products, and those with prior reactions to latex-containing devices.

Approximately 70 percent of adverse events to latex reported to the Food and Drug Administration (FDA) involve health care workers. Within the medical profession, individuals who frequently use disposable gloves, including surgeons; anesthesia providers; operating room, postanesthesia care unit (PACU), and emergency room personnel; dentists and dental assistants; and laboratory technicians are more likely to become latex sensitive than other health care workers. Adult anesthesiologists change gloves more often than pediatric anesthesiologists and have an increased prevalence of latex sensitization (52).

Diagnosing Latex Allergy

Latex allergy is diagnosed by history and confirmatory tests (53).

History

Standard questions to screen for latex allergy should be developed. There are examples of screening tools for patients in

the literature that can be of assistance in developing a questionnaire (46,54). The history should include the risk factors and occupations where latex exposure is common, as discussed previously in this chapter.

Confirmatory Tests

A patient with a history suspicious for latex allergy may be a candidate for confirmatory testing.

Immunologic testing is not foolproof, particularly in the case of latex, because of the numerous different latex proteins. Testing requires a variety of latex antigens, and there can be no certainty that a particular antigen will be included in the test solution (17). Because false negatives can occur, patients with a strong suspicion of latex allergy should be managed in a latex-safe environment even if immunologic testing indicates a negative reaction (17).

Skin-prick Test

The skin-prick test (SPT) is used to detect Type I latex allergy (38). A dilute solution of latex allergen is placed on the skin, and the skin is pricked or scratched. A wheal-and-flare reaction is considered positive for latex sensitivity. This test is inexpensive and easy to administer and interpret. It offers reasonably good sensitivity and specificity. Retrospective studies show that patients with intraoperative latex anaphylaxis are almost invariably latex-SPT positive (42).

Drawbacks to the SPT include absence of an accepted test solution (2,5,9,17,55). The risk of a systemic anaphylactic reaction exists, but it is less than with intradermal testing.

Intradermal Test

With intradermal testing, a small amount of a suspension or allergen is injected into the skin. This method is more sensitive

than skin pricking, but the chance of anaphylaxis is greater (17,56).

Patch Test

The patch test is available for diagnosis of Type IV delayed hypersensitivity (8,38). A standardized patch or a fragment of the latex product is applied to the skin and checked over several days. A positive reaction includes itching, redness, swelling, or blistering where the patch covers the skin.

In Vitro Measurement of Antibodies

In vitro tests are used to measure specific antibodies against latex allergens in blood samples (57). These tests are expensive, and the clinical significance of a positive serologic test is unclear. Subjects with antilatex antibodies are termed *latex sensitive*, although many are not symptomatic and may never become so.

Challenge Tests

Challenge (provocation, use, wear) tests may be used if the results of other tests are equivocal or if the person has a clinical history highly consistent with latex allergy but results of other tests are negative (5,35,58). The potentially allergic person handles, wears, or inhales latex proteins and is observed for reactions. However, there may be discrepancies in challenge test results, and no challenge method has become broadly accepted by clinicians.

Preventing Reactions

Successful prevention of latex reactions requires a facility-wide strategy. Health care facilities should appoint a multidisciplinary task force that includes representatives from every professional component of the institution. It should include an allergist or immunologist as consultant. It may be a good idea to have a

latex-sensitive employee on the team (9). Among the duties of this task force should be glove selection, a mechanism for reporting latex reactions, formulating policies and protocols for management of the latex-sensitive patient, and health care worker and educational programs (2,59,60).

Medical products that contain latex will need to be identified and alternatives established before an emergency arises. Manufacturers have made great strides in decreasing latex in a variety of products (57). If it is not possible to remove a latex product, barriers should be placed between the latex item and the patient.

Successful prevention of allergic reactions will occur only when institutions adopt strict policies to protect at-risk patients from unnecessary latex exposure. At-risk children in a latex-containing environment are more likely to have an allergic reaction than those in an environment where latex-containing articles have been removed (3,61).

It is impossible to totally eliminate latex exposure. The goal is to create a latex-safe environment, that is, one in which the presence of latex antigens is minimized. The need for education cannot be overemphasized. The majority of latex reactions in a center with an established protocol were attributed to human error (61).

Using powderless gloves should be a high priority (5,62,63). It helps to minimize reactions to latex at little added expense and decreases the amount of aeroallergens in the working environment. Oil-based hand creams or lotions should be avoided. They can break down latex and make the protein more likely to stick to the hands. When gloves are powdered, pulling them on and off gently will minimize aerosolizing the latex proteins.

Patients with known or suspected latex allergy should have their records flagged and wear latex-allergy wristbands. Drug prophylaxis is sometimes undertaken (56). Allergic reactions,

including anaphylaxis, may occur even when prophylactic agents are used (3,64). While having these drugs already on board may lessen the

severity of a reaction, they may mask the early signs of anaphylaxis, delaying recognition and implementation of more aggressive treatment (17). Using H_2 blockers may increase the risk of heart block for patients who develop anaphylaxis (65).

If patients requiring surgery have confirmed latex sensitivity or convincing histories of latex reactions, avoiding latex-containing products is the only effective therapy. This is not always easy, as latex allergens permeate the hospital. Even in the absence of known latex allergy, some procedures involving patients with syndromes such as spina bifida should be performed in a latex-safe area (66). For high-risk patient groups, avoiding latex products should begin at birth (67).

The FDA requires that all medical products that contain latex that may directly or indirectly come into contact with the body during use to bear labels stating that the product contains latex and that latex may cause allergic reactions in some individuals (68) (Fig. 15.1). Governmental agencies in many other countries have similar requirements (68). If a product does not have this warning, it is likely that the product is latex-free unless it is a pharmaceutical or is not regulated by the FDA. Drug manufacturers are exempt from the labeling requirement (69). Manufacturers frequently label devices as latex-free (Fig. 15.2).

The term *hypoallergenic* is no longer used for devices that contain latex. At present, there is no test that can adequately determine the level of latex proteins in a product, and there is no manufacturing process that can reduce the level below the minimum required to produce a reaction in some people. Also, the total protein content is not analogous to allergic risk.

The latex-sensitive patient should be scheduled as the first case of the day with all latex-containing materials removed the

preceding night to minimize exposure to airborne latex-laden particles (2). No one should enter that operating room with latex gloves without scrubbing after taking off latex gloves or while wearing clothing from previous latex exposure.

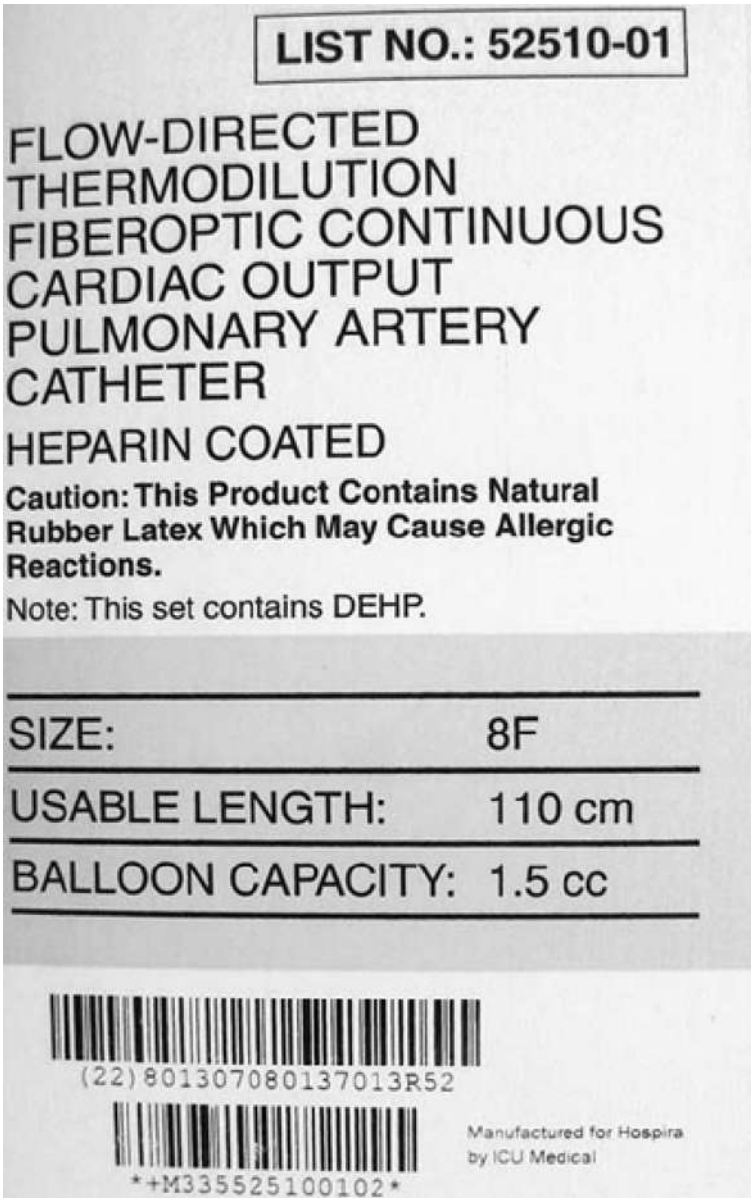

Figure 15.1 Thermodilution catheter clearly marked as containing latex.

Signs saying ĺ€Latex Allergyĺ€ or ĺ€Latex Alertĺ€ (for patients with significant risk factors for latex allergy but no overt signs or symptoms) should be posted inside and outside the operating room as well as in perioperative care areas (Fig. 15.3).

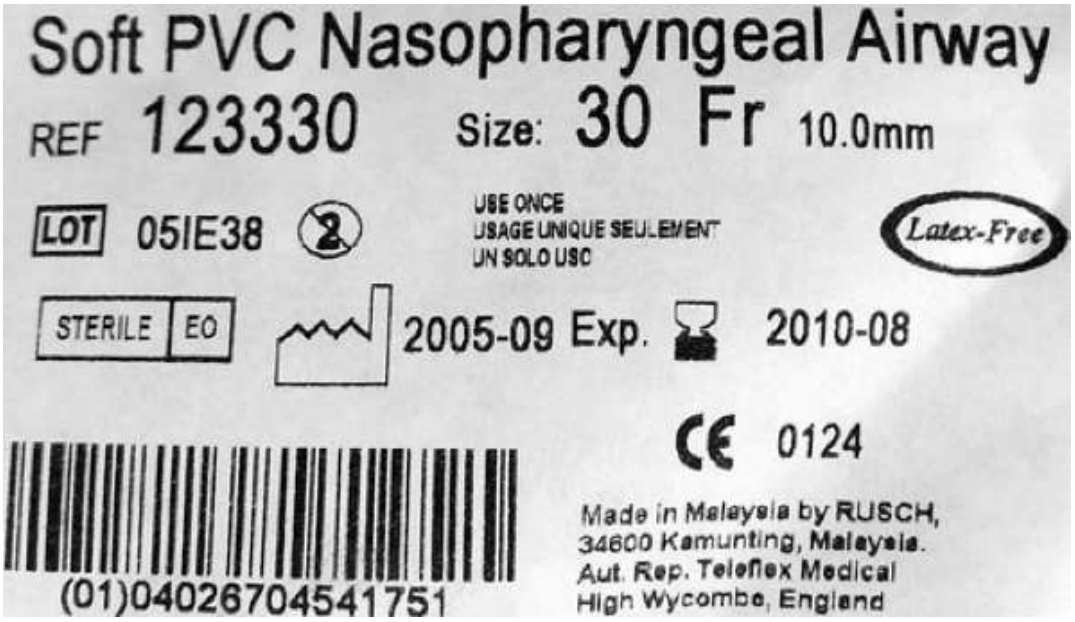

Figure 15.2 Device labeled latex-free.

Figure 15.3 A sign indicating possible latex allergy should be placed outside the operating room door.

Latex products should be limited to situations where it is thought that they are superior to nonlatex-containing products. Latex-free gloves with improved fit and feel are available (70).

A kit/cart containing latex-free products should accompany the patient throughout his or her stay. Latex precaution stickers should be placed on doctors' order sheets and the like. Signs stating ĺ€Latex Precautionsĺ€ or ĺ€Latex Allergyĺ€ should be placed on the walls and doors of the patient's room. Any department that is to receive a patient with latex allergy or sensitivity should be notified prior to transfer to that department.

Perioperative care areas where multiple patients are managed in proximity (e.g., preoperative holding areas and PACUs) should be re-evaluated. If powdered gloves are used in these areas, patients may be admitted directly to the operating room and remain there during their recovery from anesthesia. If PACUs have isolation rooms, they may be converted to latex-safe environments for patients recovering from surgery (71).

Some health care facilities have established a specific operating

room where all latex-containing materials are banned. Signs should be posted on all entrances to that operating room, reminding medical personnel of the situation (72). Traffic in the room should be kept to a minimum (2).

No latex-containing items (i.e., gowns, hats, boots, and compression stockings) should be placed on the patient. Cords and tubes for all monitoring devices should be placed in stockinettes and secured with non-latex tape (73).

Latex-free intravenous start kits containing tourniquet, bandages, dressings, tapes, and gloves are available. Intravenous tubing without latex injection ports should be used or all latex injection ports should be taped to prevent inadvertent puncture. Stopcocks or one-way valves should be used for push and piggyback medications. Intravenous fluid or commercially prepared medication bags should be pierced through the intravenous tubing port, not the latex injection port.

Although reactions to rubber syringe plungers have been reported, no problems have so far been described in medications freshly drawn and immediately administered (74). If latex-containing syringes are used, drugs should be freshly prepared in the syringe immediately before use. Glass syringes offer an attractive alternative, and totally plastic syringes and special needles are available (75,76,77). It is best to use medication from glass ampules, if available. Although it has been advocated that the contents of a vial should be drawn up after the rubber stopper has been removed (17,47,78), this may not be beneficial and may result in increased microbial contamination and waste (79). Lyophilized drugs in containers with latex should be reconstituted by using a syringe, not shaken in a multidose vial and withdrawn by using a filter. Vials should be kept upright and not shaken (4).

A filter should be used at the breathing system patient port to protect against airborne latex allergens (80,81).

It may not be possible to entirely avoid some rubber-containing

anesthetic equipmentâ€”rubber bellows, diaphragms, valves, and tubings (82). However, when these parts of equipment do not come into contact with the patient and have been previously washed, no complications have resulted (83).

Latex-free equipment including face masks, airways, mask straps, tracheal tubes, bag-valve-mask units, reservoir bags, ECG electrodes and pads, stethoscopes (tubing or diaphragm), pulse oximetry sensors, esophageal stethoscopes, nasogastric and suction tubes, tape, gas hoses, and breathing tubes should be used. Unfortunately, some latex-free reservoir bags have such poor distensibility that their use may compromise patient safety (84).

If an epidural catheter adaptor contains latex, it should be replaced with a blunt, latex-free adaptor.

Latex-free reusable blood pressure instruments and accessories are available in a variety of sizes and models. These include inflating tubing, coiled tubing, sphygmomanometers, and inflation bladders. Wrapping the area under the cuff with soft cotton can prevent contact with any latex in these devices.

In some cases, some improvising may be necessary, as with a pulmonary artery catheter (85,86).

From the surgical point of view, using non-latex gloves, drains, and catheters is mandatory. Special precautions should be undertaken to avoid latex-based equipment such as instrument mats, rubber-shod clamps, vascular tags, bulb syringes, rubber bands, and adhesive bandages. A non-latex glove can be used as a

Penrose drain, which can be a source of latex hypersensitivity (86A).

When latex-sensitive patients or staff have been identified, it is important to provide latex-free items. These should be collected into a cart that can be called into action as the need arises. The

American Society of Anesthesiologists and others have made recommendations for the contents of a latex-safe cart (2,59,86). Suggested items are listed in Table 15.1. Each item should give information on latex content and should be reviewed for this information prior to adding the item to the latex-safe cart or before use.

TABLE 15.1 Suggested Contents of a Latex-safe Cart

Latex-free or glass syringes
Syringe needles
Intravenous catheters
Intravenous tubing and extensions made from polyvinylchloride
Stopcocks (in-line, three-way, and single)
Latex-free heparin lock caps and T-pieces with side port
Alcohol wipes in a new box
Latex-safe adhesive tape from a new box
Latex-free intravenous tourniquets
Sterile gauze pads
Esophageal thermometer
Disposable blood pressure cuffs of various sizes
Isolation stethoscope
Sterile case padding
Latex-free disposable pulse oximetry finger sensors
Latex-free ECG electrodes
Latex-free resuscitation bags sized for infants, children, and adults
Nasal oxygen cannula
Oxygen extension tubing
Latex-free tracheal tubes, double-lumen tubes, and stylets
Latex-free oral and nasal airways
Silicone supraglottic device
Plastic face masks and head straps (elastic strap may have latex)
Medications for cardiac arrest and emergency situations

Vinyl gloves for any size staff
Sterile nonlatex gloves, sizes 6 to 9
Silicone urinary catheter in assorted sizes
Urimeter
Epidural and spinal trays
Polyvinylchloride suction catheters, sizes 8 to 14 French
Anesthesia breathing circuits without latex components
Anesthesia medications in vials
In-line high efficiency particulate gas filter
Policy binder with all latex policies and protocols
Reference guide for latex-containing materials
Brightly colored signs that warn of latex allergy

Treating Latex Reactions

The symptoms of irritant contact dermatitis can often be controlled by removing the irritant. Measures include wearing a soft glove liner and reducing exposure to other irritants (e.g., soaps). Treatment with topical cortico-steroids may be helpful. Use of protective hand creams, however, is contraindicated (2).

For allergic reactions, the most important step is to stop administration and/or reduce absorption of the offending agent. All potential routes of exposure, including mucosal and inhalational, must be considered.

Topical corticosteroids can be used for a rash or hives. Topical nasal steroids may be used for rhinitis (2). Antihistamines and systemic steroids can be used to treat other mild reactions (2). If the symptoms are more severe, more aggressive treatment is indicated, including antihistamines, systemic steroids, H_2 blockers, oxygen, intravenous fluids, bronchodilators, and epinephrine (2,36,87). If anaphylaxis occurs, artificial airway support may be needed as well as intravascular volume expansion, administration of vasoactive medications, and other life-support techniques. The crash cart must not contain latex-

containing items (2).

Latex precautions should accompany the patient throughout the remainder of the postoperative period (PACU, intensive care unit, and discharge unit).

The details of any allergic reaction should be clearly documented in the patient's chart. This should include a description of the anesthetic agents and techniques, surgical products used, resuscitative measures required, laboratory evaluation, and the perioperative course. The patient should be referred to an allergist and the patient's record flagged to alert subsequent caretakers.

Desensitization by using progressive contact has been described (88). It consists of increasing exposure to latex by wearing latex gloves daily for increasing periods. Sublingual desensitization may result in significant improvement in symptoms (89).

Latex Allergy and Medical Personnel

Numerous studies show a high incidence of latex allergy in health care workers (2,8,9,10,11,35,40,41,42,56,90,91,92,93,94,95). Medical personnel who wear latex gloves on a regular basis (surgeons, anesthesia providers, operating room staff, radiologists, housekeeping staff, and laboratory personnel) are at higher risk for developing latex allergies than are other health care workers (41,42,72). Occupational asthma has been reported in an administrative employee who was exposed to airborne latex allergens (96).

Health Care Institution Responsibilities

Institutions should provide education programs and training materials about latex allergy (71). This includes educating all staff members, not just professional health care providers. For example, environmental and nutritional service workers are

required to wear gloves; therefore, they should be knowledgeable about their glove choices.

Staff should be encouraged to report allergic symptoms and be periodically screened for latex-allergy symptoms. Detecting symptoms early and protecting symptomatic workers from latex exposure are essential for preventing long-term health effects. Prevention strategies should be re-evaluated whenever a worker is diagnosed with latex allergy. Studies have shown that economically feasible interventions to reduce latex exposure can successfully allow latex-allergic individuals to continue working as well as decrease the number of new cases of occupational latex allergy (5).

The use of powderless gloves (Fig. 15.4) should be encouraged. In a study in which health care workers used both powdered and powder-free gloves, the rate of conversion to latex sensitivity was the same in each group, but the converters using powdered gloves were symptomatic whereas the ones using powderless gloves showed no symptoms (92).

Using non-latex gloves for activities that are not likely to involve contact with infectious materials (food handling, housekeeping, transport) should be encouraged. This can greatly reduce the levels of latex antigens in the environment.

Wearing non-latex gloves or using some type of barrier between the latex gloves and the skin should be encouraged. Non-latex gloves are usually more expensive than gloves containing latex (97). It is likely, however, that the price differential can be decreased if the facility were to choose a single vendor of latex-free gloves. If a worker must move to another job to avoid latex-containing materials and the new job pays less, that worker may be eligible for workers' compensation. It is also possible that workers could become so sensitized that employment is not possible. Very low levels of permanent disability are needed to make the conversion to latex-free gloves cost effective (97).

Figure 15.4 Gloves that are both powderless and latex-free will help to prevent latex allergy.

Facilities should ensure that good housekeeping practices are performed to remove latex-containing dust from the workplace. This can be accomplished by identifying areas that are contaminated with latex dust (carpets, upholstery, and ventilation ducts) for frequent cleaning and changing ventilation filters and vacuum bags frequently.

Some health care institutions require that balloons that often accompany flower arrangements be non-latex (98).

For sensitized health care workers, the Americans with Disabilities Act guarantees workers ‘€reasonable modification‘€ of the workplace to accommodate the disability. The Occupational Safety and Health Administration (OSHA) rules state that in addition to gloves that are normally provided, non-latex gloves, glove liners, powderless gloves, or other similar alternatives shall be readily accessible to those employees who are allergic to latex gloves (9).

Health Care Worker Responsibilities

Workers in health care need to take advantage of latex allergy education and training to become familiar with ways to prevent latex allergy and to learn to recognize the symptoms.

Workers should protect themselves from latex exposure inside and outside the workplace. Non-latex gloves should be used for activities that are not likely to involve contact with infectious materials. Intact skin is an effective barrier, and it is important to maintain good hand care. Cuts and open sores should be covered with a plastic barrier dressing prior to wearing latex gloves (99). Oil-based hand creams or lotions should be avoided, as they may enhance the release of latex proteins from the gloves (54). After removing latex gloves, hands should be washed with a mild soap and dried thoroughly. This will decrease the load of allergen.

Health care workers should avoid wearing work clothes (scrubs) home after working in the operating room (99). Indirect exposures have caused latex allergy in children and spouses.

If signs and symptoms of latex allergy develop, the person should avoid contact with latex-containing products until he or she can be seen by a physician who is experienced in diagnosing and treating latex allergy. A diary of symptoms should be kept. Delay and

self-treatment can delay diagnosis, allowing the problem to become more serious.

The Health Care Worker with Latex Sensitivity

Depending on the severity of the reaction, latex sensitivity in health care workers can be an inconvenience or a life-threatening hazard. It can mean the end of a career (100,101). Often, health care personnel are unaware of their sensitization, as the symptoms can be nonspecific (99). The only clue might be

the temporal relationship with working. Denial can be a problem.

Latex-allergic anesthesia providers should be counseled on the risks of continued work in environments with high latex use and on strategies to limit exposure. They should have proper allergy identification, including a medical alert device, and should inform their health care providers (including dentist and local hospital). They may want to carry an allergy kit, including an epinephrine auto-injector device, non-latex gloves to wear or give to others to wear if they must care for them, and a complete list of medications taken. Friends and family should be given information about latex allergy. The individual must be on the lookout for hidden latex. Consideration should be given to avoiding foods that may contain proteins similar to those in latex.

Once latex allergy is diagnosed, the only option is to avoid contact with latex and to try to control the symptoms. Almost all the products that health care workers encounter in their daily work can be made latex-free. A latex-safe environment also prevents exposure of other workers.

There are many non-latex gloves available, both sterile and nonsterile. These include vinyl, nitrile, styrene butadiene, and neoprene (2,53,97,102). Unfortunately, these may not match the physical characteristics of latex gloves such as high elasticity, strength, flexibility, tear resistance, tactile sensation, and barrier integrity (5,53,103). Latex gloves are biodegradable and do not produce hazardous and toxic emissions when incinerated, as do synthetic gloves. Non-latex glove liners and latex gloves with integral non-latex layers are available (9). Co-workers should wear powderless, low-latex allergen gloves. This reduces the exposure to latex by those who are not yet sensitized and may decrease symptoms in sensitized patients (2,10,12,16,96,104,105).

Health care workers with latex sensitivity are not at increased risk when incidentally exposed to dry, molded, or extruded

rubber products in the health care environment; however, if direct contact with such objects is routine, exposure should be minimized by covering the object or exposed body part (5).

Because of the many factors that disseminate latex allergens and because latex allergens are so prevalent in some areas, it may not be possible to completely isolate workers from these allergens. In this case, job reassignment may be necessary. In the severely allergic worker, it may not be possible to find an area in the health care facility that will be safe.

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Questions

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

1. What factors contribute to the increasing incidence of latex allergy?

A. Increased length of surgical procedures

B. Changes in the manufacturing process

C. Younger people entering the health care industry

D. Increased use of latex products because of universal precautions

View Answer

2. Which are likely routes of sensitization to latex?

A. Skin contact

B. Inhalation

C. Ingestion

D. Parenteral injection

View Answer

3. Which item(s) listed below is unlikely to cause latex allergy?

A. Wheelchair tires

B. Washed ventilator bellows

C. Syringe plungers

D. Products sterilized with ethylene oxide

View Answer

4. Powdered gloves pose a greater threat than those without powder because

A. Latex proteins bind to the powder

B. The powder contains allergens

C. Powder may spray into the operating room when they are donned or removed

D. Filters in the ventilation system may become clogged

View Answer

5. What are the symptoms of irritant contact dermatitis?

A. Skin cracking

B. Itching

C. Scaling

D. Dryness

View Answer

6. What are the characteristics of Type IV hypersensitivity?

A. Delayed hypersensitivity

B. Always stays within the area of the antigen

C. May be associated with dizziness

D. Skin rash is seen within 5 hours

View Answer

7. Characteristics of Type I hypersensitivity include

A. Reactions may lead to mortality or morbidity

B. Symptoms can occur days later

C. Reactions range from mild to severe

D. They are mediated by IgF antibodies

View Answer

8. Primary clinical features of Type I hypersensitivity include

A. Bronchospasm

B. Cutaneous symptoms

C. Cardiovascular symptoms

D. Neurologic symptoms

View Answer

9. What are the important points to look for when taking a history in an attempt to determine the presence of latex allergy?

A. Hand dermatitis in conjunction with wearing latex gloves

B. Sensitivity to ragweed

C. Food allergy to watermelons, pineapples, strawberries, and tomatoes

D. Predisposition to multiple allergic conditions

View Answer

10. Which conditions are associated with a high incidence of latex allergy?

A. Genitourinary tract abnormalities

B. Congenital orthopedic defects

C. Esophageal strictures

D. Spinal cord injury

View Answer

11. Important features of the SPT include

A. High incidence of anaphylaxis

B. Reasonably good sensitivity and specificity

C. Availability of a good test solution

D. Patients with anaphylaxis during surgery are almost invariably skin-prick positive

View Answer

12. Preventive measures for latex allergy include

A. Determining the products that contain latex

B. Using oil-based hand creams or lotions

C. Using powderless gloves

D. Totally eliminating latex exposure

View Answer

13. Considerations for drug prophylaxis include

A. H_2 blockers may increase the risk for patients with heart block

B. It may mask the signs of anaphylaxis

C. It may delay implementation of treatment, if anaphylaxis occurs

D. It will prevent anaphylaxis

View Answer

14. Regarding labeling for latex content,

A. If the label does not indicate that it contains latex, it is latexfree

B. Products not regulated by the FDA must be labeled if they contain latex

C. Drug manufacturers must label products regarding latex

D. The FDA requires that all medical products that may directly or indirectly contact the body be labeled if they contain latex

View Answer

15. Surgical precautions that need to be taken if a patient is known to be latex sensitive include

A. No one should enter the operating room wearing latex gloves

B. The case should be posted for the first case of the day

C. Clothes that have not been exposed to latex should be worn

D. Latex alert signs should be posted inside and outside the room

View Answer

16. Which steps can be taken to limit the likelihood of latex allergy resulting from intravenous or parenteral injec-tions?

A. Using medications supplied in ampules

B. Using glass syringes

C. Preparing drugs just before use

D. Using rubber syringe plungers

View Answer

17. Methods to treat irritant contact dermatitis include

A. Reduce exposure to the irritant

B. Use of a plastic glove liner

C. Topical corticosteroids

D. Protective hand cream

View Answer

18. Steps that health care workers can take to protect themselves against latex exposure include

A. Washing hands after latex gloves are removed

B. Using non-latex gloves where infectious material will not be encountered

C. Covering breaks in the skin with a plastic barrier

D. Using oil-based creams or lotions

View Answer

Chapter 16
Face Masks and Airways

Face Masks

The face mask allows gas administration to the patient from the breathing system without introducing any apparatus into the patient's mouth. The ability to hold the mask and to administer positive pressure ventilation through the mask is a basic skill that all anesthesia providers must master. In the past, the face mask was often been used to administer an entire anesthetic. More recently, the introduction of supraglottic airway devices (Chapter 17) has led to a decrease in this practice. While some supraglottic airway devices have the word *mask* in their titles, they are very different from face masks and are dealt with separately in Chapter 17.

The face mask is also used to administer noninvasive positive pressure ventilation (NPPV) for treatment of respiratory failure (1,2).

Description

A face mask may be constructed of a number of substances, including black rubber, clear plastic, an elastomeric material, or a combination of these. The majority of anesthetics today employ a disposable plastic mask. These masks are designed to fit a wide variety of patients and are not as easy to use as many older masks that were sized and anatomically designed to fit a narrower range of patients.

Body

The body (shell, dome) constitutes the main part of the mask (3). A transparent body allows observation for vomitus, secretions, blood, lip color, and exhaled moisture. A transparent mask may be better accepted by a conscious patient (4).

Seal

The seal (rim, flap, edge) is the part of the mask that comes in contact with the face. Two general types are available. One is a pad (cushion) that is inflated with air or filled with a material that will conform to the face when pressure is applied. The second type is a flap that is a flexible extension of the body that conforms to the contour of the face. It is pressed onto the face to create a seal.

Connector

The connector (orifice, collar, mount) is at the opposite side from the seal. It consists of a thickened fitting with a 22-mm internal diameter. A ring with hooks (Fig. 16.1) may be placed around the connector to allow a mask strap to be attached.

Specific Masks

Masks come in a variety of sizes and shapes (Figs. 16.1, 16.2). An assortment should be kept readily available, because no one will fit every face well.

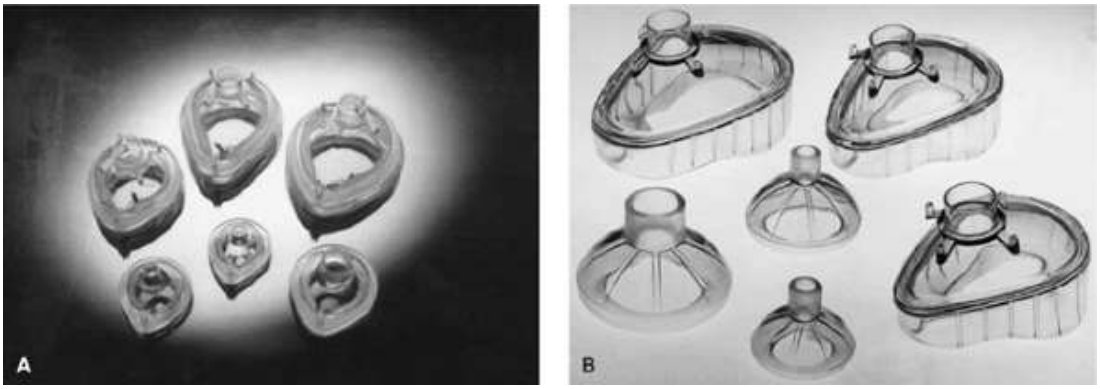

Figure 16.1 Clear, disposable masks. (**A**, Picture courtesy of Kendall; **B**, Courtesy of Rusch, Inc.)

Figure 16.2 Black rubber masks. (Courtesy of Sun Med.)

Rendell-Baker-Soucek Mask

The Rendell-Baker-Soucek (RBS) mask (Fig. 16.3), which is designed for the pediatric patient, has a triangular body. It has a low dead space (5,6). Some of these masks are scented and may have a pacifier (Fig. 16.3B). This mask has been used for the patient with a tracheostomy (7,8,9) and a patient with acromegaly (10). It may also be useful when a mask to cover only the nose is needed (11).

Endoscopic Masks

An endoscopic mask is designed to allow mask ventilation while an endoscope is being used (12,13,14,15). One is shown in Figure 16.4. A port/diaphragm in the mask body allows a fiberscope to be inserted into the nose or mouth. A lighted stylet (Chapter 19) may also be used (16). A tracheal tube previously loaded over the fiberscope or lighted stylet can then be advanced, if desired.

Scented Masks

Since face masks are often used for an inhalation anesthesia induction or for preoxygenation prior to induction, efforts have been made to make this experience more acceptable by using scents to camouflage the odors of inhalational agents

(17,18,19,20,21,22,23,24). The scent may be incorporated into the mask by the manufacturer or applied to the mask by the anesthesia provider (Fig. 16.5). Some masks are color coded according to the scent. The ethyl alcohol in some applied fruit flavors may affect the accuracy of some gas monitors (25,26). Pre-scented masks from the manufacturer do not present this problem (25).

Techniques of Use

The face mask should form a tight seal on the patient's face while fitting comfortably in the user's hand. A proper seal is essentially for preoxygenation (27,28). A poor fit requires the anesthesia provider to maintain steady pressure. This may lead to cramped hands and tired muscles and limits the user's ability to perform other tasks. With spontaneous respiration, a loose seal will result in

air dilution. With assisted or controlled ventilation, adequate gas exchange may be impossible with a poor mask fit. An inadequate seal can be compensated for some extent by increasing the fresh gas flow, but this is wasteful and contaminates the room with anesthetic gases and vapors.

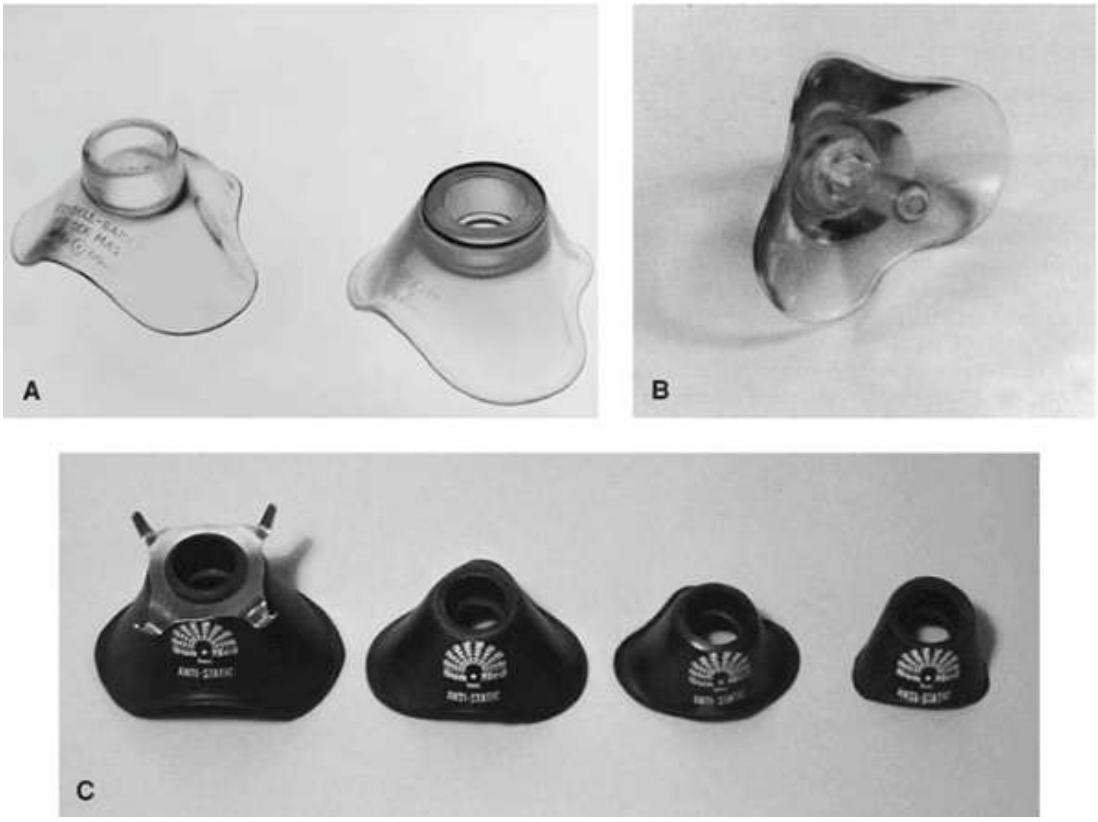

Figure 16.3 Rendell-Baker-Soucek masks. **A:** Clear plastic version. (Courtesy of Rusch, Inc.) **B:** With pacifier. (Courtesy of Ohio Medical Products, a division of Airco, Inc.) **C:** They are also available in black rubber.

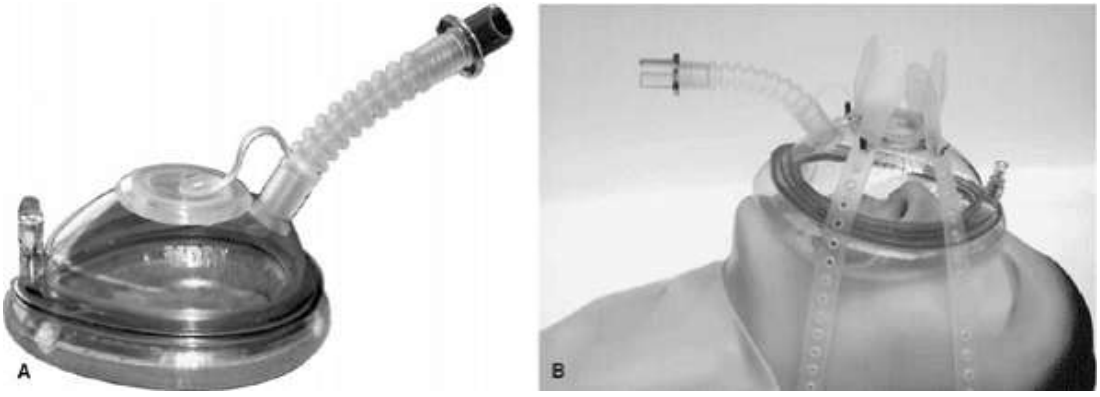

Figure 16.4 Endoscopic masks. (Pictures courtesy of VBM Medical, Inc.)

Correct mask use starts with selection of the appropriate size and shape. This may require some trial and error. The smallest mask that will do the job is the most desirable because it will cause the least increase in dead space, usually be easiest to hold, and will be less likely to result in pressure on the eyes. If a seal is difficult to establish, reshaping the mark's malleable perimeter, altering the amount of air in the seal or selecting a different mask may be helpful. If there is a leak, the mask should be checked to make certain there is an adequate seal between the breathing system connector and the mask (29).

One-hand Method

There are several methods of holding a mask to maintain an open airway and a tight seal. A commonly used method is shown in Figure 16.6. The thumb and index finger on the left hand are placed on the mask body on opposite sides of the connector. These fingers push downward to hold the mask to the face and prevent leaks. Additional downward pressure, if required, can be exerted by the anesthesia provider's chin pushing down on the mask elbow. The remaining three fingers are placed on the mandible or the inferior part of the mask. It is important that the applied pressure does not decrease airway patency. Care should be taken to prevent pressure on the eyes. In some cases, it may be necessary to extend the fingers to the right side of the mask to get a good seal. It may be beneficial to gather part of the left cheek around the left base of the mask with the palm of the left hand.

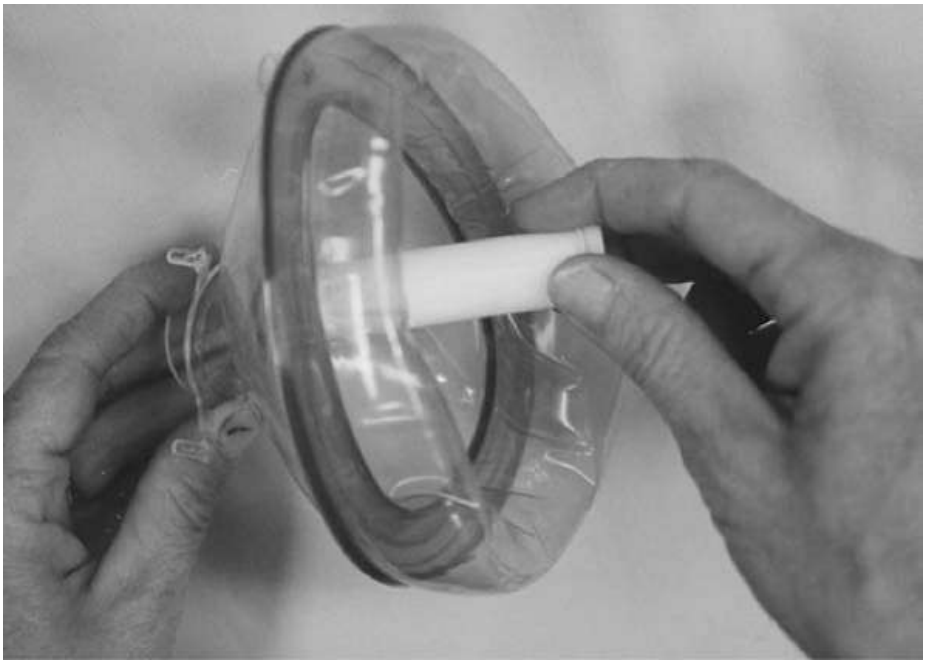

Figure 16.5 Adding scent to the face mask may make inhalational inductions more pleasant.

Figure 16.6 Holding the mask with one hand.

Two-handed Method

A second method can be used to open any but the most difficult airway and obtain a tight fit (Fig. 16.7). It requires two hands, so a second person is necessary if assisted or controlled respiration is needed. The thumbs are placed on either side of the mask body. The index fingers are placed under the angles of the jaw. The mandible is lifted and the head extended. If a leak is present, downward pressure on the mask can be increased by pressing down on the mask with the anesthesia provider's chin on the mask elbow (Fig.16.7B). If a second person is not available, the anesthesia ventilator can be used to supply positive pressure while the airway is held open by both hands (30).

Two-handed Jaw Thrust

Another method to open the airway is to have one person stand at the head of the patient and perform a jaw thrust at the angle of the left mandible while the right hand compresses the reservoir bag (31). The second person stands at the patient's shoulder, facing the first person. This second person's right hand covers the left hand of the first person, and the left hand achieves right-sided jaw thrust and mask seal.

Claw Hand Technique

The claw hand technique is useful for children undergoing short-duration ophthalmic procedures (32). The anesthesia provider stands at the side of the bed,

facing the child. The face mask is applied to the face by using the right hand with the palmer surface facing upward. The ring finger goes under the angle of the jaw, and the middle finger is placed under the angle of the jaw on the left. The index finger and thumb encircle the body of the mask. The anesthesia provider then tightens the grip on the mask to achieve a good fit. The little finger is kept free.

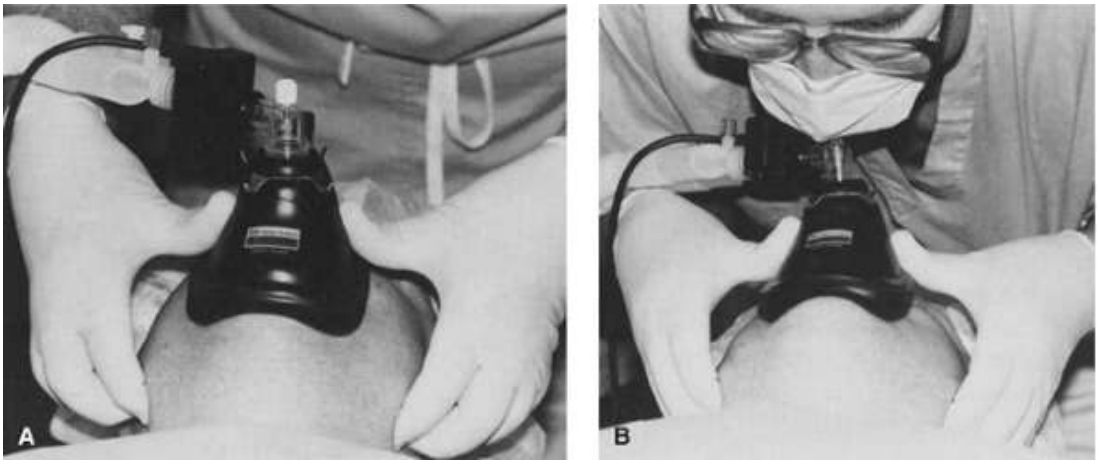

Figure 16.7 A: Holding the mask with two hands. Also shown is the Esmarch-Heiberg maneuver, which involves dorsiflexion at the atlanto-occipital joint and protrusion of the mandible anteriorly by exerting a forward thrust on the rami. **B:** The anesthesiologist's chin on the mask elbow helps to create a better seal between the mask and the patient's face.

Bearded Patient Techniques

Achieving a satisfactory mask fit is often difficult when the patient has a beard. One solution is to shave the beard (33). This is usually not acceptable to the patient. Another solution is to use a supraglottic airway device (34).

In some cases, it may be possible to place the round end of the mask between the lower lip and the alveolar ridge (35). The beard may be covered with a clear adhesive drape, a defibrillator pad with a hole cut in the middle, plastic cling wrap, or gel and gauze (36,37,38,39,40,41,42,43). A small mask can be placed over the nose and the mouth held shut (44).

Mask Ventilation of the Tracheostomy Stoma

A Rendell-Baker-Soucek mask can be used over a tracheotomy stoma to achieve controlled or assisted ventilation (8,9). It is placed around the stoma with the nasal portion pointing in a caudal direction so that the mandibular curve rests on the tracheal region and the apex on the suprasternal notch.

Difficult Face Mask Ventilation

Difficult mask ventilation is reported to occur in 5% to 6% of anesthetics (45,46,47). A variety of facial characteristics (fat, emaciated, and edentulous faces as well as those with prominent nares, burns, flat noses, receding jaws) or other problems (drainage tubes in the nose) will be encountered in clinical practice. Predictors of difficult mask ventilation include male gender, a beard, lack of teeth, age over 55 years, macroglossia, high body mass index, a history of snoring, increased Mallampati score, and low thyromental distance (46,47).

A history of sleep apnea does not seem to be a predictive sign of difficult mask ventilation (48). The airway in these patients may be improved by placing the head in the sniffing position (49).

The edentulous patient presents the most common problem. There is loss of bone of the alveolar ridge, causing a loss of distance between the points where the mask rests on the mandible and the nose. Furthermore, the buccinator muscle loses its tone in these patients. The cheeks sag, creating gaps between them and the mask. Alveolar process resorption results in shrinking at the corners of the mouth. Means to improve mask fit include inserting an oral airway, leaving the patient's dentures in place, packing the cheeks with gauze sponges, and inserting the inferior margin of the mask between the gingiva of the mandible and the lower lip (50,51).

Patients with facial deformities are particularly challenging. Mask application with the nasal projection pointed inferiorly has been used for children with certain facial deformities (3) and for patients with acromegaly (10).

If the mask is too small with an oral airway in place, the oral airway should be removed and a nasal airway used. If a mask is too long, the mouth can be elongated by inserting an oral airway.

If mask ventilation is necessary for the patient who has a nasogastric tube in place, there is usually a leak around the tube as it exits the side of the mask. This leak can be improved by adding denture adhesive around the tube at the point where it exits the mask (52).

Dead Space

The face mask and its adaptor normally constitute the major part

of the mechanical dead space. Dead space may be decreased by increasing the pressure on the mask, changing the volume of the cushion, using a smaller mask, extending the separation between the inspiratory and expiratory channels close to or into the mask, or blowing a jet of fresh gas into the mask. The leak induced with a poorly fitting face mask will reduce the dead space of the breathing system during spontaneous ventilation (53).

Mask Straps

A mask strap (mask holder, inhaler retainer, head strap, head harness, mask harness, mask retainer, headband, head-restraining strap) is used to hold the mask firmly on the face. Particular care needs to be paid to maintaining the airway when using a mask strap because obstruction is more likely to go unrecognized than when the mask is being held by the anesthesia provider's hand.

A typical mask strap (Fig. 16.8) consists of thin strips arranged in a circle with two or four projections. The head rests in the circle, and the straps attach around the mask connector. The straps at the jaw may tend to pull the jaw posteriorly. Crossing the two lower straps under the chin may result in a better fit and counteract the pull from the upper straps so that there is less tendency for the mask to creep up above the bridge of the nose (54). The best strap application is a matter of individual preference and may be the best result of a trial-and-error process (55).

Care must be taken that the straps are no tighter than necessary to achieve a seal in order to avoid pressure damage from the mask or the straps. They should be released periodically and the mask moved slightly. Gauze

sponges placed between the straps and the skin will help to protect the face from excessive pressure. Another risk of using a mask strap is that it will take longer to remove the mask if vomiting or regurgitation occurs.

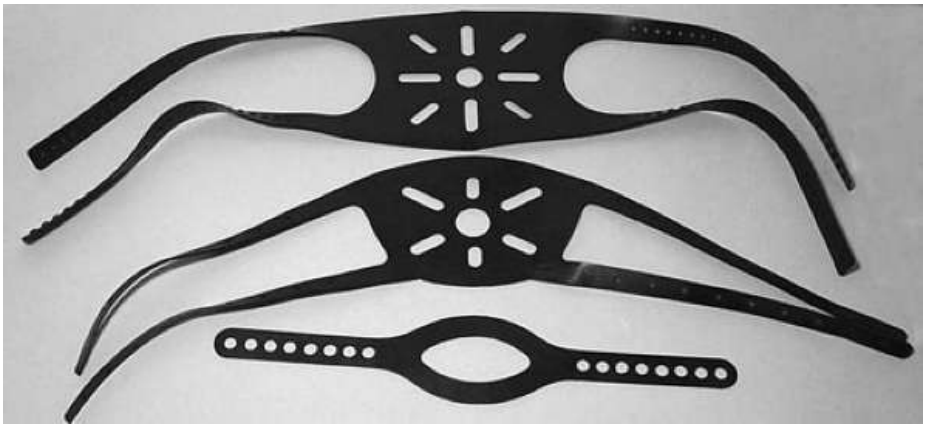

Figure 16.8 Mask straps.

Advantages

Using a face mask is associated with a lower incidence of sore throat and requires less anesthetic depth than using a supraglottic device or a tracheal tube. Muscle relaxants do not need to be used to tolerate the mask. The face mask may be the most cost-efficient method to manage the airway for short cases (56).

Disadvantages

With a face mask, one or more of the anesthesia provider's hands are in continuous use, and higher fresh gas flows are often needed. During remote anesthesia (magnetic resonance imaging and computerized tomography scanning) airway access is difficult. Compared with patients who are managed with a supraglottic airway device, patients who are managed with a face mask have more episodes of oxygen desaturation, require more intraoperative airway manipulations, and present more difficulties in maintaining an airway (57,58). In spontaneously breathing patients, the work of breathing is higher with a face mask than with a supraglottic airway device or a tracheal tube (59). Using an airway and/or continuous positive pressure will reduce the work of breathing.

Complications

Skin Problems

Dermatitis may occur if the patient is allergic to the material from which the mask is made (60). The pattern of the dermatitis follows the area of contact between the mask and skin. Chemical or gas sterilization of reusable masks can leave a residue that can cause a skin reaction (61,62). Pressure necrosis under the face mask has been reported following prolonged mask application in the presence of hypotension (1).

Nerve Injury

Pressure from a mask or mask strap may result in pressure injury to underlying nerves. Forward jaw displacement may cause a stretching nerve injury. Fortunately, the sensory and motor dysfunctions reported have been transient (63,64,65,66,67,68). If excessive pressure on the face or extreme forward jaw displacement must be exerted, tracheal intubation or a supraglottic airway device should be considered. The mask should be removed from the face periodically and readjusted to make certain that continuous pressure is not applied to one area.

Foreign Body Aspiration

The diaphragm of an endoscopic mask may rupture during tracheal tube insertion, and a piece may be pushed into the patient's tracheobronchial tree (69,70,71,72). Other parts of a mask or mask strap may be aspirated (73,74).

Gastric Inflation

When positive pressure ventilation is used with a face mask, gases are likely to enter the stomach (75,76). It is recommended that inspiratory pressure be kept below 20 cm H_2O (75).

Eye Injury

A corneal abrasion may be caused by a face mask inadvertently placed on an open eye (77). Chemicals that enter the mask cushion during cleaning and disinfection can be expelled from cracks in the cushion and come into contact with the eye when the mask is applied to the face (78,79,80,81). Pressure on the medial angles of the eyes and supraorbital margins may result in eyelid edema, chemosis of the conjunctiva, pressure on the

supraorbital or supratrochlear nerve, corneal injury, and temporary blindness from central retinal artery occlusion (82).

Mask Defects

A mask with a plastic membrane that occluded the connector has been reported (83). Another mask had a metal

wire sticking out of it (84). Incorrect assembly of a face mask has been reported (85).

Cervical Spine Movement

Most but not all studies show that mask ventilation moves the cervical spine more than commonly used methods of tracheal intubation (86,87,88,89). This may be of significance in the patient with an unstable cervical spine injury.

Latex Allergy

If rubber is a component of a face mask, a serious reaction can occur in the patient with latex allergy (90,91). This is discussed more fully in Chapter 15. Because of the seriousness of this problem, non-latex masks are recommended wherever possible.

Lack of Correlation between Arterial and End-tidal Carbon Dioxide

The difference between arterial and end-tidal carbon dioxide levels is higher with face mask ventilation than with a tracheal tube or supraglottic device, particularly with small tidal volumes (92).

Environmental Pollution

Studies show that using a face mask is associated with greater operating room pollution with anesthetic gases and vapors than when a tracheal tube or supraglottic airway device is used (93,94). Pollution can be reduced by using a close active scavenging device (95,96).

User Fatigue

Holding a mask securely onto the face and at the same time maintaining the correct jaw position can be difficult and may

result in operator fatigue. Failure to maintain the correct jaw position may result in loss of airway patency or gastric distention.

Jaw Pain

Postoperative jaw pain is more common after mask anesthesia than when a supraglottic airway device is used (97).

Airways

Purpose

A fundamental responsibility of the anesthesia provider is to maintain a patent airway. Unlike other maneuvers to maintain a patent airway, such as chin lift, jaw thrust, and tracheal intubation, cervical spine movement does not occur when an airway is inserted (98).

Figure 16.9A shows the normal unobstructed airway in a supine patient. The airway passage has a rigid posterior wall, supported by the cervical vertebrae, and a collapsible anterior wall, consisting of the tongue and epiglottis. Figure 16.9B shows the most common cause of airway obstruction. Under anesthesia, the muscles in the floor of the mouth and pharynx supporting the tongue relax, and the tongue and epiglottis fall back into the posterior pharynx, occluding the airway. The purpose of an airway is to lift the tongue and epiglottis away from the posterior pharyngeal wall and prevent them from obstructing the space above the larynx. Using maneuvers such as dorsiflexion at the atlanto-occipital joint and protrusion of the mandible anteriorly may still be necessary to ensure a patent airway (99). An oral or nasal airway decreases the work of breathing during spontaneous breathing using a face mask (59).

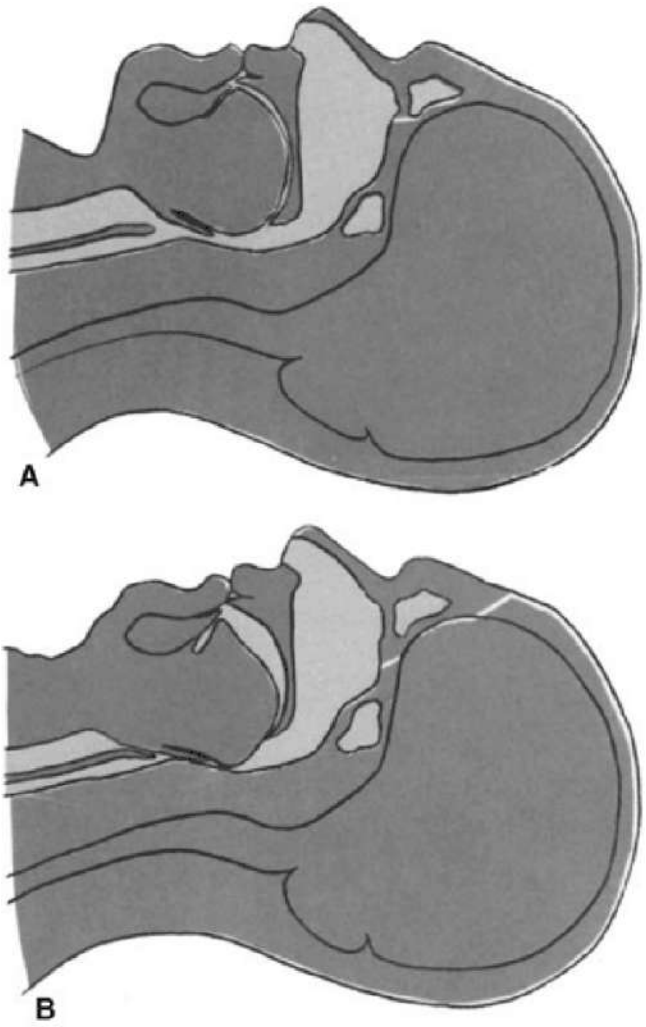

Figure 16.9 A: The normal airway. The tongue and other soft tissues are forward, allowing an unobstructed air passage. **B:** The obstructed airway. The tongue and epiglottis fall back to the posterior pharyngeal wall, occluding the airway. (Courtesy of V. Robideaux, M.D.)

Types

Oropharyngeal Airways

Figure 16.10 shows an oropharyngeal (oral) airway in place. The bite portion is between the teeth and lips, and the flange is

outside the lips. The pharyngeal end rests between the posterior wall of the pharynx and the

base of the tongue and, by exerting pressure along the base of the tongue, also pulls the epiglottis forward.

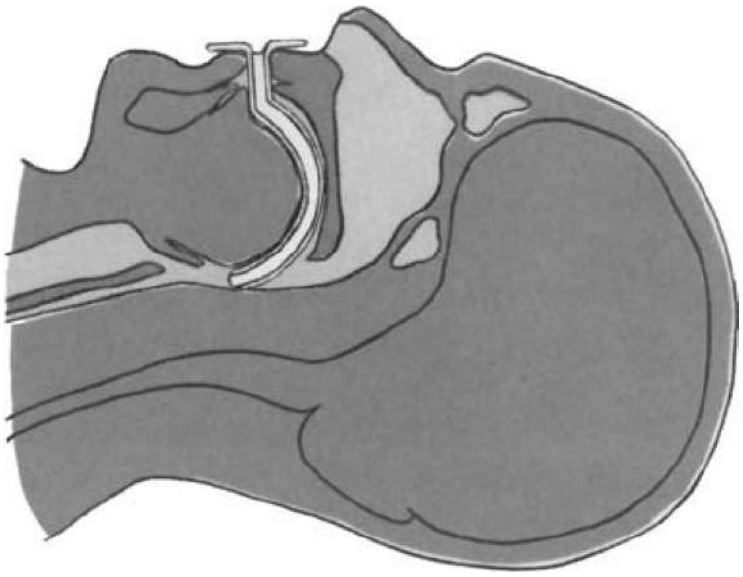

Figure 16.10 Oropharyngeal airway in place. The airway follows the curvature of the tongue, pulling it and the epiglottis away from the posterior pharyngeal wall and providing a channel for air passage. (Courtesy of V. Robideaux, M.D.)

In addition to helping to maintain an open airway, an oropharyngeal airway may be used to prevent a patient from biting and occluding an oral tracheal tube, protect the tongue from biting, facilitate oropharyngeal suctioning, obtain a better mask fit, or provide a pathway for inserting devices into the esophagus or pharynx (100). Oral airways have not been associated with an increased incidence of sore throat or other symptoms (101,102) or bacteremia (103).

Description

An oropharyngeal airway (Fig. 16.11) may be made of elastomeric material or plastic. It has a flange at the buccal end

to prevent it from moving deeper into the mouth. The flange may also serve as a means to fix the airway in place. The bite portion is straight and fits between the teeth or gums. It must be firm enough that the patient cannot close the lumen by biting. The curved portion extends backward to correspond to the shape of the tongue and palate.

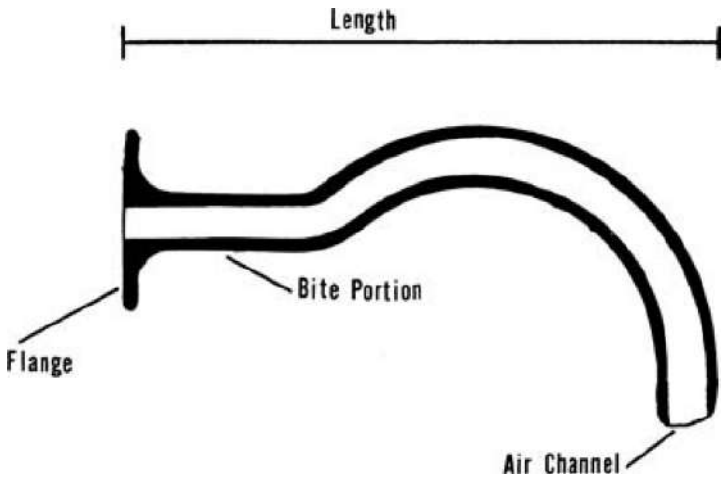

Figure 16.11 Oropharyngeal airway. All oral airways have a flange to prevent overinsertion, a straight bite block portion, and a curved section.

The American national standard (104) specifies that the size of oral airways be designated by a number that is the length in centimeters (Fig. 16.11).

Specific Airways

Guedel Airway

The Guedel airway (Fig. 16.12) has a large flange, a reinforced bite portion, and a tubular channel. Modifications to aid flexible fiberoptic intubation have been described (105,106,107,108).

Berman Airway

The Berman airway (Figs. 16.10, 16.11) has a center support and open sides. The center support may have openings. There is a flange at the buccal end. The side opening can be opened

wider to engage or disengage a tracheal tube.

Patil-Syracuse Endoscopic Airway

The Patil-Syracuse endoscopic airway was designed to aid fiberoptic intubation (109). It has lateral channels and a central groove on the lingual surface to allow a fiberscope with a tracheal tube to pass. A slit in the distal end allows the fiberscope to be manipulated in the anteroposterior direction but

limits lateral movement (110). It is made from aluminum. The airway must be removed from the oropharynx before a tracheal tube can be advanced over the fiberscope and into the glottis.

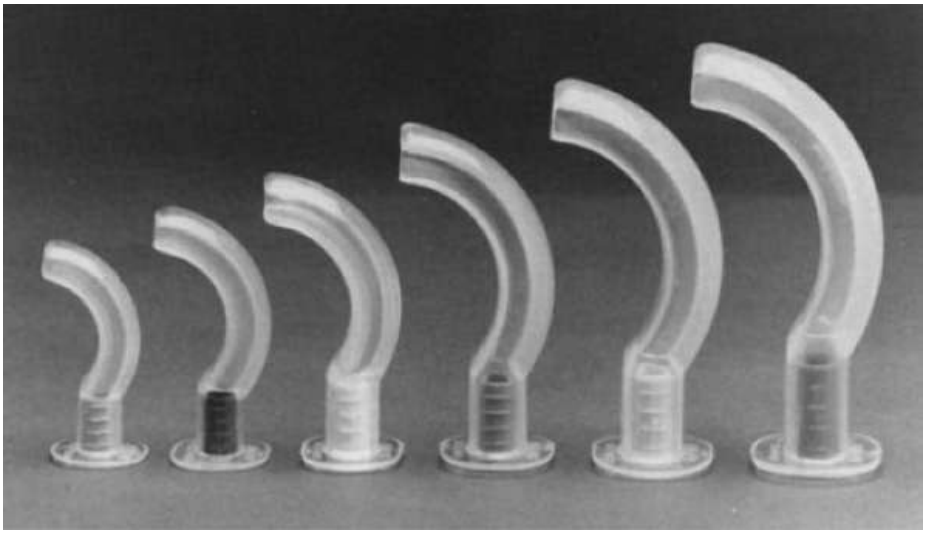

Figure 16.12 Guedel airways. The bite portions are color coded to provide easy identification of size. (Courtesy of Mercury Medical.)

Figure 16.13 Williams airway intubators. (Courtesy of Mercury Medical.)

Williams Airway Intubator

The Williams airway intubator was designed for blind orotracheal intubations (111,112,113). It can also be used to aid fiberoptic intubations or as an oral airway (114).

The airway, shown in Figure 16.13, is plastic and available in two sizes, #9 and #10, which will admit up to an 8.0 or 8.5 internal diameter (ID) tracheal tube, respectively. The tracheal tube connector should be removed during intubation, because it will not pass through the airway unless the airway is modified (115). The proximal half is cylindrical, while the distal half is open on its lingual surface.

A comparison of the Williams airway intubator with the Ovassapian fiberoptic intubating airway found that the Williams airway intubator provided a better view of the glottis in a significant number of patients (116).

Ovassapian Fiberoptic Intubating Airway

The Ovas-sapian fiberoptic intubating airway (Fig. 16.14) was designed to deliver a fiberscope as close to the larynx as

possible (110). It has a flat lingual surface that gradually widens at the distal end. At the buccal end are two vertical sidewalls. Between the sidewalls is a pair of guide walls that curve toward each other. The guide walls are flexible and permit the airway to be removed from around the tracheal tube. The proximal half is tubular so that it can function as a bite block. The distal half is open posteriorly. It will accommodate a tracheal tube up to 9.0 mm ID. Placing a black line along the middle of the airway helps to identify the midline and facilitates advancing the flexible endoscope (117,118,119).

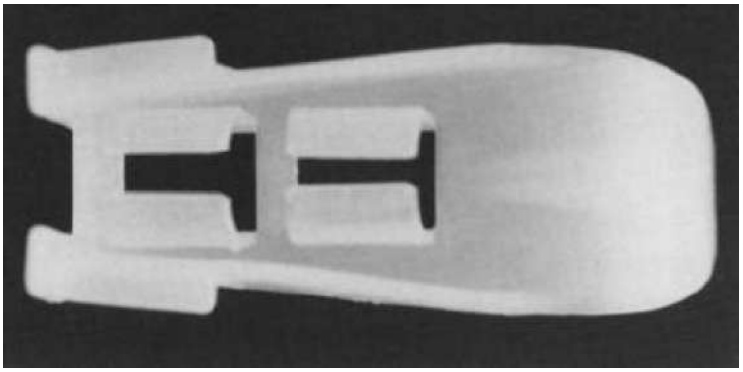

Figure 16.14 Ovassapian fiberoptic intubating airway. (Courtesy of A. Ovassapian, M.D.)

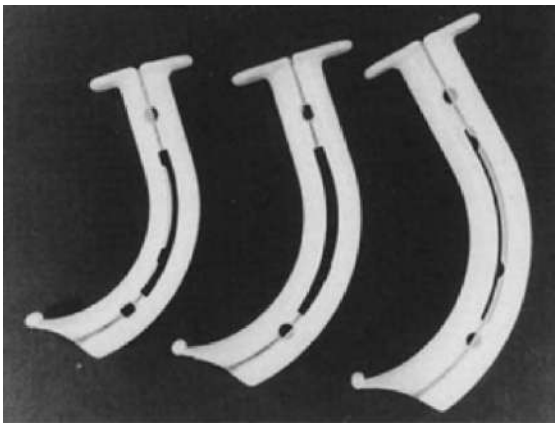

Figure 16.15 Berman intubation pharyngeal airways.

A comparison of this airway with the Williams airway intubator and the Berman intubating airway (see below) found that both other airways provided a good view of the glottis (116,120).

Berman Intubating/Pharyngeal Airway

The Berman intubating/pharyngeal airway (Berman II) (Fig. 16.15) is tubular along its entire length. It is open on one side so that it can be split and removed from around a tracheal tube. It can be used as an oral airway or as an aid to fiberoptic or blind orotracheal intubation (121). When the fiberscope is in the airway, the tip cannot be bent, limiting scope maneuverability. Partially withdrawing the airway will improve maneuverability (110).

One study found that the Berman airway offered an advantage over tongue retraction for fiberoptic intubation (122). Comparison with the Ovassapian intubating airway found that the Berman airway offers somewhat easier visualization of the cords (120). However, if the tracheal tube impinges on the airway, it is more difficult to complete the intubation with the Berman airway. Manipulating the Berman airway in place can lead to successful tracheal intubation (120).

Use

Pharyngeal and laryngeal reflexes should be depressed before an oral airway is inserted to avoid coughing or laryngospasm.

Selecting the correct size is important. Too small an airway may cause the tongue to kink and force part of

it against the roof of the mouth, causing obstruction. Too large an airway may cause obstruction by displacing the epiglottis posteriorly and may traumatize the larynx. The correct size can be estimated by holding the airway next to the patient's mouth. The tip should rest cephalad to the angle of the mandible. The best criteria for proper size and position are unobstructed gas exchange. If the airway repeatedly comes out of the mouth, it should be removed and a smaller size tried.

Figure 16.16 Insertion of oral airway. The airway is inserted 180ยฐ from the final resting position.

Wetting or lubricating the airway may facilitate insertion. The jaw is opened with the left hand. The teeth or gums are separated by pressing the thumb against the lower teeth or gum and the index or third finger against the upper teeth or gum.

One method to insert an airway is shown in Figure 16.16. The airway is inserted with its concave side facing the upper lip. When the junction of the bite portion and the curved section is near the incisors, the airway is rotated 180ยฐ and slipped behind the tongue into the final position. If resistance is met during insertion, it can usually be overcome by a jaw thrust.

An alternate method of insertion is shown in Figure 16.17. A tongue blade is used to push forward and depress the tongue. The airway is inserted with the concave side toward the tongue. As it is advanced, it is rotated to slide around behind the tongue.

If the airway has been used to facilitate fiberoptic intubation, it may be better to remove the airway after the fiberscope has entered the trachea because the airway might prevent the tracheal tube from passing into the trachea (123).

Bite Block

A bite block (gag, mouth prop, bite protector) is placed between the molar teeth or gums but not the incisors (124). It is intended to prevent the teeth from biting on a tracheal tube, supraglottic airway device, fiberscope, or other device. Not only will it protect these devices, but it may also avoid dental injury (125). A bite block is also used during electroconvulsive therapy and in unconscious individuals to protect the tongue and lips. An oral airway should not be used for these purposes (124,126,127). It is ineffective and may be harmful to the patient in this role because all the power of the bite is concentrated on the incisors, which are not designed for this pressure and are liable to break or loosen. Because a bite block does not extend into the pharynx, it is usually less irritating than an oral airway.

Figure 16.17 Alternative method of inserting an oral airway. A tongue blade is used to displace the tongue forward.

A variety of bite blocks have been developed (Figs. 16.18,16.19,16.20). Some have a channel for gas to pass. Many have an attached string that can be pinned to the

patient's gown or taped to the skin so that it can be easily retrieved. The curved portion of an oral airway can be removed, leaving the remaining portion as a bite block (128,129). A gauze roll is soft and allows pressure to be distributed over several

teeth (127). A bite block may be part of a device used to secure a tracheal tube.

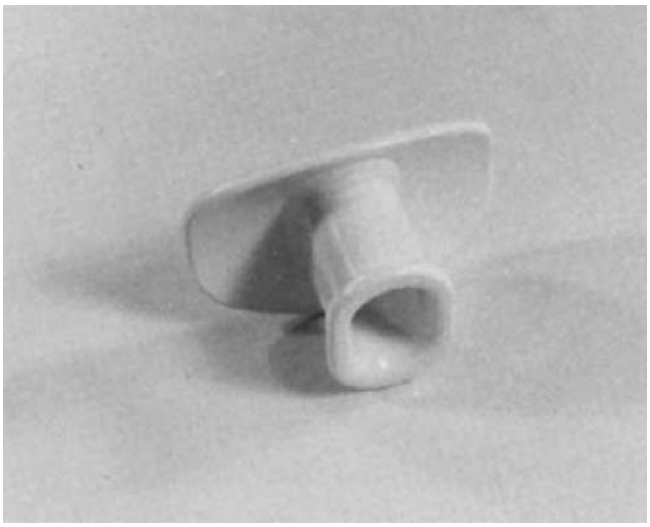

Figure 16.18 Bite block. This is placed between the teeth or gums (preferably in the molar area) to prevent occlusion of a tracheal tube or damage to a fiberoptic endoscope or to keep the mouth open for suctioning.

Figure 16.19 This bite block is designed to be placed between the molar teeth with the flat portion

extending toward the side of the face. The flat portion is used to grip for insertion and removal. (Picture courtesy of Hudson RCI.)

A bite block may become deformed so that it does not prevent biting (130). A bite block may be aspirated (130).

Nasopharyngeal Airways

A nasopharyngeal airway (nasal airway, nasal trumpet) is shown in position in Figure 16.21. When fully inserted, the pharyngeal end should be below the base of the tongue but above the epiglottis (131).

A nasal airway is better tolerated than an oral airway if the patient has intact airway reflexes. It is preferable to use a nasal airway if the patient's teeth are loose or in poor condition or there is trauma or pathology of the oral cavity. It can be used when the mouth cannot be opened.

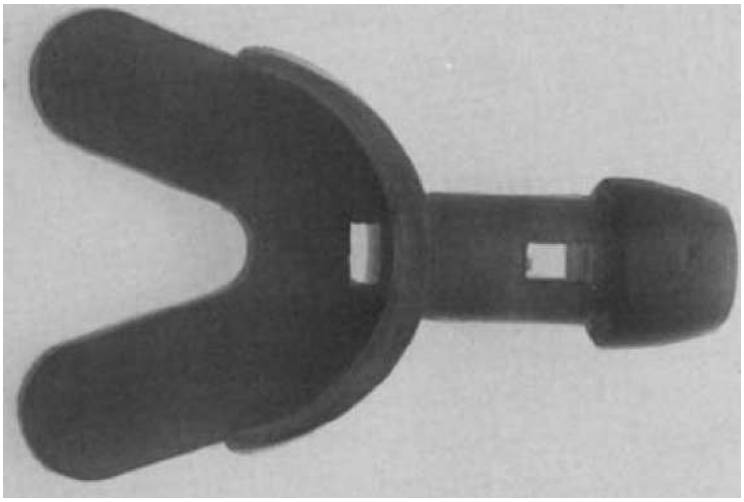

Figure 16.20 Oberto mouth prop, which is used for protecting the teeth during electroconvulsive therapy. (Courtesy of Rusch, Inc.)

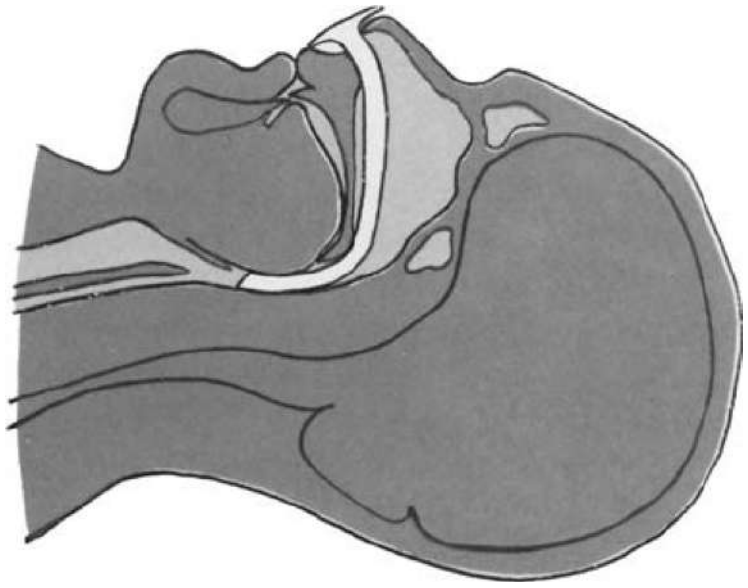

Figure 16.21 The nasopharyngeal airway in place. The airway passes through the nose and extends to just above the epiglottis. (Courtesy of V. Robideaux, M.D.)

Contraindications to using a nasopharyngeal airway include anticoagulation; a basilar skull fracture; pathology, sepsis, or deformity of the nose or nasopharynx; or a history of nosebleeds requiring medical treatment. There is no evidence that nasal airways cause significant bacteremia (103,132).

Nasopharyngeal airways have been used during and after pharyngeal surgery (133,134), in infants with Pierre Robin syndrome (135), to apply continuous positive airway pressure (CPAP) (136), to facilitate suctioning (137), as a guide for a fiberscope (137), to treat singultus (hiccups), as a guide for a nasogastric tube (138,139), to dilate the nasal passages in preparation for nasotracheal intubation (138) and as a means to maintain the airway and administer anesthesia during dental surgery (140).

A nasopharyngeal airway can be fitted with a tracheal tube connector and used with an anesthesia breathing system (141,142,143,144,145,146,147,148). These devices have been used to maintain ventilation during oral fiberoptic endoscopy (109) and to administer continuous positive pressure (136).

Environmental gas contamination may be a problem with this technique (149).

Description

A nasopharyngeal airway resembles a shortened tracheal tube with a flange at the outer end to prevent it from completely passing into the naris. Some airways come with a safety pin that can be inserted into the flange or airway wall (150). The flange is movable on some models. The American standard (104) requires that the size of a nasopharyngeal airway be designated by the inside diameter in millimeters.

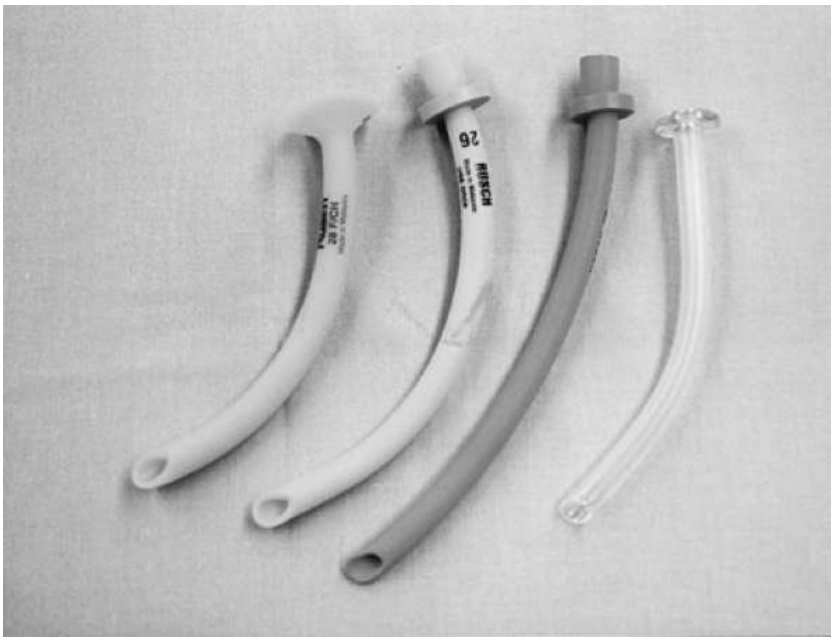

Figure 16.22 Nasopharyngeal airways. The one on the right does not contain latex.

Specific Airways

A variety of nasopharyngeal airways are available. Some are shown in Figure 16.22.

Linder Nasopharyngeal Airway

The Linder nasopharyngeal (bubble-tip) airway is shown in Figure 16.23. It is plastic with a large flange (151,152). The distal end has no bevel. The airway is supplied with an introducer, which has a balloon on its tip. The balloon can be inflated and deflated by attaching a syringe to the one-way valve at the other end of the introducer.

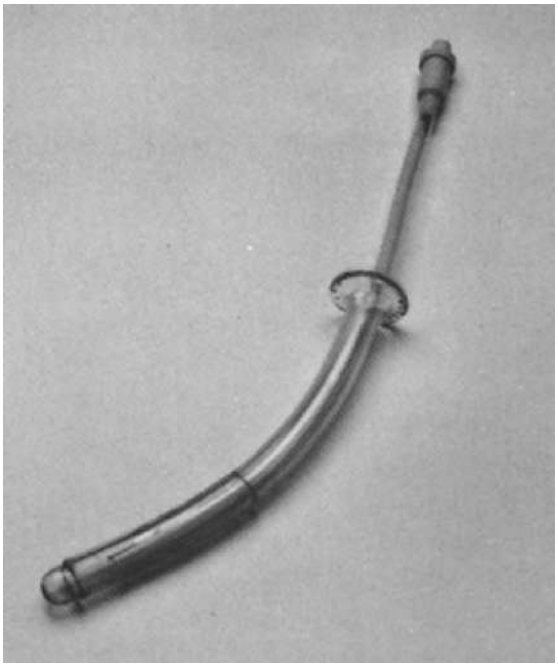

Figure 16.23 Linder nasopharyngeal airway. (Courtesy of Polamedco, Inc.)

Before insertion, the introducer is inserted into the airway until the tip of the balloon is just past the end. Air is injected until the balloon tip is inflated to approximately the outside diameter of the tube. The complete assembly is lubricated and then inserted through the nostril. After it is in place, the balloon is deflated and the introducer removed.

Cuffed Nasopharyngeal Airway

The cuffed nasopharyngeal (pharyngeal) airway is similar to a short cuffed tracheal tube (147,148,153). It is inserted through the nose into the pharynx, the cuff is inflated, and then is pulled

back until resistance is felt.

Binasal Airway

The binasal airway (Fig. 16.24) consists of two nasal airways joined together by an adaptor for attachment to the breathing system (154,155,156,157,158,159,160,161). It can be used to administer anesthesia or to provide CPAP to babies.

Insertion

The diameter of the nasal airway should be the same as needed to insert a tracheal tube (0.5 to 1 mm smaller than for an oral tracheal tube).

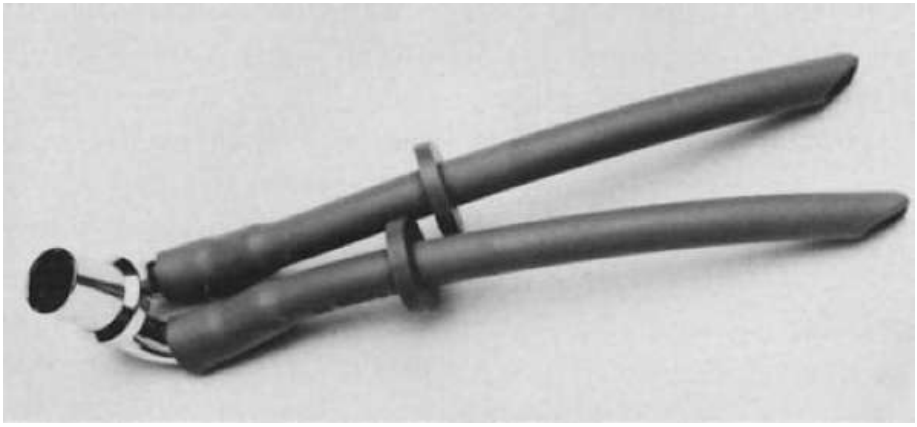

Figure 16.24 Binasal airway. (Courtesy of Rusch, Inc.)

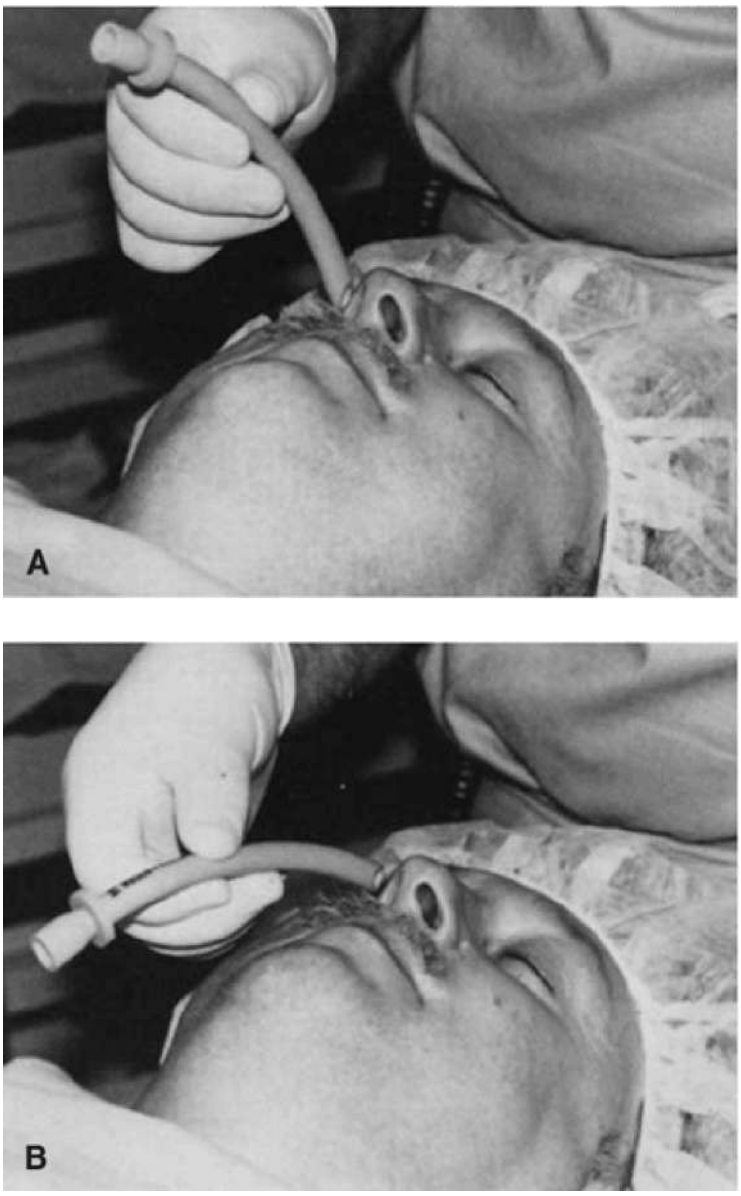

Figure 16.25 Insertion of a nasal airway. **A:** Correct method. The airway is inserted perpendicularly, in line with the nasal passage. **B:** Incorrect method. The airway is being pushed away from the air passage and into the turbinates.

Before insertion, the nasal airway should be lubricated thoroughly along its entire length. Each side of the nose should be inspected for size, patency, and the presence of polyps. A

vasoconstrictor may be applied before insertion to reduce trauma.

The nasopharyngeal airway should be inserted as shown in Figure 16.25A. The airway is held with the bevel against the septum and gently advanced posteriorly while being rotated back and forth. If resistance is encountered during insertion, the other nostril or a smaller size airway should be used. Figure 16.25B shows an incorrect method for inserting the airway. The airway is being pushed toward the roof of the nose.

The airway may be adjusted to fit the pharynx by sliding it in or out. If the tube is inserted too deeply, laryngeal reflexes may be stimulated; if too short, airway obstruction will not be relieved. Although the correct nasal airway length for a patient correlates with simple external measurements of the face and neck, studies indicate a correlation only with the patient's height (131).

Complications

Airway Obstruction

The tip of an airway can press the epiglottis or tongue against the posterior pharyngeal wall and cover the laryngeal aperture (162,163). With a nasopharyngeal airway, neck movement in rotation or anteroposteriorly may result in the lumen becoming obstructed (164). The use of a fenestrated airway may overcome this problem. The nasopharyngeal airway lumen may be compressed inside the nose (131).

A foreign body can enter an airway and cause complete or partial obstruction (165,166). In one case, the plastic packaging became stretched over the end of the airway, causing obstruction (167).

If a nasopharyngeal airway perforates the retropharyngeal space, the space may expand and cause airway obstruction (168).

Trauma

Injury to the nose and posterior pharynx is a potential complication of nasal airways. Epistaxis is usually self-limiting but can present a serious problem in some patients. To control severe nasal and nasopharyngeal bleeding, an epistaxis airway (Fig. 16.26) can be used. Pharyngeal perforation and

retropharyngeal abscess formation can occur (168). The lip or tongue may be caught between the teeth and an oral airway.

Tissue Edema

Facial, neck, or tongue edema, either unilateral or bilateral, can occur following surgery, especially in the sitting position, and can result in airway obstruction (169,170,171,172,173). Pressure from an oral airway may be a

contributing factor. To prevent this complication, the oral airway should not be left in place for an extended period. A bite block should be used instead. Excessive head or neck flexion should be avoided, and the head and neck should be checked frequently during long cases for edema or ecchymoses. Uvular edema possibly caused by the uvula becoming entrapped between the hard palate and an oropharyngeal airway has been reported (174). Another patient developed temporary deafness secondary to edema of the uvula and soft palate following prolonged nasopharyngeal airway use (175). Transient salivary gland swelling may occur with oral airway use (176,177).

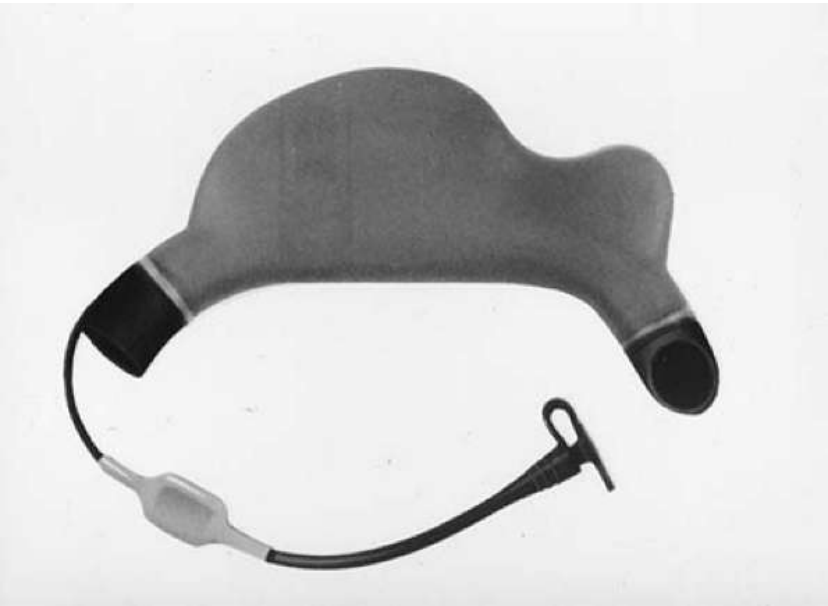

Figure 16.26 Epistaxis airway. This is inserted into the nose and inflated to provide local pressure on the bleeding site. It is available in several sizes. (Courtesy

of Rusch, Inc.)

Ulceration and Necrosis

Ulceration of the nose or tongue can occur if an airway remains in place for a long period of time (178).

Central Nervous System Trauma

The use of a nasal airway in a patient with a basilar skull fracture can result in its entering the anterior cranial fossa (179,180).

Dental Damage

Teeth can be damaged or avulsed if the patient bites down hard on an oral airway (181,182,183). An oral airway should be avoided if there is evidence of periodontal disease, teeth weakened by caries or restorations, crowns, fixed partial dentures, pronounced proclination (the front teeth having a forward inclination and overlapping the lower front teeth), or isolated teeth. In these cases, the use of a nasopharyngeal airway and/or a bite block between the back teeth may be preferable.

Laryngospasm and Coughing

Inserting an airway before adequate anesthetic depth is established may cause coughing or laryngospasm, especially if the airway contacts the epiglottis or vocal cords.

Retention, Aspiration, or Swallowing

Part or all of an airway may become displaced into the pharynx, tracheobronchial tree, or esophagus (184,185,186,187,188,189,190,191). Placing a safety pin through the nasal airway flange may prevent it from slipping into the nose (192).

Devices Caught in Airway

In one case, a cuff became detached when an esophageal stethoscope was removed from a patient with an oral airway in place (193). It was postulated that the cuff became caught in the

side grooves of the airway. Another case was reported where a fiberscope inadvertently traversed a fenestrated oral airway, making it impossible to pass a tracheal tube (194).

Equipment Failure

An oral airway may fracture at the connection between the bite portion and the curved section (195,196,197). A defect in the Williams intubating airway that could tear the tracheal tube cuff has been reported (198).

Latex Allergy

If an airway contains latex, a severe reaction may occur if the patient is sensitive to latex (90). Non-latex oral and nasal airways are readily identified and available. Chapter 15 provides more details on latex allergy.

Gastric Distention

A nasopharyngeal airway that is too long may enter the esophagus with resultant gastric distention (131).

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Questions

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

1. Complications associated with use of a face mask include

A. Movement of the cervical spine

B. Facial nerve injury

C. Chemical irritation of the eyes

D. Sinusitis

View Answer

2. Which maneuvers can be used to secure a patent airway?

A. Jaw thrust

B. Posterior protrusion of the mandible

C. Chin lift

D. Posterior flexion of the atlanto-occipital joint

View Answer

3. Airways developed to aid in fiberoptic intubation include

A. Patil-Syracuse

B. Williams

C. Ovassapian

D. Guedel airway

View Answer

4. Contraindications to nasal airways include

A. Hemorrhagic disorders

B. Sepsis

C. Basilar skull fracture

D. Seizure disorders

View Answer

5. Which external measurements correlate with the proper length of a nasal airway?

A. Tip of nose to 2 cm above the thyroid cartilage

B. The distance from the tip of the thumb to the tip of the index finger measured to the hand and back

C. Tip of the earlobe to cricoid cartilage

D. The patient's height

View Answer

6. Complications associated with the use of oral airways include

A. Swelling of the tongue

B. Edema of the uvula

C. Ulceration of the tongue

D. Swallowing of the airway

View Answer

7. Predictors of difficult mask ventilation include

A. High body mass index

B. Age over 65 years

C. History of snoring

D. History of sleep apnea

View Answer

8. Techniques to improve mask fit in the edentulous patient include

A. Packing the cheeks with gauze sponges

B. Not removing the dentures

C. Inserting the inferior margin of the mask between the gingiva of the mandible and the lower lip

D. Using a nasal airway

View Answer

,64,65,66,67,68,69,70,71).

,142,143,144,145,146,147,148).

58,259,260,261,262,263,264,265,266,267,268,269).

08,309,310,311,312,313,314,315,316,317,318),

3,434,435,436,437,438,439,440,441,442).

56,657,658,659,660,661,662,663,664,665,666,667,668,669,670,671,672,673,674,675).

,777,778,779,780,781,782,783,784).

,784,785,786,787,788,789,790,791,792,793,794,795,796,797,798,799,800,801,802,803,804,805,806,807,808,809,810,811,812,813,814,815,816,817,818,819,820,821,

878,879,880,881,882).

,890,891).

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5,1046,1047,1048,1049,1050).

089,1090,1091,1092,1093,1094,1095,1096,1097,1098,1099,1100,1101,1102,1103,1104,1105,1106,1107).

36,1137,1138,1139,1140,1141,1142,1143,1144,1145,1146,1147,1148,1149,1150).

1),

276,1277).

Chapter 18
Laryngoscopes

Laryngoscopes are used to view the larynx and adjacent structures, most commonly for the purpose of inserting a tube into the tracheobronchial tree. Other purposes include placing a gastric tube or transesophageal echocardiac probe, foreign body removal, and visualizing and assessing the upper airway. They range from simple rigid scopes with a light bulb to complex fiberoptic video devices. The wide range of available devices attests to the diverse difficulties encountered in their use.

Rigid Laryngoscopes

Description

Rigid laryngoscopes are manufactured either as a single-piece or a separate detachable blade and handle. In the latter case, the light source is either a lamp attached to the blade or a lamp in the handle with a light guide in the blade. For a detachable handle and blade, the light source is energized when the blade and handle are locked in the operating position. A hook-on (hinged, folding) connection between the handle and blade is most commonly used. The handle is fitted with a hinge pin that fits into a slot on the base of the blade. This allows the blade to be quickly and easily attached or detached. A single-piece laryngoscope has a switch on the handle that controls power to the lamp. Standards covering rigid laryngoscopes include the American Society for Testing and Materials (ASTM) F-965 and F-1195 and the International Standards Organization (ISO) 7376 (1,2,3).

Handle

The handle is the part held in the hand during use. It provides the power for the light. Most often, disposable batteries are the power source. Handles with rechargeable batteries are available (4). Fiberoptic-illuminated laryngoscopes may use a remote electrically operated light source. Most handles are designed to

accept either fiberoptic-illuminated or lamp-in-bulb blades, but some can accept either one.

Handles designed to accept blades that have a light bulb have a metallic contact, which completes an electrical circuit when the handle and blade are in the working position. Handles containing batteries and using fiberoptic illumination contain a halogen lamp bulb. When the handle and blade are locked in the working position, an activator switch is depressed. This provides a connection between the bulb and the batteries. A halogen lamp bulb has a longer life than other light bulbs. Studies have shown that the illumination is better with lamp-in-blade than fiberoptic systems (5,6,7,8).

Handles are available in several sizes (Fig. 18.1). The surface is usually rough for improved grip. Short handles may be advantageous for patients in whom the chest and/or breasts contact the handle during use, when cricoid pressure is being applied, or when the patient is in a body cast (9). Another technique for handling this situation is to insert the blade laterally into the mouth,

then to advance and rotate it until it is in a midline position (10,11).The blade can be detached from the handle before it is inserted into the mouth and then can be attached to the handle after it is placed (12).

Figure 18.1 Laryngoscope handles. (Courtesy of Rusch, Inc.)

Although most blades form a right angle with the handle when ready for use, the angle may also be acute or obtuse. An adapter may be fitted between the handle and the blade to allow the angle to be altered (13,14,15) (Fig. 18.1). The Patil-Syracuse handle (Fig. 18.2) can be positioned and locked in four different positions (16).

Some handles allow the bulb and battery portion to be removed as a unit. This allows the outer part of the handle to be cleaned and disinfected or sterilized.

Blade

The blade is the component that is inserted into the mouth. When a blade is available in more than one size, the blades are

numbered, with the number increasing with size. Table 18.1 shows the appropriate size markings according to the ISO standard (3). Disposable blades are available (Fig. 18.3).

The blade is composed of several parts, including the base, heel, tongue, flange, web, tip, and light source (Fig. 18.4).

Figure 18.2 Patil-Syracuse handle. With this handle, the blade can be adjusted and locked in four different positions (45ยฐ, 90ยฐ,135ยฐ, or 180ยฐ). (Courtesy of Mercury Medical.)

The base is the part that attaches to the handle. It has a slot for engaging the hinge pin of the handle. The end of the base is called the *heel*.

The tongue (spatula) is the main shaft. It serves to compress and manipulate the soft tissues (especially the tongue) and lower

jaw. The long axis of the tongue may be straight or curved in part or all of its length. Blades are commonly referred to as curved or straight, depending on the predominant shape of the tongue. In general,

straight blades provide better laryngeal visualization, while curved blades make intubation easier (17). When a satisfactory view is obtained but intubation is difficult, the use of a bougie or a stylet (Chapter 19) may be helpful (18).

TABLE 18.1 Size Markings for Laryngoscopes

Marking	*Intended Use*
000	Small premature infant
00	Premature infant
0	Neonate
1	Small child
2	Child
3	Adult
4	Large adult
5	Extra-large adult

From International Standards Organization. Anaesthetic and respiratory equipmentℓ€”-laryngoscopes for tracheal intubation (ISO 7376). Geneva, Switzerland: Author, 2003.

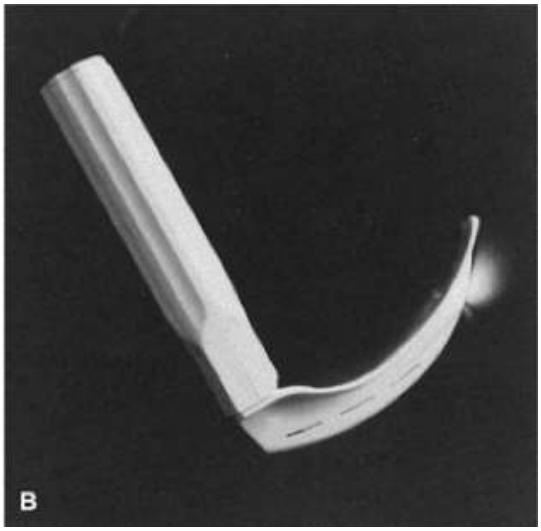

Figure 18.3 A: Reusable handle with curved (Macintosh) and straight (Miller) disposable blades. **B:** Disposable handle and blade. (Courtesy of Rusch, Inc. and Vital Signs.)

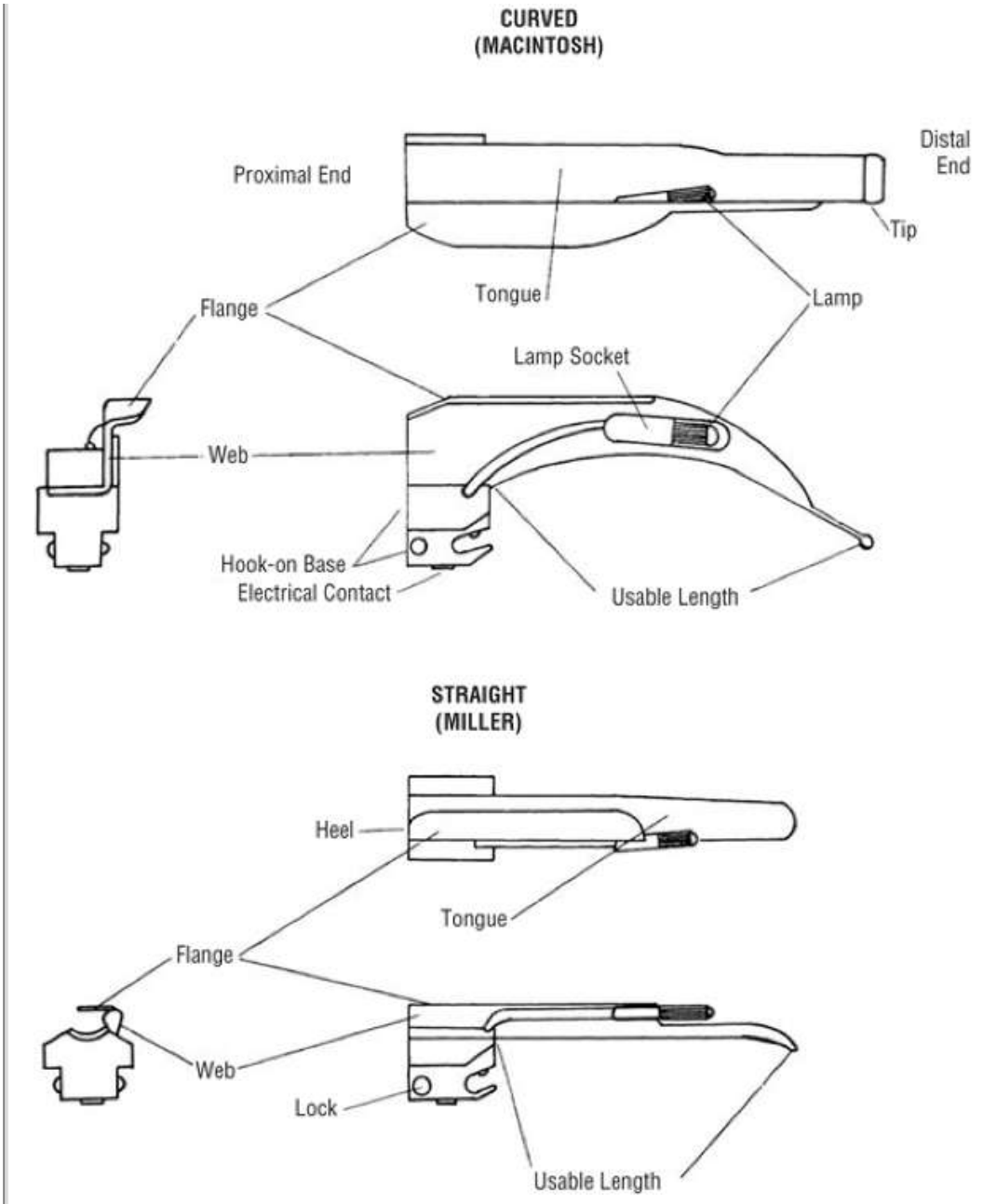

Figure 18.4 The parts of the Macintosh **(top)** and the Miller **(bottom)** blades are illustrated. The tip is the distal end of the blade intended for insertion into the patient. The proximal end is the part closest to the handle. (Redrawn from a drawing in Committee, American National Standards Institute. Draft standard, laryngoscopes for tracheal intubation (Z-79). Philadelphia: ASTM.)

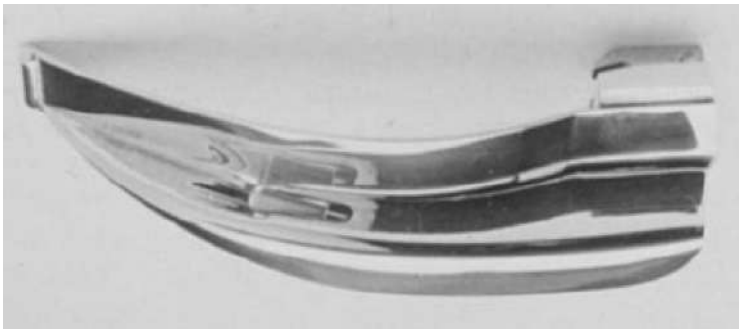

Figure 18.5 Left-handed Macintosh blade. (Courtesy of Penlon Ltd.)

The flange projects off the side of the tongue and is connected to it by the web. It serves to guide instrumentation and deflect tissues from the line of vision. The flange determines the cross-sectional shape of the blade. The vertical height of the cross-sectional shape of a blade is sometimes referred to as the step (19).

The tip (beak) contacts either the epiglottis or the vallecula and directly or indirectly elevates the epiglottis. It is usually blunt and thickened to decrease trauma.

The blade may have a lamp (bulb) (Fig. 18.5) or a fiberoptic bundle that transmits light from a source in the handle (Fig. 18.6). The lamp screws into a socket that has a metallic contact. On most blades, the socket is located near the tip. When the blade is in the working position, electrical contact with the power source in the handle is made. The socket is subject to soiling by fluids that can affect the electrical contacts, causing the light to fail.

A fiberoptic-illuminated blade has an encased fiberoptic bundle that transmits light from a source in the handle or the base of the blade. Because there is no bulb or electrical contact in the blade, cleaning and sterilization are easier. The ISO standard (3) requires fiberoptic-illuminated blades to have a green mark on the heel.

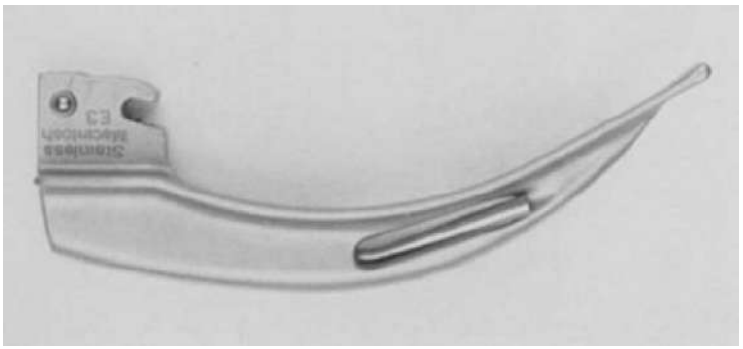

Figure 18.6 English Macintosh blade. (Courtesy of Welch Allyn, Inc.)

In most cases, using a laryngoscope presents little or no difficulty to the experienced operator, and skill is of more importance than the type of blade employed. There are, however, situations in which a certain blade may be particularly advantageous (20). These situations have led to the development of a number of different blades. The blades discussed here are all available commercially in the United States at the time of this writing. A number of other blades have been described in the literature.

Macintosh Blade

The Macintosh (Figs. 18.3, 18.4, 18.14, 18.15) is one of the most popular blades (21,22,23). The tongue has a gentle curve that extends to the tip. In cross section, the tongue, web, and flange form a reverse Z. Numerous modifications have been suggested (24,25,26,27,28,29,30,31,32,33,34,35,36,37). The no. 4 blade may be more useful than the no. 3 in normal and large-sized adults (38).

Cervical spine movement is greater with the Macintosh blade compared with the Miller blade, a lightwand, or the GlideScope (39,40,41,42).

Left-handed Macintosh Blade

The left-handed (reversed) Macintosh blade (Fig. 18.5) has the

flange on the opposite side from the usual Macintosh blade (43). This blade may be useful for abnormalities of the right side of the face or oropharynx, left-handed intubators, individuals with limited use of the left arm, intubating in the right lateral position, or positioning a tracheal tube directly on the left side of the mouth (44,45,46,47,48).

English Macintosh

The English Macintosh (Fig. 18.6) is similar to the conventional Macintosh except the flange is curved and lower at the handle end. Two studies have found that this blade provided better results than other commonly used blades (49,50).

A modification is shown in Figure 18.7. It has a reduced flange to decrease pressure on the maxillary incisors.

Figure 18.7 English Macintosh blade with reduced flange.

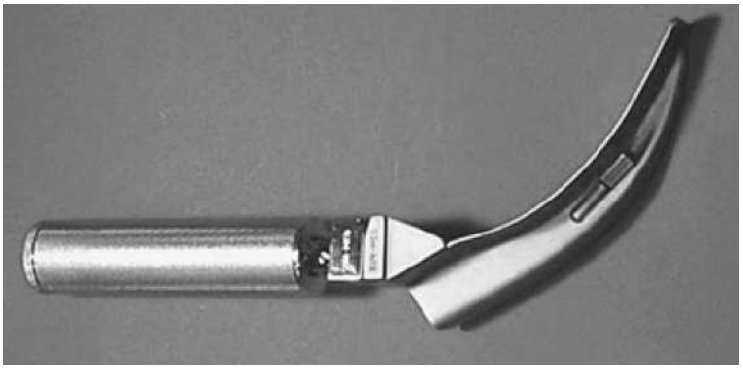

Figure 18.8 The polio blade. (Courtesy of Sun Med.)

Polio Blade

The polio blade (Fig. 18.8) is also a modification of the Macintosh. The blade is offset from the handle at an obtuse angle to allow intubation in iron lung respirators or body jackets; after the anesthesia screen is in place; and of patients with obesity, breast hypertrophy, kyphosis with severe barrel chest deformity, a short neck, or restricted neck mobility (51,52). Disadvantages of this blade are that little force can be applied, and control is minimal (12).

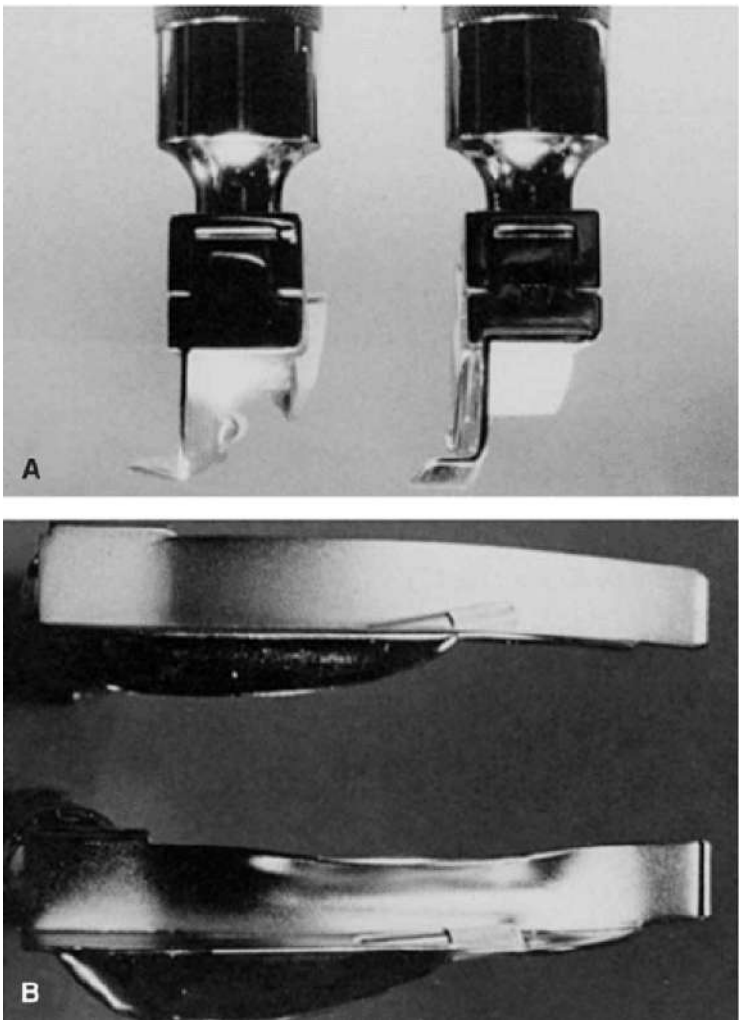

Figure 18.9 A: The improved vision (IV) Macintosh blade **(left)** and the conventional Macintosh blade **(right)**. Note the improved vision when the blade is viewed from the proximal end. **B:** Conventional Macintosh blade **(top)** and the IV Macintosh blade **(bottom)**. On the IV Macintosh, the midportion of the spatula is concave. (Courtesy of Gabor B. Racz, M.D.)

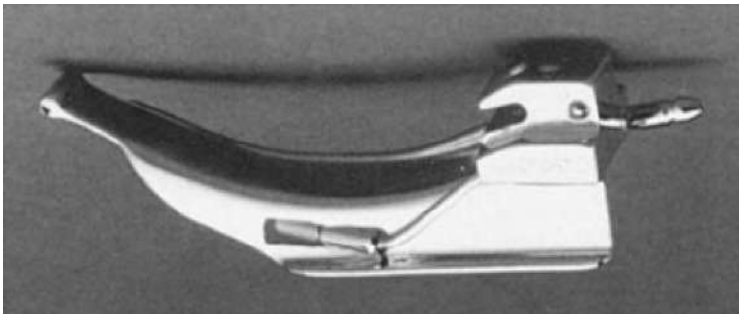

Figure 18.10 The oxiport Macintosh blade. (Courtesy of Mercury Medical.)

Improved Vision Macintosh Blade

The improved vision (IV) Macintosh blade (Fig. 18.9) is similar to the standard version except that the midportion of the tongue is concave (36,53).

Oxiport Macintosh (Mac/Port)

The Oxiport Macintosh blade (Fig. 18.10) is a Macintosh blade with a tube added to deliver oxygen.

Tull Macintosh

The Tull (suction) blade (Fig. 18.11) is a modified Macintosh that has a suction port near the tip. The suction channel extends next to the handle and has a finger-controlled valve so that suction can be controlled by the laryngoscopist.

Fink Blade

The Fink blade (Fig. 18.12) is another modification of the Macintosh. The tongue is wider and has a sharper curve at the distal end. The height of the flange is reduced, especially at the proximal end. The light bulb is placed farther forward than on the conventional Macintosh blade.

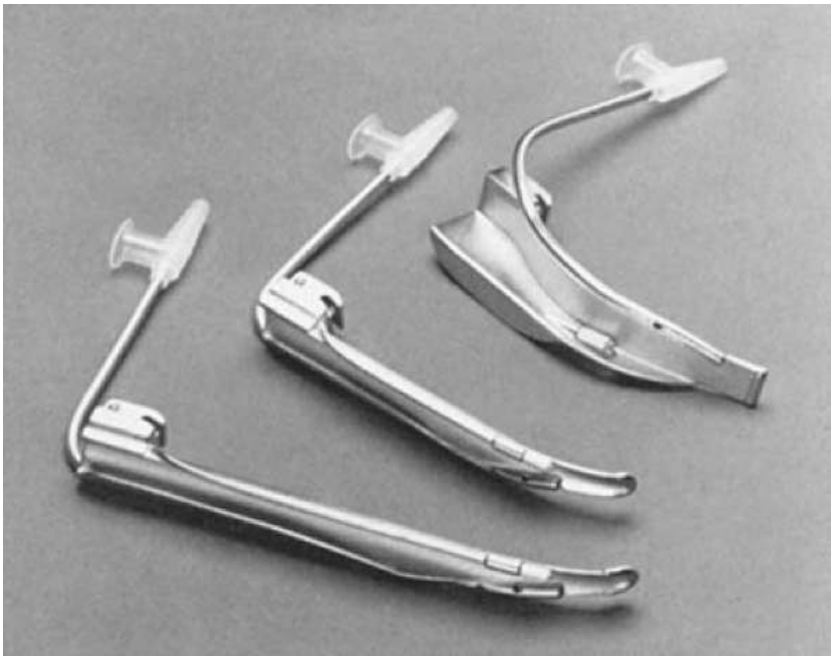

Figure 18.11 Tull (suction) Macintosh and Miller blades. The finger-controlled valve allows suction to be regulated by the laryngoscopist. (Courtesy of Mercury Medical.)

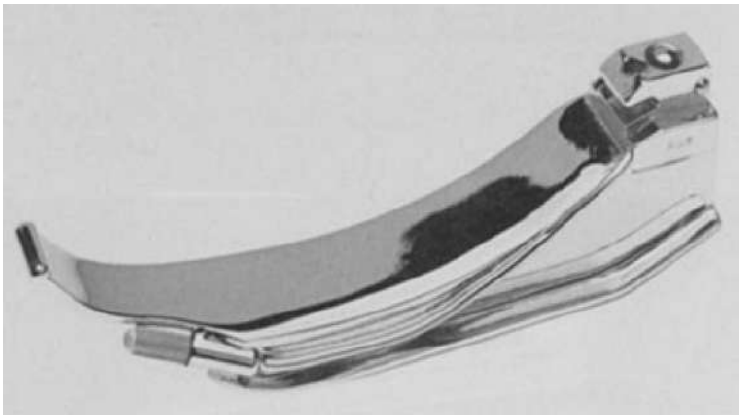

Figure 18.12 The Fink blade. Note that the tongue is more curved at the tip, and the flange is reduced at the proximal end compared with the Macintosh blade. The light bulb is placed nearer the distal end.

(Courtesy of Puritan-Bennett Corp.)

Bizzarri-Giuffrida Blade

The Bizzarri-Giuffrida blade (flangeless Macintosh) (Fig. 18.13) is a modified Macintosh on which the flange is removed, except for a small part that encases the light bulb (20,36,54). This modification was made to limit damage to the upper teeth. The blade is designed for patients with a limited mouth opening, prominent incisors, receding mandible, short and thick neck, or anterior larynx.

Upsher Low Profile

The Upsher low profile (ULP) blade (Fig. 18.14) is a modified Macintosh with a low flange and a fairly straight proximal section that leads to a tip with a significant curve. It is designed for insertion into a small mouth.

Upsher ULX Macintosh Blade

The ULX blade (Fig. 18.15) has a little more curve than the standard Macintosh blade.

Miller Blade

The Miller (Figs. 18.3, 18.4, 18.16) is one of the most popular blades (55). The tongue is straight with a slight upward curve near the tip. In cross section, the flange, web, and tongue form a C with the top fattened. Some versions of the blade have the lamp socket on the tongue, while others have it on the web. The lamp may be on either the right or left side of the blade. If the bulb is on the left side, the bulb is easier to change but can be covered by the tongue. Placing the bulb on the right side allows it to be protected by the flange (56). Several modifications have been described (57,58,59,60,61).

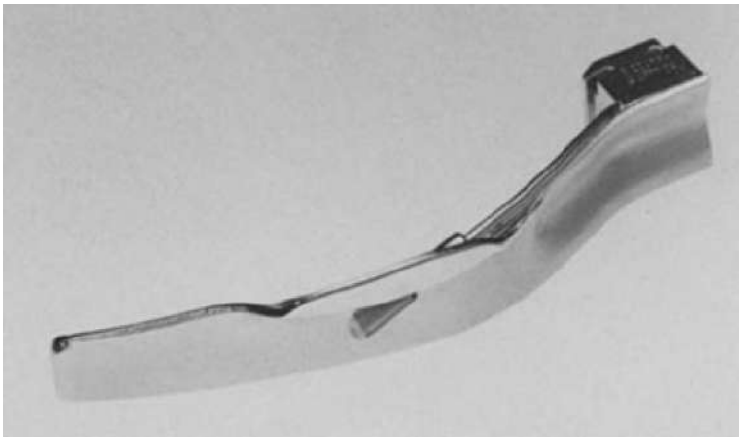

Figure 18.13 The Bizzarri-Giuffrida blade. (Courtesy of Puritan-Bennett Corp.)

Figure 18.14 Upsher low profile blade. **Top:** A standard Macintosh blade. **Bottom:** A ULP blade.

In comparing the Macintosh and Miller blades, it was found that force, head extension, and cervical spine movement were less with the Miller (39,40,41).

Oxiport Miller Blade

The Oxiport Miller (Miller/port, oxyscope) blade (Fig. 18.17) has a built-in tube that allows delivery of oxygen during intubation (62,63,64). It may also be used for suctioning. When using this blade, oxygen insufflation during intubation has been found to lessen oxygen desaturation in spontaneously breathing anesthetized patients (65,66).

Tull Miller Blade

The Tull (suction) Miller blade is a standard Miller blade with a suction tube whose port ends near the blade tip (Fig. 18.11). Near the handle is a finger-controlled port that allows suction to be controlled.

Mathews Blade

The Mathews blade (Fig. 18.18) is straight with a wide and flattened petalloid configuration at the tip. It is designed for difficult nasotracheal intubations.

Wisconsin Blade

Unlike the Miller blade, the Wisconsin blade's tongue has no curve (Fig. 18.19). The flange is curved to form two thirds of a circle in cross section

(20). The flange depth is narrow at the proximal end and is wider in the distal portion.

Figure 18.15 ULX blade. The ULX blade is at the top. A standard Macintosh blade is at the bottom. (Picture courtesy of Mercury Medical.)

The Whitehead modification of the Wisconsin blade (Figs. 18.20, 18.40) has a reduced flange and is open proximally and distally.

Wis-Foregger Blade

The Wis-Foregger blade (Fig. 18.21) is a modification of the Wisconsin blade, with a straight tongue and a flange that expands slightly toward the distal end (67). The distal portion of the blade is wider and formed slightly to the right.

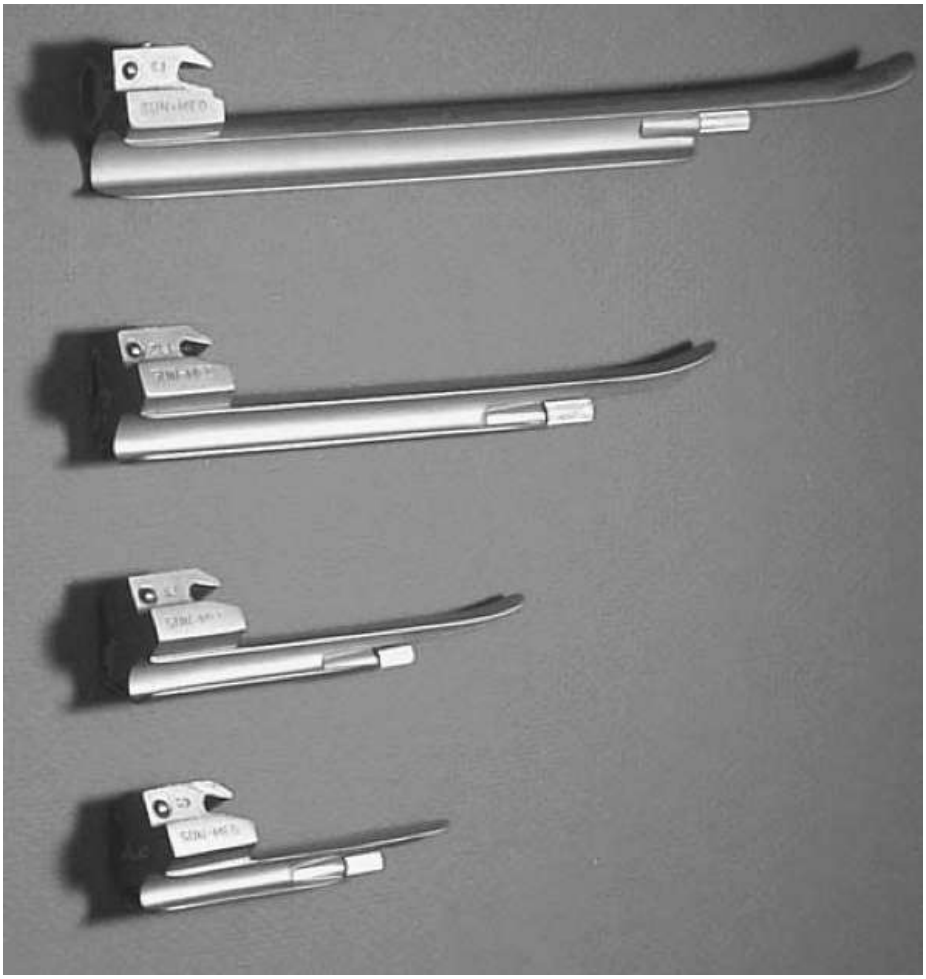

Figure 18.16 Miller blades. (Courtesy of Sun Med.)

Wis-Hipple Blade

The Wis-Hipple blade (Fig. 18.22) is a modified Wisconsin blade. The tongue is straight, and

the flange is large and circular. Compared with the Wisconsin blade, the flange is straighter and runs parallel to the tongue and the tip is wider. It is designed primarily for use in infants.

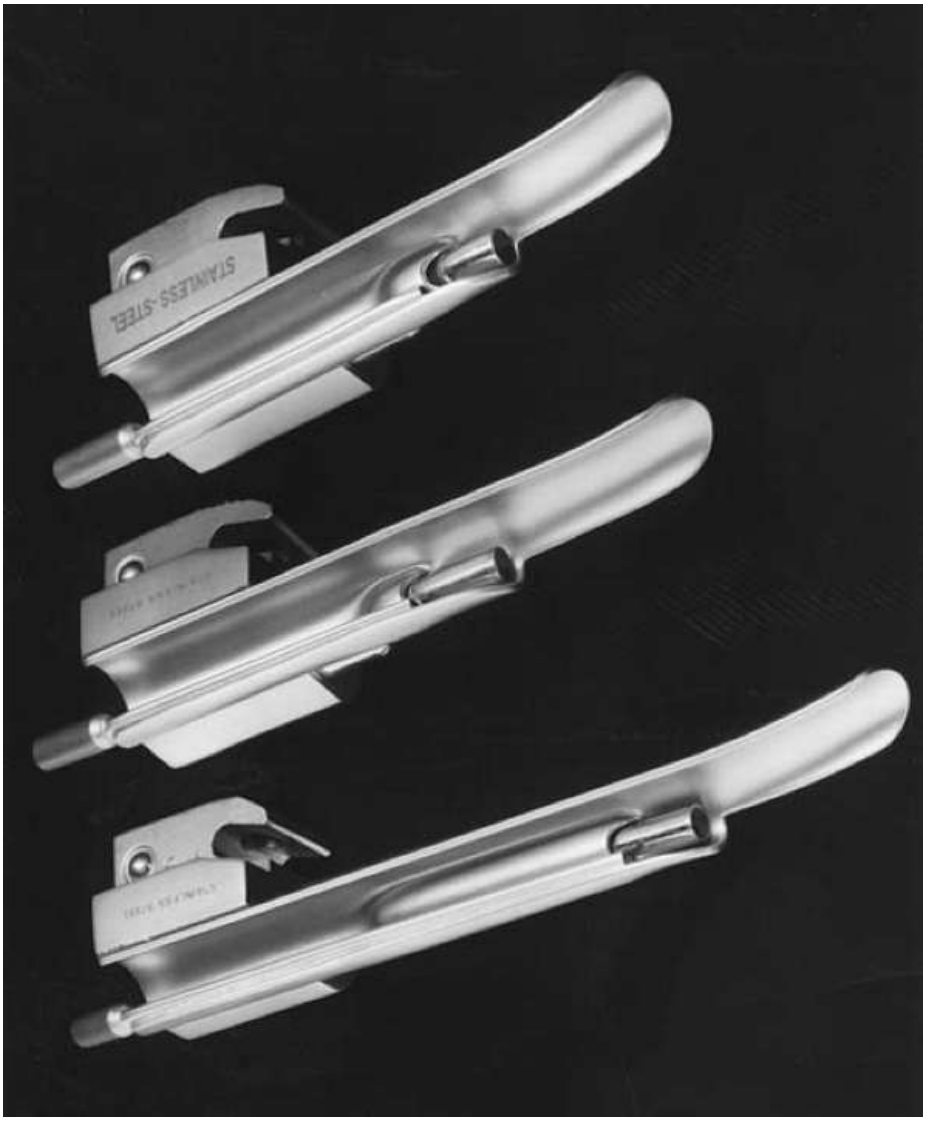

Figure 18.17 Oxiport Miller blades. (Courtesy of Rusch, Inc.)

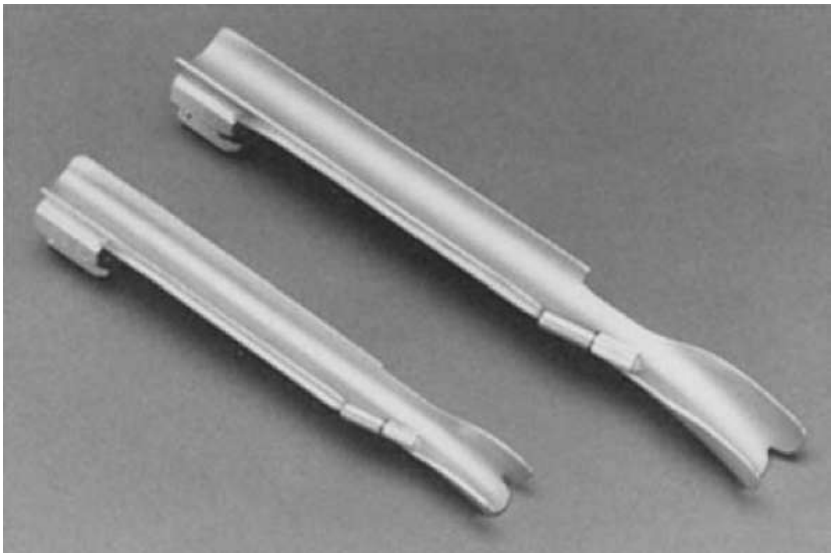

Figure 18.18 The Mathews blade. (Courtesy of Mercury Medical.)

Schapira Blade

The Schapira blade (Fig. 18.23) is a straight blade with a tip that curves upward (68). The vertical component is minimal.

Alberts Blade

The Alberts blade (Fig. 18.24) combines characteristics of the Miller and Wis-Hipple blades with a cut-away flange to increase visibility. There is a recess to facilitate tracheal tube insertion. The blade forms a 67-degree angle with the handle. It is used for pediatric patients.

Michaels Blade

The Michaels blade (Fig. 18.24) differs from the Alberts blade only in that it forms a 93-degree angle with the handle.

Soper Blade

The Soper blade (Fig. 18.25) combines the Z shape on the flange of the Macintosh blade with a straight blade (20,69). It has a slot built into the tip, which is intended to prevent the epiglottis from slipping off the blade.

Heine Blade

The Heine blade (Fig. 18.26) is straight with a slight upward curve at the tip. The flat flange is curved away from the blade. It is useful for children with large tongues.

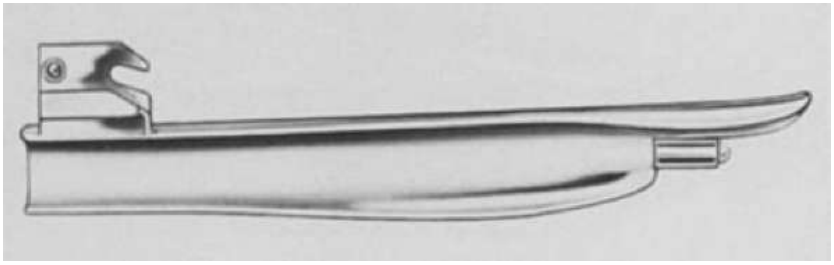

Figure 18.19 The Wisconsin blade. (Courtesy of Ohio Medical Products, a division of Airco, Inc.)

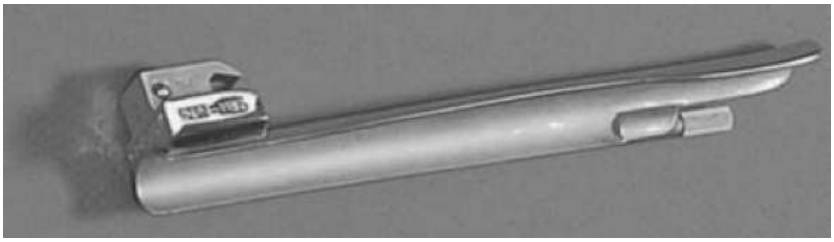

Figure 18.20 Whitehead modification of Wisconsin blade. (Courtesy of Sun Med.)

Snow Blade

The Snow blade (Fig. 18.27) is a hybrid blade consisting of a Miller tongue and a Wis-Foregger flange (70). It is curved 1 inch from the tip.

Flagg Blade

The Flagg blade (Fig. 18.28) has a straight tongue. The flange has a C shape that gradually decreases in size as it approaches the distal end.

Guedel Blade

The Guedel blade (Fig. 18.29) is a straight blade on which the tongue is set at a 72ยฐ angle to the handle. The flange has the shape of a U on its side. The light is close to the tip, which has an uptilt of 10ยฐ.

Bennett Blade

The Bennett blade (Fig. 18.30) is a modification of the Guedel blade. It also forms an acute angle with the handle. The upper part of the flange has been omitted.

Eversole Blade

The Eversole blade (Fig. 18.31) has a straight tongue. The flange forms a C with the tongue and web near the proximal end. Midway to the tip, the upper flange tapers.

Seward Blade

The Seward blade (Fig. 18.32) has a straight tongue with a curve near the tip (71). It has a small reverse Z-shaped flange. The blade is useful for nasotracheal intubation because its shape allows a Magill forceps to be introduced with minimum loss of view. It is intended for use in children younger than 5 years old.

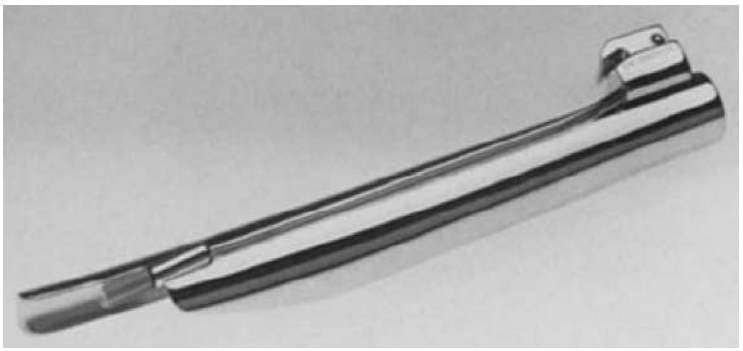

Figure 18.21 The Wis-Foregger blade. (Courtesy of Puritan-Bennett Corp.)

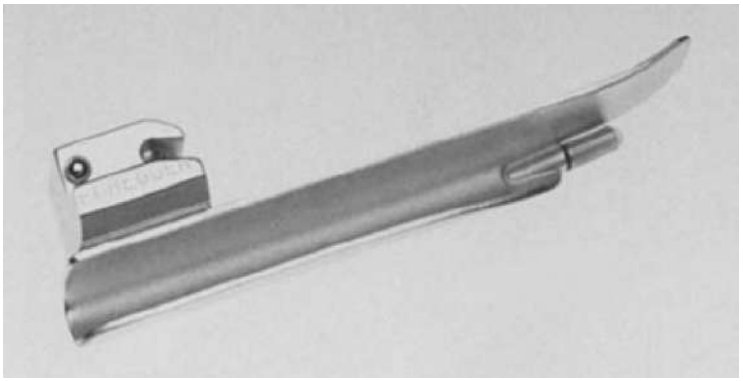

Figure 18.22 The Wis-Hipple blade. (Courtesy of Puritan-Bennett Corp.)

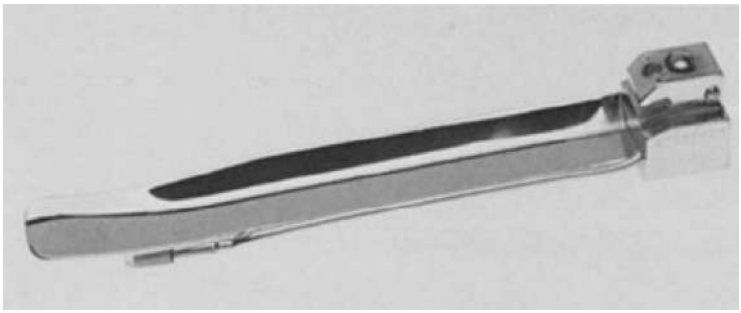

Figure 18.23 The Schapira blade. (Courtesy of Puritan-Bennett Corp.)

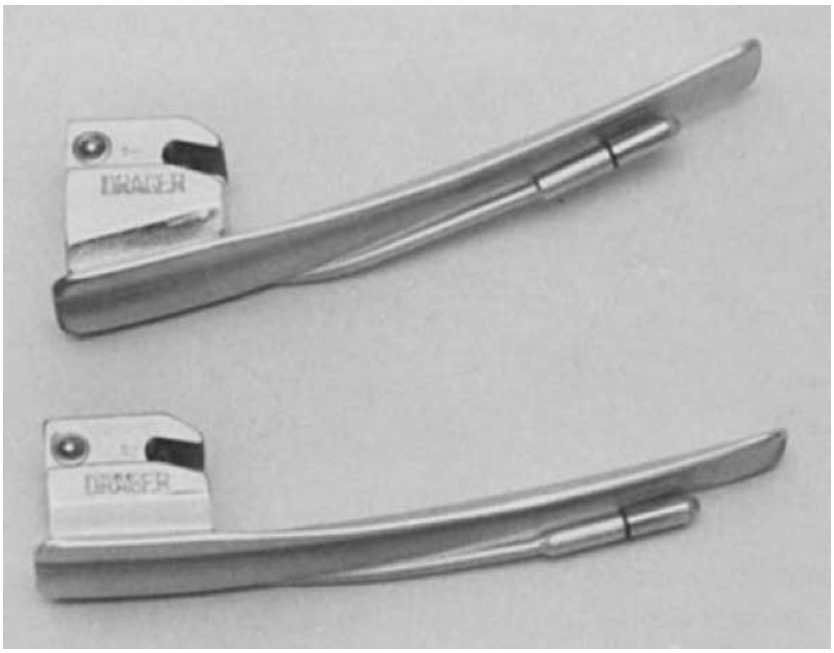

Figure 18.24 The Alberts **(top)** and Michaels **(bottom)** blades. The Alberts blade offers a sharp 67ยฐ angle, whereas the Michaels blade has a slight 93ยฐ angle. (Courtesy of North American Drager.)

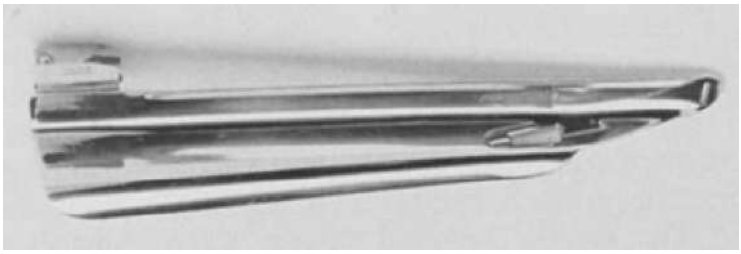

Figure 18.25 The Soper blade. (Courtesy of Penlon Ltd.)

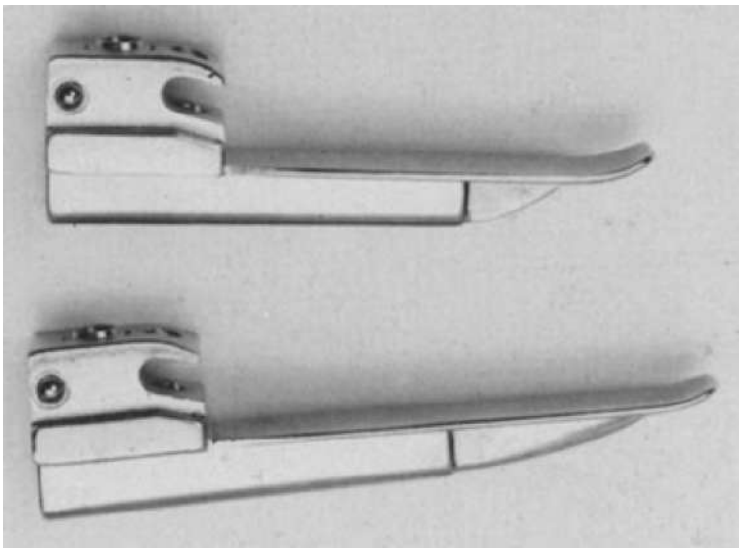

Figure 18.26 Heine blades. (Courtesy of Heine Ototechnic Manufacturing Co., Inc.)

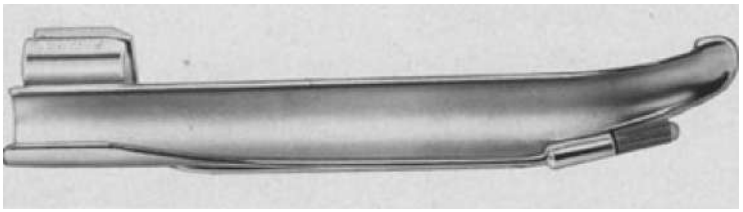

Figure 18.27 The Snow blade. (Courtesy of Air Products and Chemicals, Inc.)

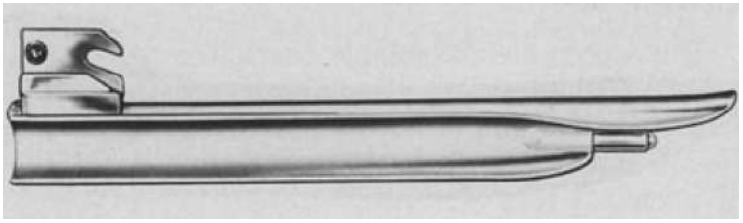

Figure 18.28 The Flagg blade. (Courtesy of Ohio Medical Products, a division of Airco, Inc.)

Figure 18.29 The Guedel blade. (Courtesy of Penlon Ltd.)

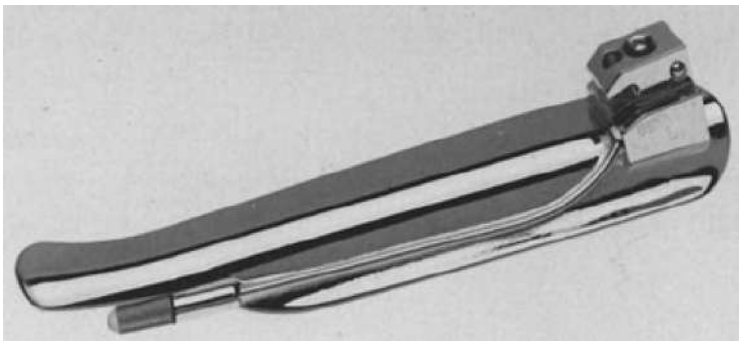

Figure 18.30 The Bennett blade. (Courtesy of Puritan-Bennett Corp.)

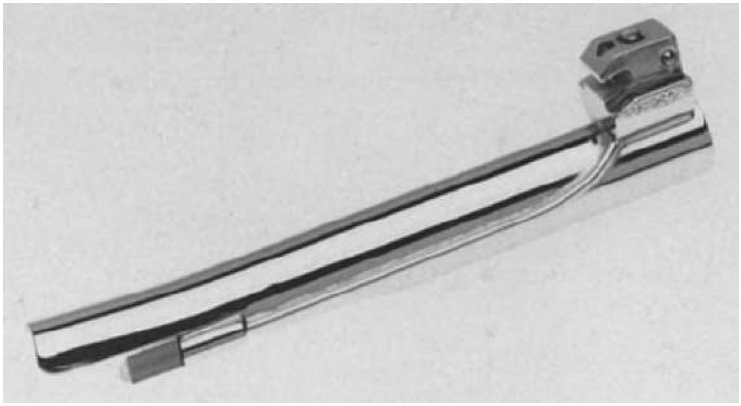

Figure 18.31 The Eversole blade. (Courtesy Puritan-Bennett Corp.)

Phillips Blade

The Phillips blade (Fig. 18.33) is straight with a low flange and a curved tip similar to a Miller blade (72). The light bulb is on the left side of the blade.

Racz-Allen Blade

The Racz-Allen blade is straight with a curved tip (73). The proximal portion of the blade flexes to relieve pressure on the teeth. The vertical portion is hinged and held in position by a spring. The spring allows lateral deflection of the vertical portion without occluding the view. Exposure is improved by tilting the laryngoscope handle to the left. The hinged portion is concave along its length. The tongue surface is rough and unpolished to reduce slippage.

Robertshaw Blade

The Robertshaw blade (Fig. 18.34) has a straight tongue with a gentle curve near the tip (74). It is designed to lift the epiglottis indirectly. The flange is extended to the left. The blade was designed for infants and children. It may be useful for nasotracheal intubation, because it allows a Magill forceps to be introduced with a minimum loss of view.

Oxford Infant Blade

The Oxford infant blade (Fig. 18.35) has a straight tongue that curves up slightly at the tip. It has a U shape at the proximal end, with the bottom limb of the *U* decreasing toward the tip so that the distal part is open. It tapers from a maximum width at the proximal end to the tip. Although intended primarily for newborns, it can be used for children up to 4 years of age.

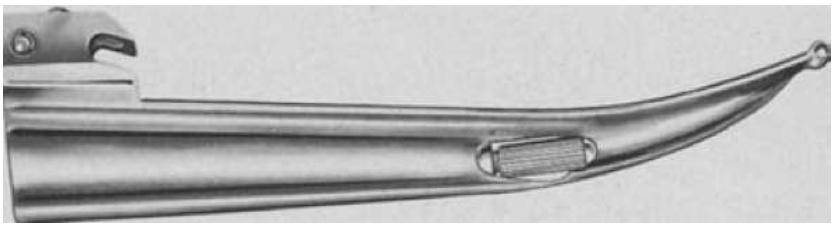

Figure 18.32 The Seward blade. (Courtesy of Penlon Ltd.)

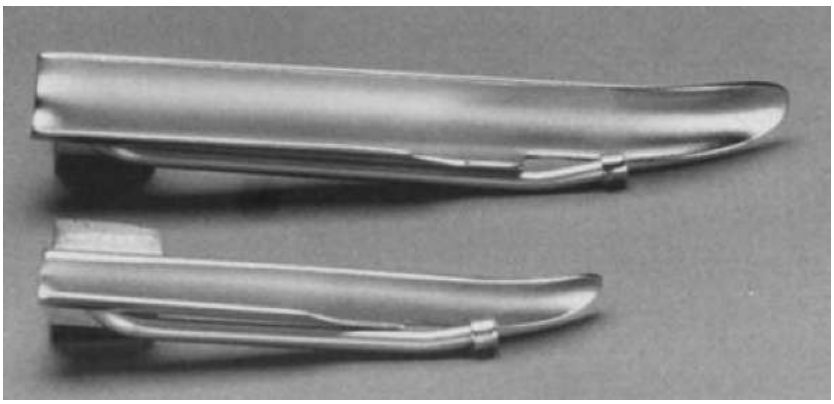

Figure 18.33 Phillips blades. (Courtesy of Mercury Medical.)

Bainton Blade

The Bainton blade (Fig. 18.36) has a straight tongue (20,75). The distal 7-cm section is tubular so that it is protected from obstruction by edematous tissue, blood, secretions, intraoral masses, and scar tissue and has an intraluminal light source. The tip is beveled at a 60ยฐ angle to create an oval opening at the distal end of the tube. A tracheal tube of 8 mm or less can be inserted through the tubular lumen without significantly obstructing vision.

The Bainton blade is designed for patients with right-sided or circumferential pharyngeal lesions. The tubular portion can displace tissues circumferentially and thus overcome this problem.

A modified two-piece tubular pharyngolaryngoscope is also

available. The two parts of the blade are held together by a screw during intubation. A tracheal tube is placed intraluminally into the glottis and then the two pieces are dismantled and removed from around the tube.

Double-angle Blade

The spatula of the double-angle (Choi) blade (Fig. 18.37) has two angulations, 20 and 30 degrees, to improve lifting of the epiglottis. The spatula and tip form a wide, flat surface. The bulb is located on the left edge of the blade between the two curvatures. The flange has been eliminated. The blade may be

especially useful for the patient with an anterior larynx. The absence of the flange leaves more room to pass the tracheal tube than with a straight blade.

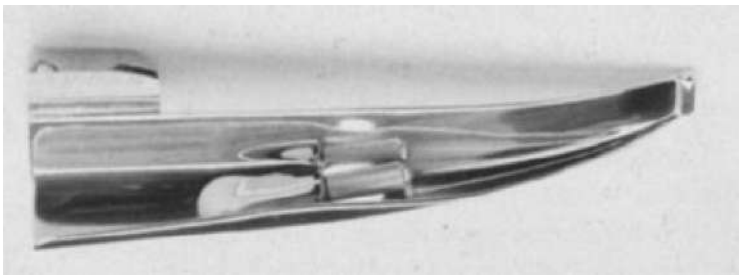

Figure 18.34 The Robertshaw blade. (Courtesy of Penlon Ltd.)

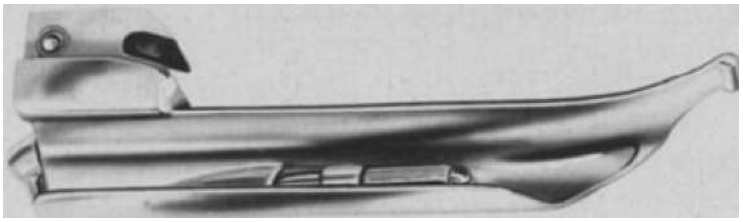

Figure 18.35 The Oxford infant blade. (Courtesy of Penlon Ltd.)

Blechman Blade

The Blechman blade (Fig. 18.38) is a modification of the Macintosh blade, with the tip angled sharply to elevate the epiglottis. The flange has been removed near the handle end of the blade.

Belscope Blade

The Belscope blade (Fig. 18.39) is a straight blade bent forward 45 degrees near its midpoint (78). The tip is beaded on the underside, and the handle is offset. The blade is designed to be used like a straight blade, with the tip lifting the epiglottis. It is available in several lengths.

When a satisfactory view of the larynx cannot be obtained, a prism of transparent acrylic can be attached to the blade just proximal to the angle (Fig. 18.39B). Moisture condensation on the prism can be prevented by applying an antifog preparation to the prism and/or warming it before use. Another measure to prevent fogging is to direct a continuous flow of oxygen over the prism through a suction catheter taped to the blade (79). Because the image of the larynx is rotated, the user's head must be moved higher and farther forward than when the prism is omitted.

Figure 18.36 The Bainton blade. Note the distal tubular section. (Courtesy of Mercury Medical.)

Several studies have shown that an improved view of the larynx can often be obtained with the Belscope compared with other blades (80,81,82,83). The Belscope provides a greater distance between the posterior end of the blade and the upper teeth, making it less likely to contribute to dental damage than other blades (82). This blade feels different from other blades, so practice is necessary to acquire proficiency (77,84). Intubation may take longer and be less successful when the prism is used (85).

Cranwall Blade

The Cranwall blade (Fig. 18.40, *top*) has a curved tip like a Miller blade. There is a reduced flange to decrease the potential for damage to the upper teeth. It may be useful for an anesthesia provider who has limited use of the left arm (48).

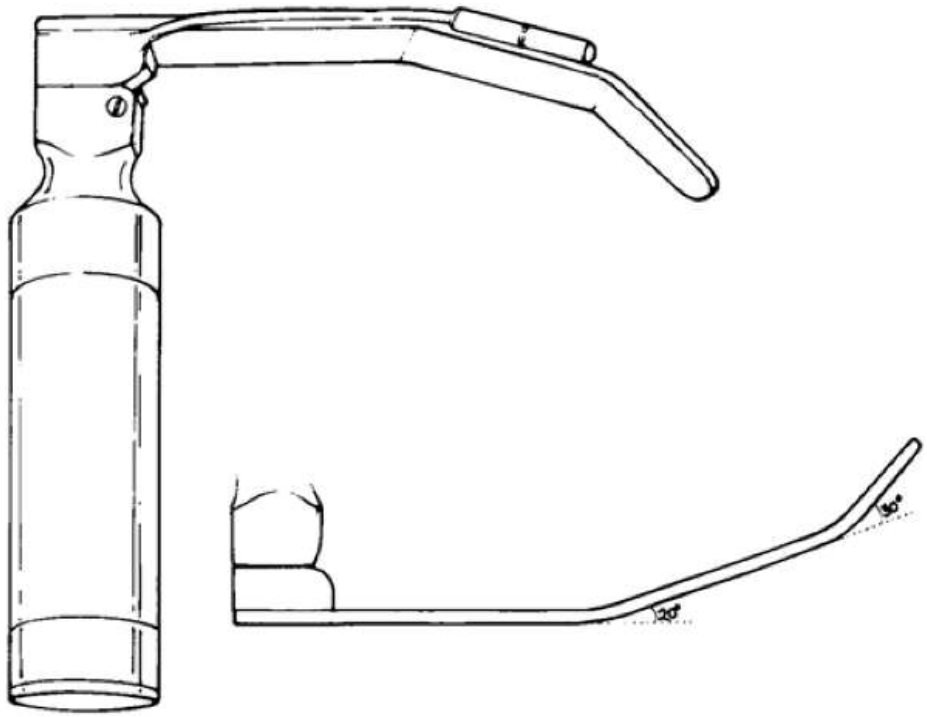

Figure 18.37 The double-angle blade. (Courtesy of Jay J. Choi, M.D.)

Figure 18.38 Blechman blade. (Courtesy of Mercury Medical.)

CW Blade

The CW blade is shown in Figure 18.41. It is designed to be inserted and removed with the horizontal flange almost parallel to the teeth.

Flexible-tip Blades

There are a number of flexible tip blades that have a hinged tip that is controlled by a lever attached to the proximal end of the blade (86,87) (Fig. 18.42). When the lever is pushed toward the handle, the tip of the blade is flexed (Fig. 18.42B). Flexible-tip blades are available under various names, including McCoy, Flipper, Flex Tip, levering laryngoscope blade, and articulating laryngoscope blade. Various blades having a flexible tip are available, including pediatric blades, and Miller (Fig. 18.43) and Macintosh (Fig. 18.42) blades are available. The tip is less rounded than on the usual Macintosh blade (88). It may be helpful to use a narrow handle with these blades (89).

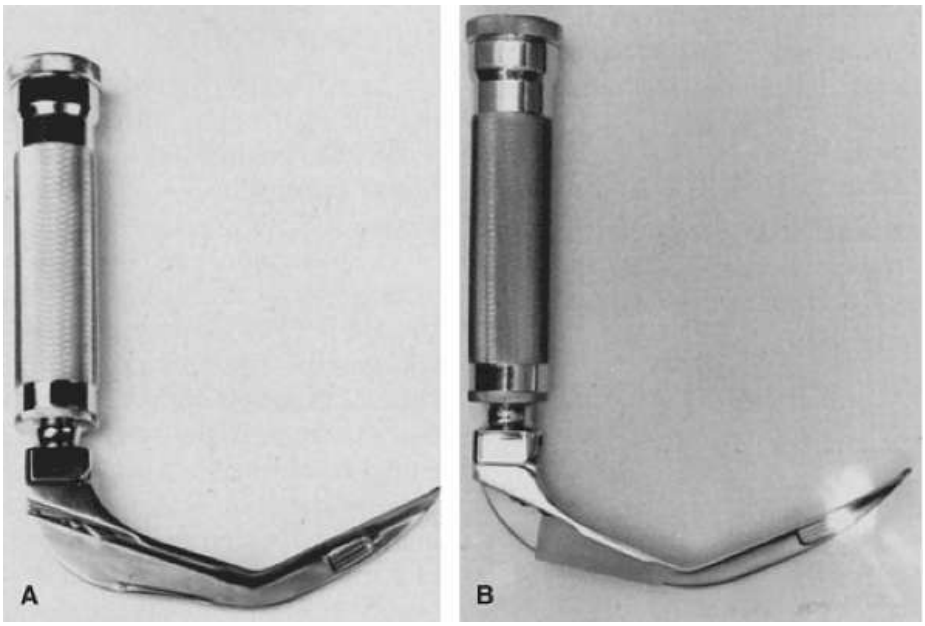

Figure 18.39 The Belscope blade. **A:** Blade without prism. **B:** Blade with prism attached. (Courtesy of Dr. Paul Bellhouse.)

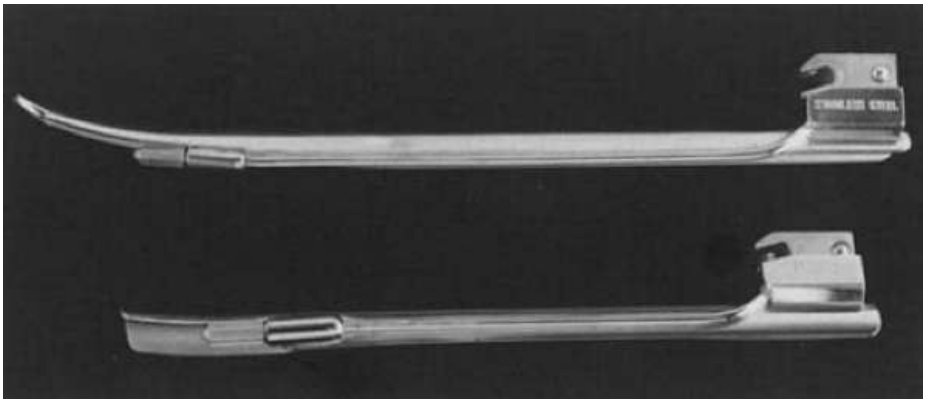

Figure 18.40 Cranwall **(top)** and Whitehead **(bottom)** blades. (Courtesy of Bay Medical, Inc.)

The flexible tip blade may be helpful when a difficult intubation is encountered (88,90,91,92,93,94,95,96,97,98,99). Even if the blade does not improve the view of the larynx, it may improve

the likelihood of successful intubation by elevating the epiglottis (100,101,102). It may be especially useful in patients with minimal neck movement (97,103,104,105,106). External laryngeal pressure may further improve the view but also may worsen it (96,105,107,108,109). In some patients in whom the view is satisfactory with the Macintosh blade, using the levering blade may make the view worse (49,88,110,111).

Studies have shown that using the flexible tip blade results in significantly less force being applied and a reduction in the stress response compared with the Macintosh blade (112,113).

Problems have been reported with the flexible tip blades (114,115). In one case, the connection of the lever mechanism was broken, so the tip of the blade would not flex. The hinged tip from the blade has become detached (116). Arytenoid dislocation has been reported with its use (117).

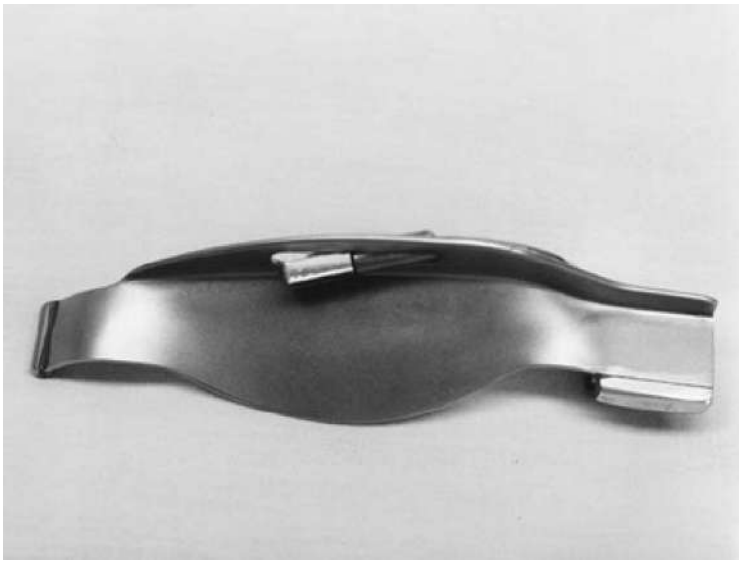

Figure 18.41 CW blade.

Flexiblade

The Flexiblade is a stainless steel blade with six slots and seven windows on the flange (118,119). The blade consists of a rigid

rear portion, a flexible intermediate portion, and a rigid front portion. A lever (control trigger) is attached at the proximal end of the blade. Squeezing the trigger causes the intermediate portion to become more curved. The blade is inserted with the control trigger released.

The Flexiblade can be used for both routine and difficult intubations (49). In most cases, the view improves when the blade is flexed (120,121,122,123,124).

The Flexiblade has been reported to have broken after only five uses (120). It is important that the blade is not manually flexed and that it is disengaged from the blade by rotating in the horizontal and not the vertical direction (125). Another problem involved incorrect assembly (126). The light bundle was on the wrong side of the blade and pointing away from the larynx.

There have been reports of damage to the teeth and gums (127,128). A tongue laceration was noted after an attempt at intubation with an incorrectly assembled blade (125).

Vital View Blade

The Vital View laryngoscope blade is a disposable plastic blade that contains a fiber light. One study showed no significant difference in the view of the glottis or the success rate of tracheal intubation with the Vital View compared with a reusable metal blade (129).

Henderson Blade

The Henderson blade is a large, straight blade with a straight tip that extends well beyond the main part of the blade (130). In cross section, the blade is semitubular. It can accommodate an 8-mm tracheal tube (131). When used with the paraglossal technique, a better view is obtained by optimizing control of the soft tissues and improving the line of sight.

Cardiff Blade

The Cardiff blade is designed for use in children from birth to adolescence (132,133). Several sizes are available (133). The distal part is curved at an angle of 85 degrees. Proximally, the blade has a Z-shape. The

web and flange are attenuated distally so that the terminal part continues as a curved spatula, narrowing at the tip. It terminates with a thickened, transverse bead.

Figure 18.42 Curved flexible tip blades. **A:** Unflexed. **B:** Pushing the lever toward the blade causes the tip to be flexed. (Courtesy of Heine USA Ltd.)

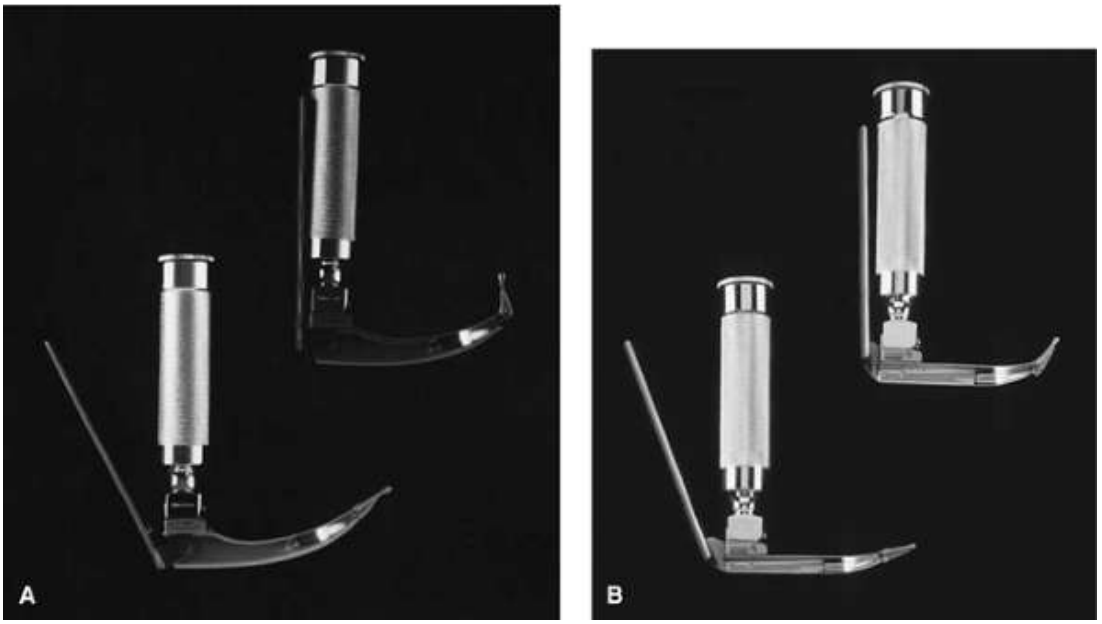

Figure 18.43 Straight blades with flexible tips.

Viewmax Blade

The Viewmax laryngoscope (Fig. 18.44) has an optic side port on a standard Macintosh blade that refracts the image approximately 20 degrees from the horizontal. This modification allows for a more anterior view from a position 1 cm behind the left tip of the blade while at the same time allowing the standard direct view.

Dorges Blade

The Dorges laryngoscope blade combines features of both the Miller and Macintosh blades (133). Compared with the Macintosh, the flange has a lower height, and the curve of the blade is less. It is available in only one size and can be used in patients >10 kg. It has 10- and 20-kg markings on the blade. Studies have found that the Dorges did not perform any better than the standard Macintosh blade in easy or difficult intubation scenarios (111,133).

Figure 18.44 Viewmax blade. (Courtesy of Rusch, Inc.)

Truview Blade

The Truview blade is a standard Macintosh blade that incorporates an unmagnified optic side (prism). Adult and pediatric sizes are available. The prism causes a 20-degree angle of refraction. It can be used as a straight or curved blade.

Prisms

Prisms that can be attached and detached from the laryngoscope blade are available in various sizes (Fig. 18.45). They are attached to a laryngoscope blade by using a clip. A refraction is provided in the line of sight, thereby bringing into view structures within a few millimeters of the tip of the blade. The image is right side up. It is important to warm the prism before use to prevent condensation.

The Huffman prism (134,135,136) is a block of Plexiglas shaped to fit on the proximal end of a no. 3 Macintosh blade (Fig. 18.46). The Huffman prism laryngoscope blade has the prism built into the blade. An additional 20ยฐ refraction from right to left is added because the prism is to the left of the midline. The prism laryngoscope blade allows either conventional direct laryngeal exposure or indirect viewing through the prism.

Techniques of Use

The optimal position for laryngoscopy for most adult patients is approximately 35-degree flexion of the lower

cervical spine and an 85-degree to 90-degree head extension at the atlanto-occipital level, the so-called sniffing position (137). Elevation beyond the sniffing position may improve the view in cases of difficult laryngoscopy (138). The lower cervical spine portion can be maintained in a flexed position by using a pillow under the head. Atlanto-occipital joint extension is achieved by pressure on the top of the head and/or upward traction on the upper teeth or gums. In obese patients, considerable shoulders and head elevation may be necessary so that an imaginary horizontal line connects the patient's sternal notch with the external auditory meatus (139). A cushion designed to provide the best possible position has been developed (Fig. 18.47). In children, it may be unnecessary to flex the lower cervical vertebrae. In neonates, it may be necessary to elevate the shoulders because the head is relatively large.

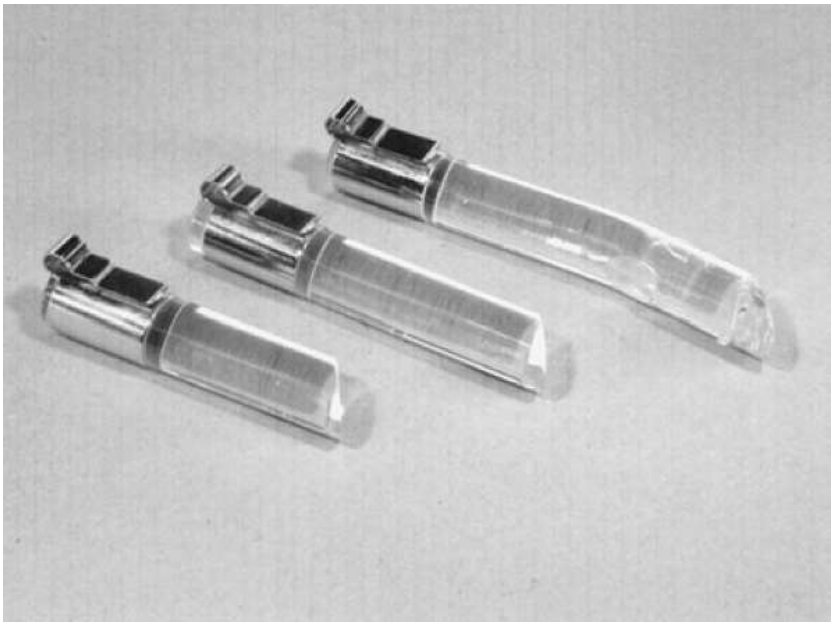

Figure 18.45 Prisms for attachment to laryngoscope blades. (Courtesy of Anesthesia Asssociates, Inc. San Marcos, CA.)

Ambient light should not be overly bright (140). The operating light should not shine on the face.

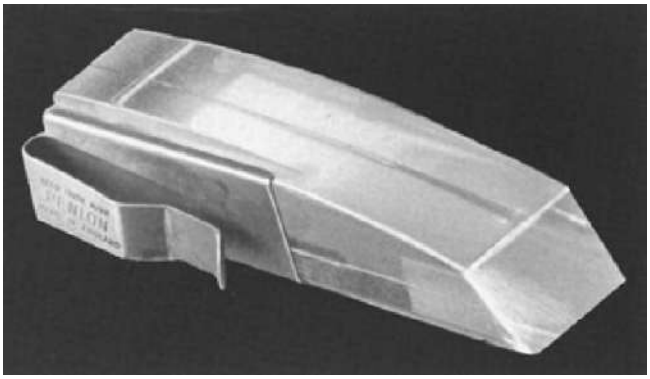

Figure 18.46 The Huffman prism. (Courtesy of Penlon Ltd.)

The laryngoscope handle is held in the gloved left hand. Moistening or lubricating the blade will facilitate insertion if the mouth is dry. In some situations, the chest will impinge on the handle, making it difficult to insert the blade. In these cases, a short handle may be used, the blade may be inserted sideways (10), or the blade may be inserted and then attached to the handle (12,141).

The fingers of the right hand are used to open the mouth and spread the lips. In patients with dentition, the optimum opening of the mouth is often achieved with a thumb-over-index-finger approach, with the index

finger on the maxillary teeth and the thumb placed on the lower teeth.

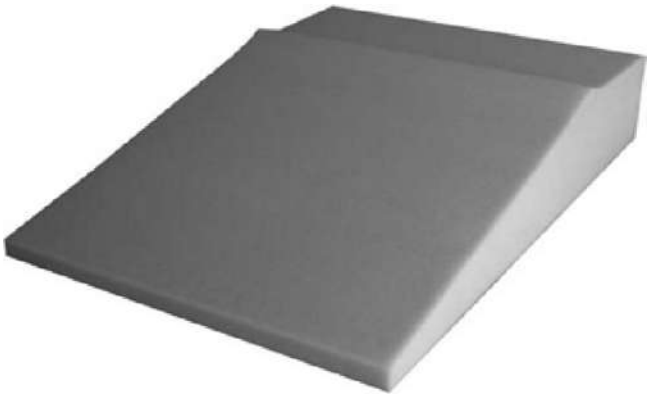

Figure 18.47 Troop elevation pillow. A standard pillow should be used with this. The elevation pillow helps to achieve a better position for ventilation and laryngoscopy in large-framed and obese patients. The head and neck are elevated above the level of the chest and abdomen. The upper airway is more isolated, and the weight of the abdomen is moved away from the diaphragm. This pillow is easier and quicker to use and more stable than a stack of blankets. (Courtesy of Mercury Medical.)

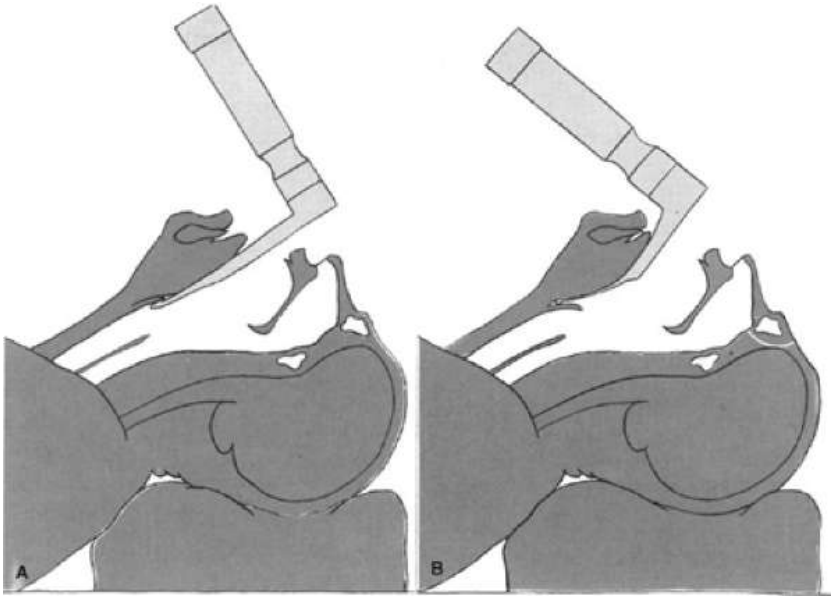

Figure 18.48 **A:** Intubation with a straight laryngoscope

blade. The tip of the blade picks up the epiglottis. **B:** Intubation with the curved laryngoscope blade. The epiglottis is below the tip of the blade. A small pillow under the head allows better visualization of the larynx. (Courtesy of Vance Robideaux, M.D.)

The blade is inserted at the right side of the mouth. This reduces the likelihood that the incisor teeth will be damaged and helps to push the tongue to the left. The blade is advanced along the side of the tongue toward the right tonsillar fossa so that the tongue lies on the left side of the blade. The right hand keeps the lips from getting caught between the teeth or gums and the blade. If the tongue is slippery, placing tape on the lingual blade surface may be helpful (142). When the right tonsillar fossa is visualized, the blade tip is moved toward the midline. The blade is then advanced behind the base of the tongue, elevating it, until the epiglottis comes into view.

There are two methods for elevating the epiglottis, depending on whether a straight or curved blade is being used.

Straight Blade Technique

The straight blade is shown in position for intubation in Figure 18.48A. The blade is made to scoop under the epiglottis and lift it anteriorly. The vocal cords should be identified. If the blade is advanced too far, it will elevate the larynx as a whole rather than expose the vocal cords. Occasionally, the blade will expose the esophagus. It should then be withdrawn slowly. If it is withdrawn too far, the tip of the epiglottis will be released and flip over the glottis.

A straight blade can also be inserted into the vallecula (the angle made by the epiglottis with the base of the tongue) and used in the same manner as a curved blade (see below).

Another technique using a straight blade has been reported to succeed after failure with a Macintosh blade (143). The blade is passed from the right corner of the mouth into the groove between the tongue and the tonsil, displacing the tongue to the left. The blade is advanced, the epiglottis identified, and the blade tip passed posterior to the epiglottis. Next, the blade is lifted anteriorly, elevating the epiglottis directly so that the glottis

is exposed. The blade is then moved toward the midline, pushing the tongue to the left. With this approach, an assistant may be needed to retract the corner of the mouth so that the tracheal tube can be manipulated into place. The use of a bougie or stylet in the tracheal tube may be helpful (144). Alternately, the laryngoscope handle may be switched from left to right and the tracheal tube introduced from the left side of the mouth (145).

Curved Blade Technique

Figure 18.48B shows the curved blade in position. After the epiglottis is visualized, the

blade is advanced until the tip fits into the vallecula. Traction is then applied along the handle at right angles to the blade to move the base of the tongue and the epiglottis forward. The glottis should come into view. It is important that the end of the handle opposite the blade is not pulled backward. This will cause the tip to push the larynx upward and out of sight and could cause damage to the teeth or gums (146,147).

A curved blade can also be used as a straight blade, lifting the epiglottis directly, if it is long enough (148).

In cases of difficult laryngoscopy, a left-molar or right-molar approach often improves the laryngeal view (149). The left-molar approach is may be especially helpful and may spare the incisor teeth (150,151).

Other Maneuvers

Even with correct technique, the larynx will not always be visualized. Displacing the larynx by external backward, upward, and rightward pressure (BURP) on the thyroid cartilage may improve visualization of the glottis (149,152,153,154,155,156,157). Mandibular advancement may also improve the view (158). Inflating a Fogarty catheter attached to the back of the tongue blade portion may improve visualization in some cases (99,159,160,161,162,163,164,165).

Figure 18.49 Disposable laryngoscope covers. **A:** The cover ensheaths both the blade and the handle. **B:** Only the blade is covered. (Courtesy of Blue Ridge Products.)

Cleaning

The cleaning of laryngoscopes has been a subject of debate for several years. Since blades are inserted into the mouth and often cause bleeding, there is potential for cross infection among patients. The handle, while not in direct contact with the patient, may be contaminated with blood or secretions from the anesthesia provider's hands.

Recommended cleaning procedures, including washing the blade and liquid chemical sterilization, are discussed in detail in Chapter 34. Some blades can be steam autoclaved. Steam autoclaving may reduce the luminance of fiberoptic blades over time (166,167).

Disposable laryngoscope blades and handles are available Fig. 18.3). When the entire blade and handle are disposable, the battery and/or light source are usually reusable. While some studies show that some single-use plastic blades perform less satisfactorily than reusable blades (168,169,170,171), some

single-use blades were rated highly by anesthesia providers (169,172,173). Disposable metal blades may break more easily than reusable ones (174). Plastic laryngoscopes have less potential for dental fracture than metal blades (175). Disposable covers are available for the blade or the entire blade and handle (Fig. 18.49). However, they reduce illumination (176,177).

Flexible Fiberoptic Endoscopes

The flexible fiberoptic endoscope (fiberscope) is used to place and evaluate placement of tracheal, double-lumen, tracheostomy, and gastric tubes and bronchial blockers; check tube patency; evaluate the airway; and locate and remove secretions (178,179,180,181,182,183). The flexible fiberoptic endoscope can be used with a video camera and screen.

Description

The fiberscope (Fig. 18.50) is composed of several parts, which include the light source, handle, and flexible insertion portion (184,185,186).

Light Source

Handle with Batteries

A handle with batteries that uses a halogen light bulb is compact, convenient, and inexpensive. However, the illumination will usually be weaker than that from a separate source.

Separate Light Source

The light source is contained in a separate box, uses mains power, and is connected to the scope by a universal (light transmission) cord. A bright light without much heat is produced. Ultraviolet light is filtered in the fiberscope but not in the light source or transmission cord. When the cord is attached to an active light source and the open end can focus the light onto a flammable material, a fire can result. Fires are discussed in detail in Chapter 32.

Handle

The handle (control body, body) (Fig. 18.51) is the part held in

the hand during use. It houses the batteries, if they are used as the power source, or there may be a connector for a separate light source. Other parts of the handle include the eyepiece, focusing ring, working channel port, and the tip control lever or knob. By turning the focusing (adjusting) ring, the image can be brought into focus. A camera can be attached to the eyepiece for remote viewing.

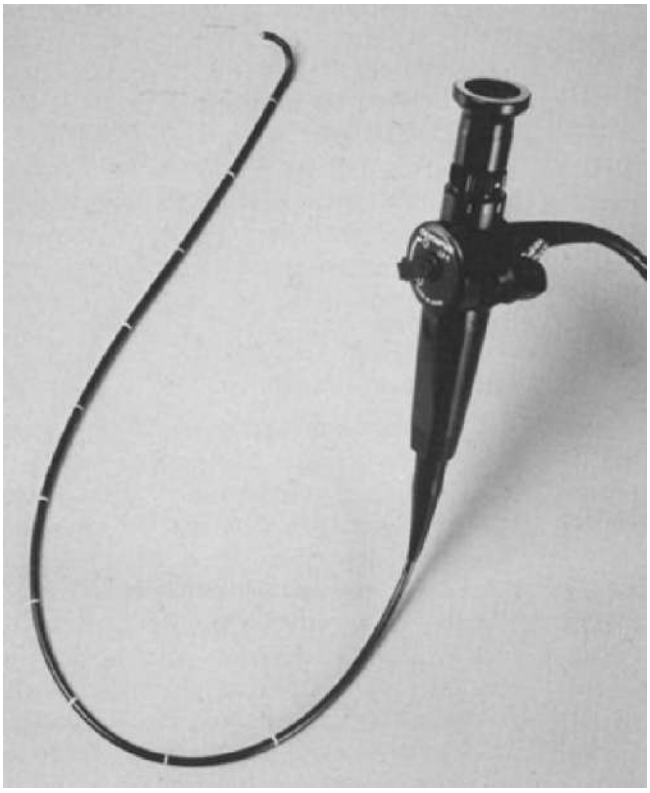

Figure 18.50 Flexible fiberoptic laryngoscope. Light is supplied from a separate source. The lever on the handle controls deflection of the tip in two directions. Two ports attach to the working channel. One is for insufflation or injection, and one is for suctioning. (Courtesy of Olympus Corp.)

The tip (bending, angulation) control lever or knob may be on the side of the body or a thumb-controlled lever system on the back of the handle. By turning this lever, the insertion cord tip can be flexed or extended in one plane. A full range of motion

can be achieved by rotating the entire instrument. Many fiberscopes have a tip-locking lever that locks the tip in a desired position.

Figure 18.51 Handle of flexible fiberscope. The syringe is attached to the working channel. At the bottom is the lever for controlling the tip. Above it to the left is the connection for the light source. At the top is the connection for suction tubing and the suction control. The eyepiece, to which a camera may be attached, is to the right.

Insertion Cord

The insertion cord (shaft, tube) is the portion of the fiberscope that is inserted into the patient and over which the tracheal tube can be passed. It contains an image-transmitting bundle, one or two light-conducting bundles, two angulation wires, and sometimes a working channel. These are surrounded by a protective wire mesh and vinyl covering. Circular depth marks are usually present. This portion is fully submersible, which facilitates cleaning.

The outside diameter of the insertion cord determines the smallest size tracheal tube that the cord can pass through. The inside diameter of the tracheal tube should be at least 1 mm larger than the insertion cord outside diameter. The connection of the handle to the insertion portion is usually tapered to hold

the tracheal tube.

The insertion cord length varies. For tracheal intubation in adults, a 50-cm insertion cord is usually sufficient. Double-lumen bronchial and nasotracheal tube insertion may require a length of 55 to 60 cm.

Image-conducting Bundle

The image-conducting (optic fiber, image transmission, image guide) bundle transmits the image from the distal lens to the eyepiece. The fibers are arranged so that the relationship of one fiber to the other is the same at each end of the bundle. Such a bundle is called *coherent* and allows a clear image to be transmitted. A lens at the user's end allows the image transmitted by the fibers to be focused. Except at the ends where the fibers are fused for strength, the bundle is flexible but delicate. When broken, a fiber will no longer pass its image, and the viewer will see a black dot in that fiber's location.

Light-conducting Fiber Bundle

The light-conducting fiber (light guide, light transmission, illumination) bundle transmits light from a powerful source without producing dangerous heating. Unlike the image-conducting bundle, the fibers are not arranged in a precise manner. This is known as an *incoherent* bundle.

Working Channel

Most scopes have a working (instrument) channel that extends the length of the scope. This can be used for suctioning, injecting saline or medications, insufflating gases, or passing instruments (such as forceps, brush, guidewire, or stylet).

Tip Flexion Cables

Two tip flexion cables (angulation wires, control wires, tip-bending control wires) connecting the tip to the bending knob on the handle are placed along the sides of the insertion cord.

Endoscopic Accessories

Accessory devices to protect the fiberscope from the teeth, keep it in the midline, and direct it to the vicinity of the larynx are

often used. These are discussed in Chapter 16. A nipple from a baby bottle may be used in an awake infant (187). Endoscopy using a supralaryngeal airway device is discussed in Chapter 17. Another useful item is a device to support the jaw (188,189).

It is useful to have a cart for fiberoptic endoscopes (Fig. 18.52). This cart will contain the video camera and accessories such as a video recorder, light source, and a display screen. A cabinet to store the fiberoptic scope in such a way that it will not be damaged is also an important part.

Techniques of Use

Intubation

When using a flexible fiberoptic scope for intubation, the choice of tracheal tube is important (182,190,191,192,193,194). The tracheal tube will be more likely to advance into the trachea if the largest scope that fits easily inside the tracheal tube is used (195,196). A tube with a tip designed to minimize the distance between the fiberscope and the tube's leading edge may pass more easily than a standard tube (197,198,199,200,201,202,203,204). A spiral embedded tube may pass more easily than a tube with a preformed curve (205,206,207,208). Warming a standard tracheal tube may facilitate passage. A sleeve may be placed on the fiberscope to increase its diameter (209,210).

An airway exchange catheter that fits over the endoscope may be used (211,212).

A fiberscope can be inserted either nasally or orally in awake or anesthetized patients who are either breathing spontaneously or being ventilated (213). Although fiberoptic intubation can be performed in unconscious individuals, most authors recommend that when possible it be performed in the awake patient using sedation and topical anesthesia. Loss of consciousness is associated with a loss of tone in the submandibular muscles that directly support the tongue and indirectly support the epiglottis.

Because this instrument is expensive and delicate, great care must be taken to prevent damage. A minor blow can break glass fibers. As well, care must be taken to avoid forceful bending along the cord. The insertion portion should not be withdrawn or advanced with the tip angulated.

Before use, the light should be tested. The tip should be treated with antifogging solution or be placed in warm water (not saline) for several minutes before use. Alternatively, the tip can be briefly held against the buccal mucosa to warm the lens. Hot air from a convective warming device (Chapter 31) may be directed over the tip. The focusing ring should be adjusted by viewing small print at a distance of 2 to 3 cm. The flexible portion should be coated with a lubricating gel, but the lubricant should not contact the lens. Tubing for suction or oxygen insufflation should be attached to the appropriate port.

Oxygen supplied through the working channel will support patient oxygenation, clear secretions, and defog the optics. Control lever function should be assessed. The tracheal tube should be advanced up the scope and anchored firmly on the wider portion of the insertion cord.

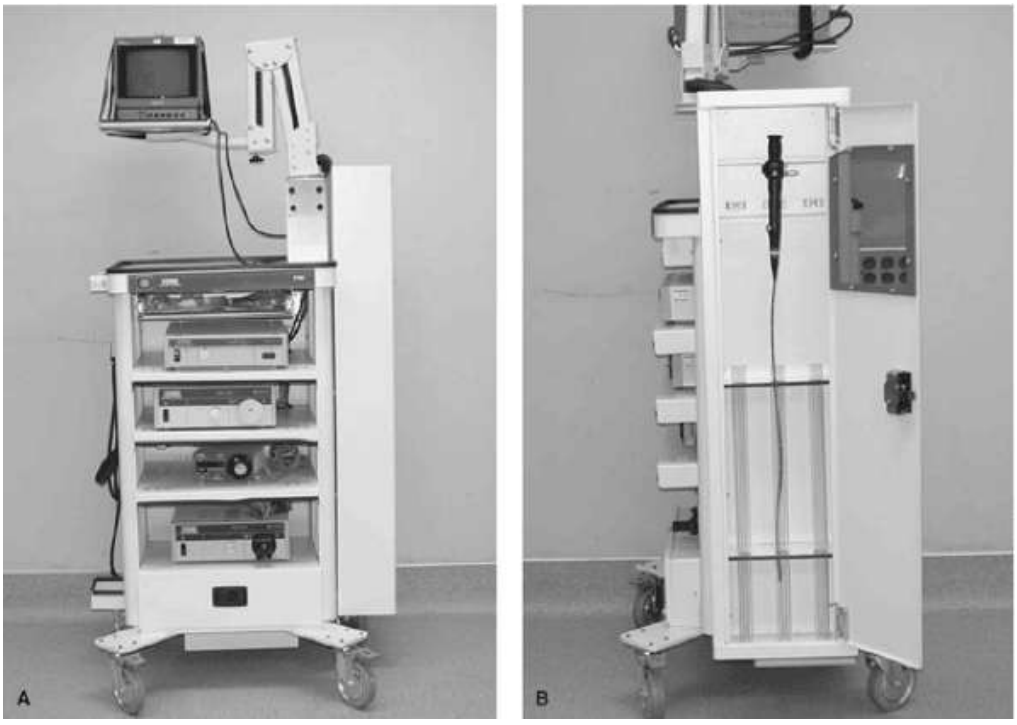

Figure 18.52 Cart for endoscopic equipment. **A:** Front view. The monitor can be used to view the image at the end of the fiberscope. The light source is placed on the shelf. The cabinet at the right is used to store flexible endoscopes. **B:** Side view showing cabinet.

The proximal control section is held in one hand with the index finger on the suction/insufflation port and the thumb on the lever that controls angulation of the distal tip. The other hand holds the shaft of the scope and guides its advance.

Optimal positioning for fiberoptic laryngoscopy includes extending the cervical spine rather than flexion as recommended for direct laryngoscopy (214,215).

Because the cables are not strong enough to lift or dislodge tissues, it is important to have an air space at the end of the tip. In the anesthetized patient, visualization is often difficult or impossible unless some means to expand the pharynx is used. This may be accomplished by having a second person pull the tongue anteriorly or elevate the jaw (216,217,218,219,220). Occasionally, it may be necessary to lift the larynx by grasping it externally. Alternately, a tongue retractor or a rigid laryngoscope can be used to push the tongue forward (101,151,218,219,221,222,223,224,225,226). The awake patient can be asked to stick out his or her tongue, which is then held gently between gauze by an assistant. Special airways have been developed to aid fiberoptic intubation. These are discussed in Chapter 16.

Disorientation in the airway is best resolved by slowly withdrawing the tip and examining the area with gentle up and down tip deflection, by rotating the scope as a unit, or by alternately advancing the tip and withdrawing it slightly. If the view is consistently foggy or hazy, irrigation with saline and suction will usually resolve this problem. Adherent secretions may require the instrument to be withdrawn and the tip mechanically cleaned with a moist gauze. If suction is being applied, it may draw tissue over the scope tip.

If blood or secretions are present, the glottic opening may be located by using capnography (227,228) or by placing a guide wire passed retrograde through the working channel (229,230). Retrograde intubation is discussed in Chapter 21.

Passing the tracheal tube over the fiberscope frequently meets resistance. Rotating the tracheal tube 90ยฐ counterclockwise may be helpful (231,232,233,234,235,236). Other helpful maneuvers include applying a jaw thrust, applying external

pressure on the larynx, and elevating the epiglottis by using a rigid laryngoscope or the fingers (102,237,238,239). Another method to overcome resistance is to insert a smaller tracheal tube beyond the tracheal tube tip

(240,241). Still another technique is to pass an airway exchange catheter via the tracheal tube beside the flexible scope until the tip of the catheter is visualized near the carina (242).

If the tip of the fiberscope protrudes through the tracheal tube's Murphy eye, it may not be possible to slip the tube off the endoscope or to withdraw the fiberscope from the tracheal tube (243,244). The fiberscope and tracheal tube may need to be withdrawn as a unit. To avoid this problem, the tracheal tube should be threaded onto the fiberscope before endoscopy, or the fiberscope should be advanced through the tube under direct vision, identifying both the side and distal openings and taking care to pass the fiberscope through the distal one. The endoscope tip should be in the neutral position as the tracheal tube is advanced and the fiberscope is withdrawn.

A variety of techniques are available. The first is to thread a tracheal or double-lumen tube with the lumen lubricated over the cord until it abuts the handle, advance the flexible portion until the tip enters the trachea or bronchus, then thread the tube over the endoscope. With the second technique, the tracheal tube is first advanced into the pharynx so that it acts as a guide to bring the tip of the scope close to the entrance of the larynx. The fiberscope is passed through the tube and into the trachea, then the tube is threaded over it. A third technique is to use the fiberscope to place a guide wire or stylet into the trachea (245,246,247,248). The fiberscope is withdrawn, and a tracheal tube is passed over the guide and into the trachea. This may be especially useful in small patients. A stylet may be inserted alongside the fiberscope in the tracheal tube, but this will mean that the shape of the tracheal tube cannot be altered.

Oral Intubation

Oral intubation is considered more difficult than nasal intubation. The tip enters the larynx at an acute angle to the glottis whereas via the nasal route, it is at an oblique angle. Intubation may be easier if used with an accessory that will protect the instrument

from the patient's teeth, guide it into the midline, and keep the tongue from falling backward. These methods are discussed in Chapter 16. The insertion cord is placed in the midline and advanced under direct vision, curving downward at the posterior pharyngeal wall, seeking the epiglottis. It is important that the tip be kept in the midline as it is advanced. When the epiglottis has been located, the fiberscope tip is rotated downward so that it passes beneath the epiglottis and is then turned upward until the vocal cords are seen. The tip is then passed between the cords and advanced several centimeters into the trachea. For bronchial intubation, the tip is advanced into the desired mainstem bronchus.

With the fiberscope tip in place, the lubricated tube is advanced over the scope, which functions as a stylet. The bevel should face posteriorly (249). The fiberscope should be used to verify that the tube tip is correctly positioned and then withdrawn, leaving the tube in place.

Nasal Intubation

Fiberoptic nasotracheal intubation is usually easier than orotracheal intubation because midline positioning is easier to maintain, the patient cannot bite the scope, and the nasopharyngeal anatomy naturally directs the tube into the trachea. It is associated with less cervical spine motion than direct laryngoscopy or other methods of airway management (250). A nasopharyngeal airway may be used to lubricate and dilate the nasal passages, then removed. The fiberscope should be advanced through the tracheal tube before insertion, because it may not be possible to insert a tube loaded over a fiberscope through a narrowed nasal passage after successful insertion of the fiberscope into the trachea (251).

Tracheal Tube Exchange

To exchange a tracheal tube, the new tube is threaded over the fiberscope. In one technique, the insertion portion of the fiberscope is advanced into the tube to be replaced (252). As the old tube is pulled out, it is cut and removed from around the fiberscope. The new tube is then advanced into place over the fiberscope.

In an alternative technique, the existing tube is visualized in the

pharynx by using the fiberscope and is followed down to the level of the vocal cords (253). It may be advisable to insert an airway exchange catheter through the old tracheal tube before removing it to allow for ventilation or reintubation over it if the new tracheal tube cannot be passed into the trachea (252). The cuff on the existing tube is then deflated, and the fiberscope is advanced through the space around the tube past the cords. The old tube is removed, and the new one is advanced over the fiberscope into position.

Extubation

The fiberscope can be used to evaluate a difficult extubation (254), especially in a patient who would be difficult to reintubate. The fiberscope is inserted through the tube and the tube withdrawn from the larynx. The working channel can be used to insufflate oxygen. If necessary, the tube can be reinserted over the fiberscope.

Advantages

Flexible fiberoptic endoscopy is a very reliable approach to difficult airway management. It can be used orally or nasally and when access to the airway is limited. It can be used in patients of any age and in any position.

The flexible fiberscope can be used to intubate patients who are difficult or impossible to intubate with a rigid laryngoscope (178,246,255,256,257,258,259,260,261). It is especially useful for patients with unstable cervical spines and for those at high risk for dental damage (262,263,264). It can be

used in cases where the patient cannot be placed in the supine position (265). It can be used by an anesthesia provider who has limited use of the left arm (48).

Insufflating oxygen or jet ventilation through the suction channel may provide additional time when difficulty in passing the tracheal tube into the trachea is encountered.

Disadvantages

The flexible fiberoptic endoscope is more expensive, fragile, and difficult to use and clean than a rigid laryngoscope (266). Fiberoptic intubation requires more time than intubation with a

rigid laryngoscope, so it is of limited use in emergency situations or during a rapid sequence induction. It requires considerable experience and skill maintenance. It does not allow direct manipulation of airway structures.

Intubation with the flexible fiberoptic scope may be difficult or impossible with certain patients (267,268). A major impediment to its successful use is the presence of significant amounts of blood and/or secretions. If aluminum hydroxideâ€“ or magnesium trisilicateâ€“based antacids are used, there may be a whitish film on the end of the scope that impedes vision (269).

Gastric distension and rupture, tension pneumo-thorax, and subcutaneous emphysema have all occurred after oxygen insufflation through the working channel (270,271,272,273).

Laryngeal trauma may occur with fiberoptic intubation (274). This is frequently associated with difficulty in passing the tracheal tube into the trachea over the fiberscope.

Cleaning

Cleaning procedures will vary with the particular scope being used. It is important to read the instruction manual carefully, because improper care can cause extensive and expensive damage to the scope. Cleaning methods are discussed in more detail in Chapter 34.

Indirect Rigid Fiberoptic Laryngoscopes

Bullard Laryngoscope

Description

The Bullard laryngoscope (Fig. 18.53) has a rigid metal blade specially shaped to follow the contour of the

oropharynx and rest beneath the epiglottis. Fiberoptic bundles for illumination and operator viewing are housed in a sheath on the posterior aspect of the blade. A viewing arm with eyepiece extends at a 45-degree angle from the handle. A snap-on diopter for users with uncorrected vision is available. Later versions have an eyepiece that can be focused. A video camera can be attached to the eyepiece for remote viewing.

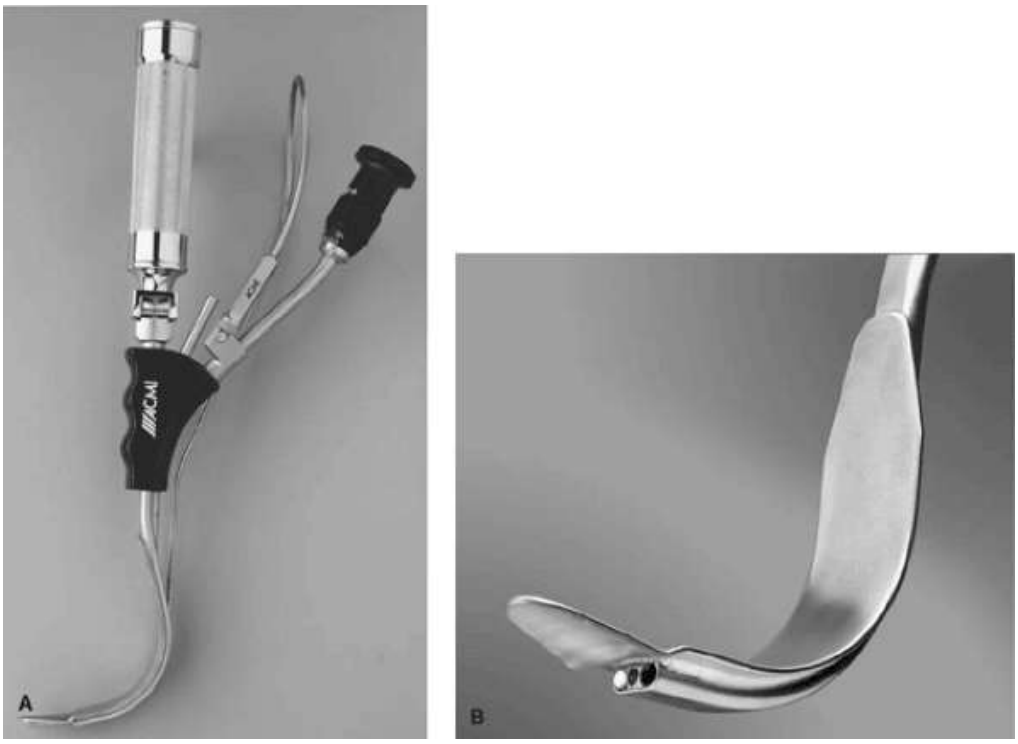

Figure 18.53 A: Bullard laryngoscope with a battery handle and a introducing stylet. Between the handle and the stylet is a port for attaching a syringe or inserting a wire. **B:** Patient end. At left is the light channel. In the middle is the working channel. The image-transmitting bundle is at the right. If an extender is used, it is slipped over the tip.

The power source may be batteries and a halogen bulb in the handle or an adaptor for a flexible fiberoptic cable that is connected to a high-intensity light source.

A working channel extends from the scope body to the point where the light bundles end at the tip. It can be used for suction, oxygen insufflation, administration of local anesthetics or saline, or passage of an airway exchange or jet ventilation catheter (275,276). The end nearest the handle has a Luer lock connector for attaching a medication syringe.

Three sizes are available: pediatric, pediatric long, and adult (Fig. 18.54). The pediatric version is used for babies. The pediatric long version is used for patients up to 8 to 10 years of

age. The adult version is intended for adults and children over 8 to 10 years but may be useful in younger patients (277,278). A plastic blade extender is available and may be especially useful in taller patients (279). The extender is also useful when intubating male patients but is often not helpful or even a hindrance when intubating females. The pediatric handle may be used with the adult blade to decrease the weight.

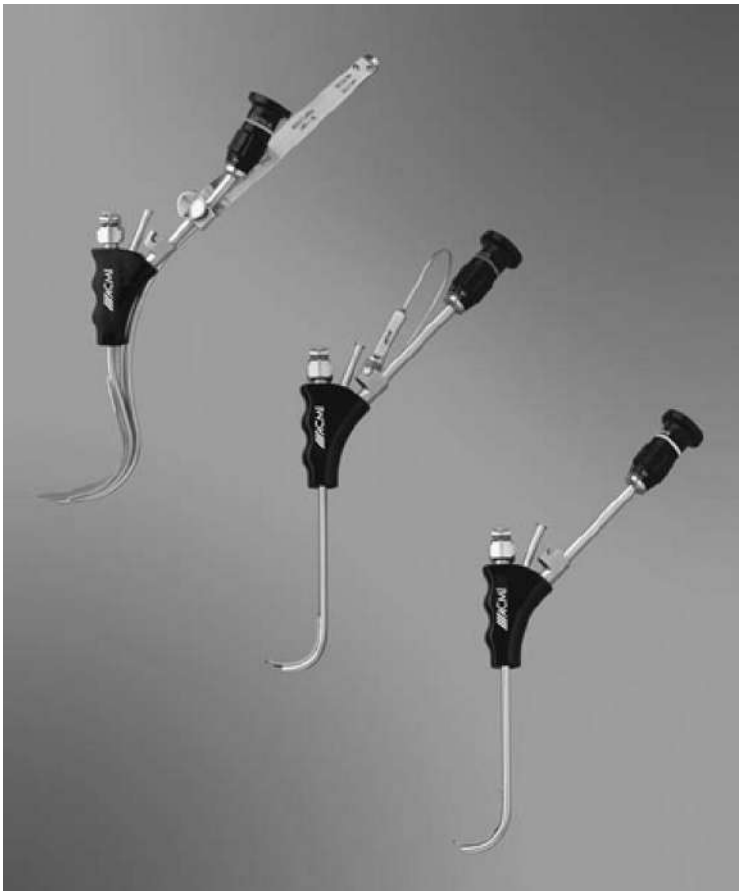

Figure 18.54 Bullard laryngoscopes. The handle contains batteries that power a halogen light bulb. Note that the curve of the adult blade differs from the other two. (Courtesy of Circon ACMI, a division of Circon Corp.)

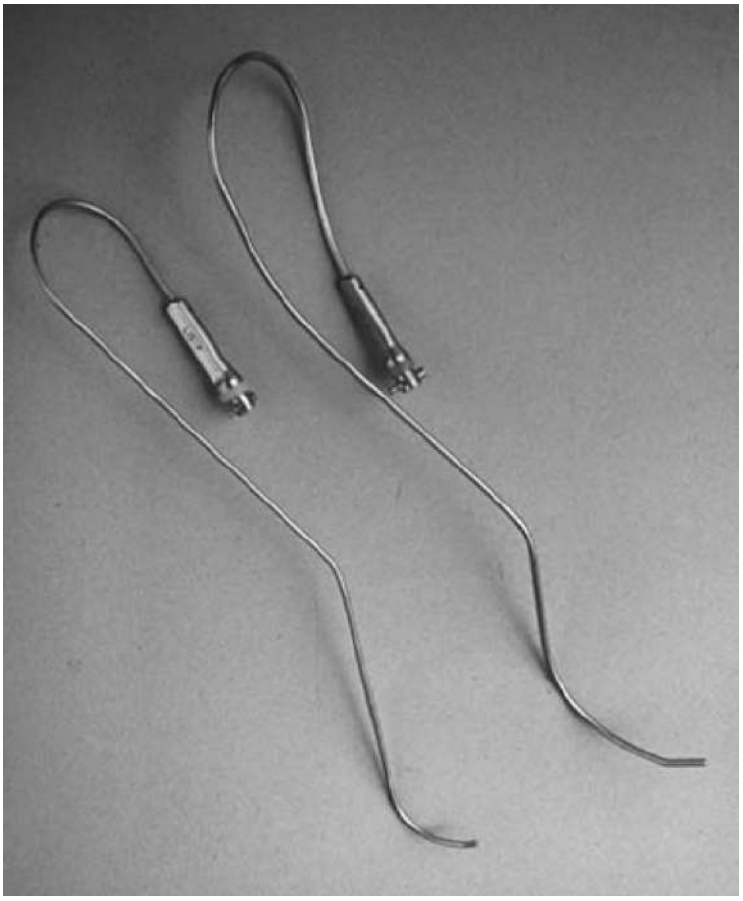

Figure 18.55 Introducing stylets for Bullard laryngoscope. The adult version is on the left and the pediatric version on the right. (Courtesy of Circon ACMI, a division of Circon Corp.)

Two stylets are available. They are designed to follow the contour of the laryngoscope blade and attach to the body of the laryngoscope.

Introducing (Intubating) Stylet

The introducing stylet (Fig. 18.55) has a curve of approximately 20 degrees to the left near the tip to bring the end of the stylet into the field of vision and to facilitate passage of the tracheal tube into the laryngeal inlet. It attaches near the base of the viewing arm with a spring-loaded, locking mechanism.

Multifunctional Stylet

The multifunctional stylet (Fig. 18.56) consists of a long, hollow tube that is curved at the tip to direct the tube into the field of vision. It may attach to the viewing arm by using a screw clamp. Its hollow core can serve as a guide for a flexible fiberscope, tracheal tube exchanger, or small catheter. It can also be used to instill local anesthetic into the trachea.

Techniques of Use

Bullard laryngoscopy can be performed in the awake patient with topical anesthesia or in an anesthetized

patient who is either paralyzed or breathing spontaneously (280,281). For patients who are breathing spontaneously, oxygen can be insufflated through the working channel (282,283,284). This will help to blow secretions away from the vision bundles and prevent fogging (285). Jet ventilation can be administered by using the working channel (286,287,288). Suction can also be applied to the channel, but this may pull tissue against the end of the fiberoptic bundle and impede vision.

Figure 18.56 Multifunctional stylets with screw clamps. The adult version is at the top. The pediatric version is at the bottom. Note the end of the lumen through which

a wire can be inserted. (Courtesy of Circon ACMI, a division of Circon Corp.)

Before use, the image bundle window at the distal end of the sheath should be wiped clean. Intubation can be accomplished with a styleted tracheal tube, a tracheal tube with a directional tip, or one of the Bullard stylets. A Parker or spiral-embedded tube is a good choice (279). If the pediatric introducing stylet or the multifunctional stylet is used, the tracheal tube connector must be removed before it is backloaded over the stylet.

Before the tracheal tube is placed on the stylet, a small amount of lubricant should be applied to the stylet and the tube. Warming the tube may make passage into the trachea easier. The tracheal tube is threaded over the lubricated stylet so that the tip of the stylet protrudes through the Murphy eye. The pediatric and multipurpose stylets should be positioned near the tracheal tube tip but not protruding through the end.

The stylet–tracheal tube combination is fastened to the laryngoscope. This brings the vertical part of the stylet behind and to the right of the laryngoscope in the groove formed by the blade anteriorly and the lens housing in the middle. When properly loaded, the tip of the introducing stylet should be visible at the four o'clock position. The multipurpose stylet tip may not be visible.

If the patient is large, it may be helpful to add the plastic tip extender to the tip of the scope. An attempt should be made to remove the blade extender after it clicks into place (289). It may come off in the mouth if incorrectly attached (290).

Antifog solution should be added to the tip of the fiberoptic bundle (279). An alternative is to place the laryngoscope at the end of the tubing from a convective warming device (Chapter 31) for a few minutes prior to intubation (291). This will warm the blade and prevent fogging.

The user is positioned at patient's head and the scope held in the left hand with the handle horizontal. The patient's head is kept in the neutral position.

Oral Intubation

Either by manually opening the mouth or with the aid of a tongue blade, the Bullard blade is inserted in the midline of the oral cavity, with the handle horizontal. The handle sometimes impinges upon the chest during insertion, especially in obese patients. In these cases, it can be removed prior to insertion and then reconnected or a short handle used (279,292).

When using the introducing stylet, it can be positioned to the right of the blade as it is inserted into the mouth. The fingers of the left hand that holds the scope can maneuver the stylet behind the blade once it is in the mouth. One mistake that many users make is trying to look through the eyepiece as the blade is being inserted. When doing this, the scope often gets turned to one side or the other, and the clinician is unable to identify where the tip is placed. It is recommended that the blade be inserted without looking through the eyepiece but watching that the scope remains in the midline during insertion. As the blade is advanced, the handle is rotated to the vertical position so that the blade slides over the tongue. Once the blade has been rotated around the tongue and it feels that it has seated in the pharynx, upward movement along the axis of the handle is exerted to visualize the larynx. This is the first time that the clinician should look through the eyepiece. If properly placed, either the epiglottis or the glottis should come into view through the eyepiece. The blade can be used to lift the epiglottis directly or indirectly. Occasionally, it may be necessary to displace the blade slightly posteriorly and then lift vertically to optimize visualization.

Once the larynx is visualized, the stylet tip is manipulated with the left hand until it points between the cords. Under visualization, the tube is advanced off the stylet until the cuff passes the vocal cords. The laryngoscope and stylet are then removed. If the tube does not enter the trachea, the tube and stylet must be withdrawn and the stylet placed through the Murphy eye before another attempt at intubation is made. In some cases, the tip of the tracheal tube will impact on the right arytenoid or aryepiglottic fold (293). If this occurs, the scope and stylet should be repositioned to the left. If this does not work, another maneuver is to rotate the tube 180 degrees, positioning the end of the bevel near the blade and having the tip of the stylet protrude through the tracheal tube. If the tube passes

through the vocal cords but cannot be advanced past the level of the cricoid cartilage, the laryngoscope should be angled forward slightly.

If the multifunctional scope is used, the tip may not be visible when the scope is properly placed. An intubation catheter can be advanced slightly until it is visualized. The catheter is then placed through the vocal cords and the tracheal tube advanced over the catheter. The multifunctional stylet does not have the maneuverability that the introducing stylet affords.

Nasotracheal Intubation

A stylet is not used for nasotracheal intubation. A directional tip tracheal tube may be useful in this situation (294,295,296). The larynx is visualized by using the Bullard laryngoscope inserted through the mouth, and the patient's head position and thyroid cartilage are manipulated to allow the tracheal tube to be advanced between the vocal cords under direct vision.

Another method used for nasal intubation was described for an infant with Treacher Collins syndrome (297). The patient was first intubated orally. A small tube changing catheter was placed though the nose and under direct vision manipulated alongside the orotracheal tube. The oral tube was removed, and a nasal tube was passed over the catheter into the larynx.

Advantages

The Bullard laryngoscope is useful in patients who are difficult to intubate, including those in whom head and neck movement is limited or undesirable; those with limited mouth opening, poor dentition, pharyngeal or laryngeal pathology, or facial fractures; and the morbidly obese (276,282,285,298,299,300,301,302,303,304,305,306,307,308,309). It has proved useful in children with Treacher Collins and Pierre-Robin syndromes (297,310,311). It causes less cervical spine movement than conventional laryngoscopy (41,312). Compared with flexible fiberoptic intubation, the Bullard laryngoscope provides quicker intubations (281,313).

Other advantages include rapidity of intubation, low risk of failed intubation or trauma to lips and teeth, and less discomfort in the awake patient than direct laryngoscopy (287). It is more resistant to problems with secretions and more rugged than a flexible

fiberscope. While there is a learning curve, this laryngoscope can soon be used quickly and efficiently. A skilled assistant is not needed to perform a jaw thrust or to hold an airway in place. It requires a mouth opening of only 7 mm. Later versions are fully immersible for cleaning.

Disadvantages

Use of the Bullard scope requires experience and maintenance of skills. The equipment is somewhat expensive. Cleaning is somewhat involved. Intubation may take slightly longer than with a rigid laryngoscope (314). It cannot be used by an anesthesia provider who has limited use of the left arm (48).

Using a tracheal tube larger than 7.5 mm may cause the introducing stylet to be displaced posteriorly, which may make intubation more difficult (315). Certain tracheal tubes (e.g., the metallic laser tube) (Chapter 19) will not fit over the stylet. Double-lumen tubes will not fit the stylets. In these cases, another tube can be inserted by using the Bullard, and a tube exchanger can be used to insert the desired tube.

There are reported cases where the blade extender was accidentally dislodged because it was not securely attached (290,316,317).

WuScope

Description

The WuScope (Fig. 18.57) combines a rigid, tubular blade and a flexible fiberscope. It can be battery powered or used with a fiberoptic light source (318).

Flexible Fiberscope Portion

The fiberscope has short light- and image-transmitting fiberoptic bundles and tip deflection control. The upper segment of the insertion cord has the same configuration as the cone-shaped WuScope handle.

Blade Portion

The blade portion has three detachable metal parts: handle, main blade, and bivalve element. The bivalve element can be

attached or released from the handle and the distal main blade by separate interlocking mechanisms.

The handle is a cone-shaped tube that receives the fiberscope at the top and connects to the main blade at the base. The handle-to-blade angle is 110 degrees. An extender adjusts the length of the fiberscope insertion portion for the adult blade.

The main blade and bivalve element are anatomically shaped. When positioned together, they form two passageways: a larger one for a suction catheter or tracheal tube and a smaller one for the fiberscope (Fig. 18.58). An oxygen channel is alongside the slot for the fiberscope.

Figure 18.57 WuScope. Shown from left to right are the fiberscope, the large-adult bivalve element, the large-adult main blade, the adult bivalve element, the adult main blade, the extender, and the handle. (Picture courtesy of ACHI Corporation.)

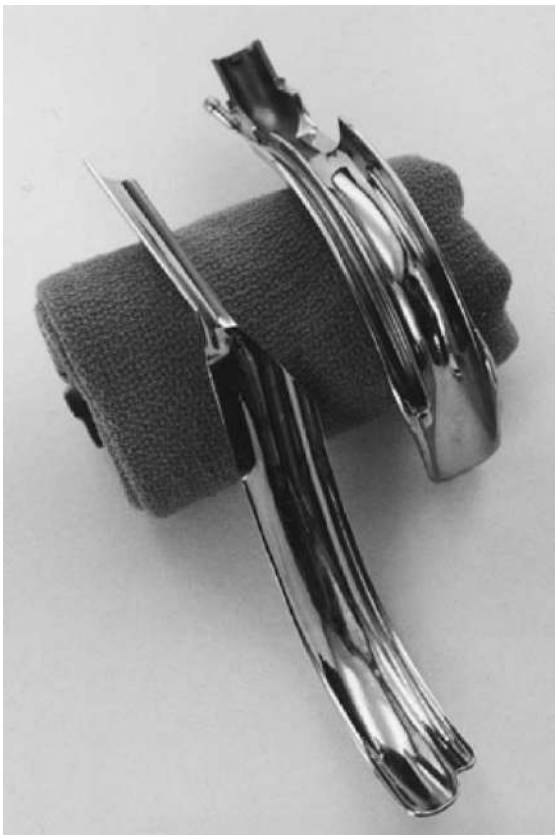

Figure 18.58 Three channels of the WuBlade for the suction catheter and tracheal tube, fiberscope, and oxygen.

Different sizes of blades and bivalve elements can be used with the handle. The adult blade can accommodate a tracheal tube of up to 8.5 mm, while the large-adult blade can contain a 9.0-mm tube.

Techniques of Use

The WuScope can be used to facilitate intubation in the awake or anesthetized patient. The patient's head should be in the neutral position.

The components are assembled (Figs. 18.59, 18.60). If the adult blade is used, the extender should be attached to the handle. The tracheal tube should be lubricated and inserted until the Murphy eye is just beyond the

distal edge of the bivalve element. Use of the tracheal tube that is designed for use with the Fastrach intubating laryngeal mask may facilitate passage through the glottis (204). The suction or airway exchange catheter should also be lubricated. Oxygen tubing should be connected to the oxygen channel. Antifogging solution should be applied to the lens.

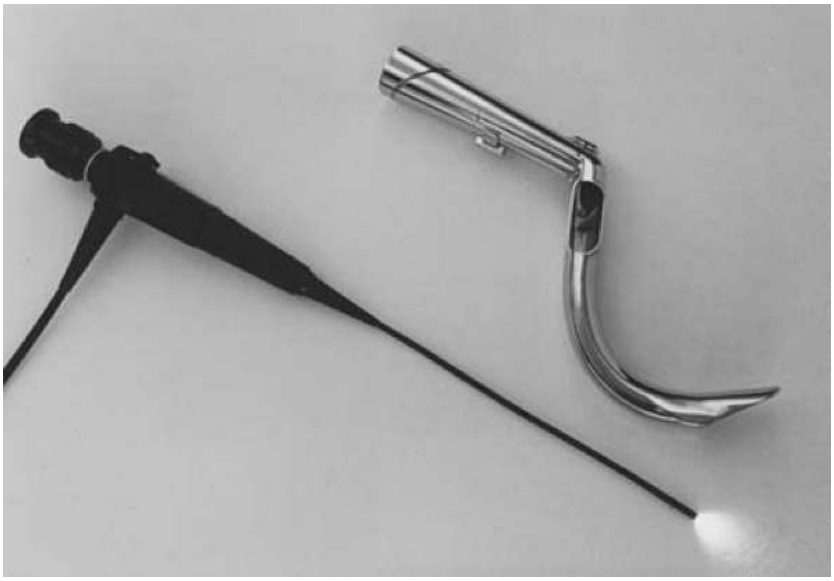

Figure 18.59 WuScope, partially assembled, showing fiberscope and assembled handle, blade, and bivalve element.

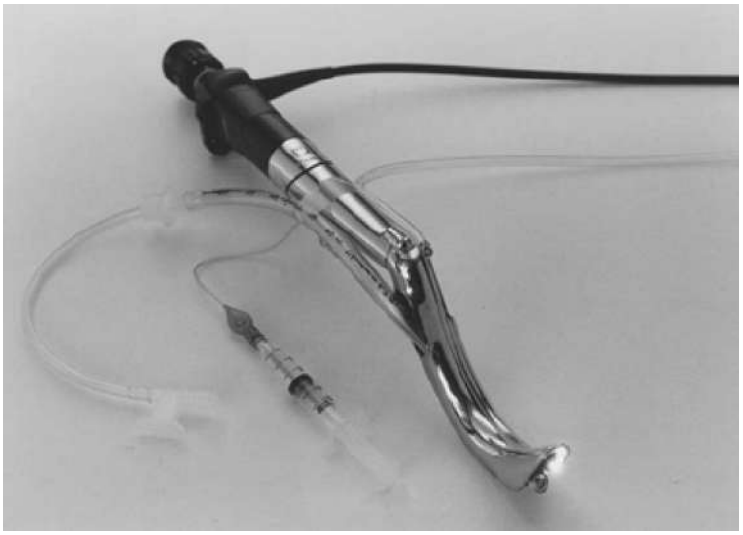

Figure 18.60 Fully assembled WuScope with a tracheal tube in the tracheal tube passage, a suction catheter in the tracheal tube lumen, and oxygen tubing connected to the oxygen port.

Orotracheal Intubation

Holding the metal portion of the handle, the scope is inserted into the patient's mouth in the midline much like an oropharyngeal airway. The handle is gradually rotated toward the operator as the blade advances over the tongue. The operator looks through the eyepiece and identifies the posterior pharyngeal wall and epiglottis as the scope is advanced. If the epiglottis blocks the view, the device may be withdrawn slightly and readvanced to lift it up. A suction catheter in the tracheal tube passageway can be used to remove excessive blood or secretions.

When the larynx comes into view, the distal main blade is adjusted, if necessary, to align the tracheal tube with the glottic opening. Once the tracheal tube is properly positioned, it is advanced into the trachea. Alternatively, a suction catheter or airway exchange catheter may be advanced through the tracheal tube into the trachea. An intubation guide that can be maneuvered may be useful (319). This then serves to direct the tracheal tube through the glottis. The bivalve element is removed first. The handle, main blade, and fiberscope are then removed

as a unit, leaving the tracheal tube in place.

Nasotracheal Intubation

For nasotracheal intubation, the bivalve element is not attached to the scope. After a tracheal tube is passed into the oropharynx through the nostril, the scope is positioned inside the mouth in a manner similar to oral intubation. The concave undersurface of the distal main blade is directed to straddle the tracheal tube and to guide it toward the glottis. The tracheal tube is advanced into the trachea, and the device is removed from the mouth.

Tracheal Tube Exchange

The WuScope can be used to exchange a tracheal tube (320). A new tracheal tube mounted in the WuScope is advanced into the oropharynx and positioned anterior to the existing tube. A catheter is passed through the tracheal tube and into the larynx beside the old tube. The existing tube is withdrawn, and the new tube is advanced into the trachea over the catheter.

Advantages

The WuScope has been used successfully to place both tracheal and double-lumen bronchial tubes in difficult-to-intubate patients (318,321,322,323,324,325,326). Its tubular structure protects the fiberoptic lens from blood, secretions, and redundant soft tissue. This may make it especially useful in the patient with airway obstruction resulting from hematoma or edema. No forceps or stylet is needed, so the risk of airway injury is low. Suctioning and oxygen administration can be performed simultaneously. Unlike flexible fiberoptic endoscopy, one can view the tracheal tube as it advances through the glottic opening into the trachea.

The handle-to-blade angle facilitates entry in obese patients and in those with barrel chests, short necks, or large breasts. There is no need for head extension or tongue lifting. Minimal jaw opening is necessary.

Figure 18.61 UpsherScope. The **larger photograph** shows the delivery slot for the tracheal tube. The blade is attached to a conventional Upsher handle. The **inset** shows the opposite site of the blade with the eyepiece. A fiberoptic cable from the light source is attached to the handle. (Courtesy of Mercury Medical.)

Disadvantages

Limitations include a high initial cost, the need for new cleaning and disinfecting routines, the need to learn and master new skills, and the time required to assemble and disassemble the device. The flexible fiberscope may be damaged. It may not be useful in a patient with a severely limited mouth opening. Application of cricoid pressure decreases the ease of intubation when using this device (327).

UpsherScope

Description

The UpsherScope (Fig. 18.61) consists of a C-shaped metal blade, shaped to approximate the curve of the oropharynx (328). The open part of the C to the right ends about 1 inch from the end of the blade. The distal part of the blade has an upward curve. To the left are two tubes that carry fiberoptic bundles. Both bundles end where the semicircular channel ends.

Proximally, the viewing bundle terminates in an eyepiece with a focusing ring while the light bundle makes contact with the fiberoptic light source at the handle. An Upsher handle must be used. A remote light source can be used. A camera can be attached for remote viewing. It is presently available only in an adult size. A pediatric version is said to be in development.

Techniques of Use

Prior to intubation, the viewing fiberoptic bundle should be treated with an antifogging solution. The tracheal tube should be lubricated and placed in the delivery slot with the tip not quite protruding from the distal end of the channel (Fig. 18.62). Inserting a bougie through the tracheal tube significantly improves the chances of successful intubation (329). The blade is clipped to the handle and the viewing lens focused. Head and neck flexion will increase the probability of success.

The scope should be introduced centrally into the mouth. A jaw lift is usually helpful. Occasionally, chest impedance may make it necessary to introduce the scope sideways, then rotate it to a central position. It is then advanced along the oropharyngeal curve. When the larynx comes into view, the scope tip is positioned under the epiglottis, and the scope is elevated to align

the lower part of the blade with the arytenoid cartilages. The tracheal tube, bougie, or airway exchange catheter is then advanced under direct vision between the vocal cords. The scope is then removed from the tube and rotated out of the mouth.

Figure 18.62 UpsherScope with tracheal tube loaded onto it.

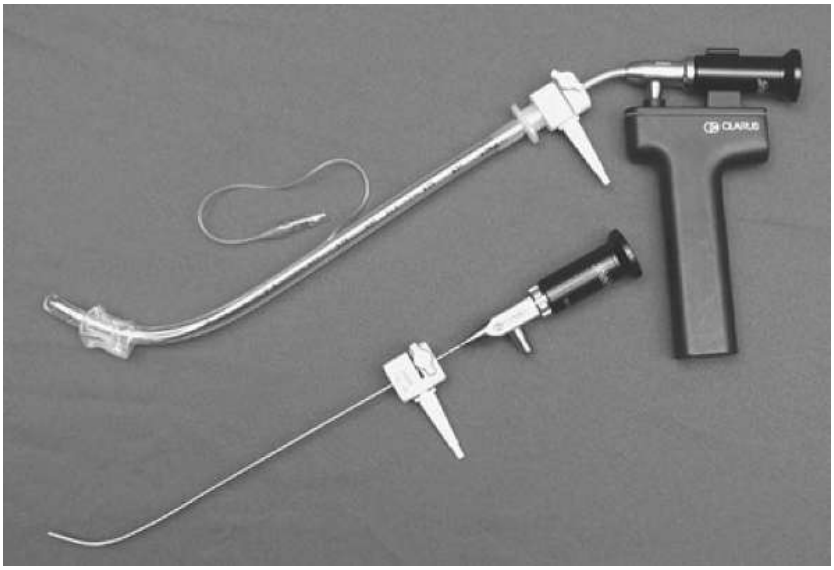

Figure 18.63 Shikani optical stylet. Both the adult and pediatric stylets can be attached to the same handle. Note the tube stop and the connection for oxygen

tubing.

If the tube is difficult to advance, this can often be corrected by rotating the tracheal tube 90ยฐ, further flexion of the head on the neck, modification of the vector of lift, rotating the tip of the scope to the left or right, or passing a guide with subsequent passage of the tracheal tube over it (328,329). The blade sometimes rolls off the tongue to the side. When this occurs, a paramedian approach should be attempted.

Advantages

The UpsherScope is useful to intubate patients with difficult airways within a reasonable time (328). It can be used with all sizes of adult tracheal tubes. It can be cleaned by using the Steris system.

Disadvantages

In routine intubation, the UpsherScope has demonstrated no advantages over conventional laryngoscopy. The time needed to perform intubation and the number of attempts have been significantly longer and higher with the UpsherScope (330). The UpsherScope is not suitable for nasotracheal intubation. Secretions can obscure the view (328,329).

Optical Intubating Stylets

A number of devices that combine fiberoptic imaging with an intubation stylet have been described (331,332,333,334,335,336,337,338,339,340,341,342,343,344). These are referred to as optical intubating stylets, optical stylets, intubating fiberoptic stylets, stylet laryngoscopes, or visual scopes. Some have a mechanism to alter the shape of the stylet during use. Most can be attached to a video transmission system so that intubation can be observed on a monitor. Some have a port for oxygen insufflation, drug administration, or suction. Some are battery operated. Others require a separate light source, and some can be used either way. Some can be used with a fiberoptic handle for a rigid blade.

Description

Shikani Optical Stylet

The Shikani optical stylet (Seeing Optical Stylet, SOS) (Fig. 18.63) is a stainless steel malleable stylet (336,337,345,346,347). It comes in a preformed J-shape but can be bent at the tip. It has a handle, eyepiece, adjustable tube stop, and integral port for insufflating oxygen through the tracheal tube. The eyepiece has a fixed focus on the area around the tip of the fiberoptic bundle. It can be used with several light sources.

There is both an adult and a pediatric size. The adult size will fit a tracheal tube of 5.5 mm or larger. The pediatric size will fit a tube of 3 mm or larger.

Bonfils Retromolar Intubation Fiberscope

The Bonfils intubation fiberscope (Fig. 18.64) is a nonmalleable stylet laryngoscope with a 40ยฐ distal curve (348). It has a 5-mm outside diameter and a length of 40 cm. A 6.0 mm or larger tracheal tube can be inserted over it. It has a movable eyepiece as well as a slide adapter for stabilizing the tracheal tube. The adaptor has a connector to administer oxygen during intubation. It can be used with batteries or a separate fiberoptic light source.

Techniques of Use

Prior to intubation, antifogging agent is placed on the lens or the stylet is warmed in water or saline. It should

be inserted into the tracheal tube without its tip protruding past the tip and then fixed to the tube. With a pediatric tracheal tube, it may be necessary to remove the connector.

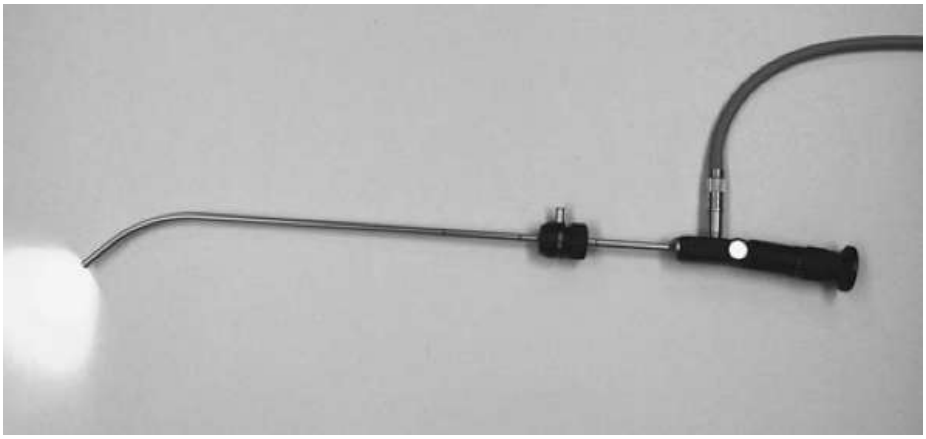

Figure 18.64 Bonfils intubating fiberscope.

The patient is placed in the neutral position or with a pillow under the head. If secretions are present, they should be removed before proceeding further. A rigid laryngoscope or jaw thrust should be used to lift the epiglottis (336,344,347,349). It may also be helpful to grasp the tongue and draw it out of the mouth. The handle is held in the right hand and the stylet inserted into the mouth in the midline and advanced into the hypopharynx just beyond the tip of the epiglottis. The stylet is then advanced under direct vision through the vocal cords. For some patients, it may be necessary to apply external pressure on the larynx. If secretions are a problem, insufflating oxygen may improve the view. If orientation is lost, the scope should be withdrawn until orientation is re-established.

When an intratracheal position is achieved, the tube should be advanced into the trachea. The stylet is removed by rolling the handle toward the patient's chest, following the curve. It should not be pulled straight out.

A retromolar approach is sometimes used (350). The scope is inserted between the cheek and the molars on the patient's right side with the end of the scope pointing toward the midline.

An optical stylet can be used via a Fastrach Intubating Laryngeal Mask Airway (ILMA) (351). It can also be used as a lightwand. It can be used to check tracheal tube position. It may be used to place a double-lumen endobronchial tube (352) or to direct a suction catheter into a mainstem bronchus.

Advantages

Optical stylets are relatively easy to use for routine and difficult intubations, although practice will be required to achieve and maintain proficiency (307,332,334,335,336,337,340,343,344,346,347,353,354). Intubation with this device may be successful after failed direct laryngoscopy (350). Since the trachea can be visualized, esophageal intubation should not occur. The incidence of sore throat and the increase in heart rate are less than with conventional laryngoscopy (332,340,355,356). The risks of dental trauma and soft tissue damage will be reduced if a conventional laryngoscope is not used in conjunction with the optical stylet. The use of an optical stylet may result in less cervical spine movement than when conventional laryngoscopy is used (357).

The optical stylet is more portable, rigid, and rugged and costs less than a fiberscope. However, bending may damage the fiberoptic fibers. It may be a useful alternative when a fiberoptic endoscope is not available.

Disadvantages

Intubation time may be longer than with conventional laryngoscopy (335). Intubation is faster than with the intubating LMA-Fastrach, but the time to ventilation is shorter with the ILMA-Fastrach (342). The initial cost of the monitor, light source, and associated equipment is high. Secretions on the lens may cause intubation failure (334,340). The major limitation is that it cannot be oriented in a precise direction. Nasal intubation cannot be performed with some of these devices.

Video Laryngoscopes

A video laryngoscope can be created by attaching a video system to a flexible fiberscope or an optical stylet. Several laryngoscopes that are specially designed to work with a video system are commercially available (Fig. 18.65).

Video laryngoscopy has many advantages. The displayed anatomy is magnified, and a larger viewing angle is provided. The operator and assistant can coordinate their movements because each sees the same image on the monitor (358). The

ability to project the image seen through the laryngoscope makes it a good teaching tool,

allowing the supervisor to monitor the intubation process more effectively (359,360,361). Positioning the monitor over the patient's chest allows the intubator to work and observe in one axis (359).

Figure 18.65 Video laryngoscope stand. The whole unit is portable. (Courtesy of Saturn Biomedical.)

Using a video laryngoscope may result in less neck movement than when using a conventional laryngoscope, depending on the particular laryngoscope (362). It allows the anesthesia provider

to maintain a distance from the patient during intubation, and this could make it useful in patients who have infectious diseases (363). In one case, the recorded intubation was useful in demonstrating to the patient that the intubation had been performed properly and was not responsible for the dislocation of the arytenoid cartilage (364).

In addition to allowing laryngoscopy and intubation to be visualized, it can be used to observe bougie placement (365,366), movement of the vocal cords after thyroid surgery (367,368,369,370), verify tracheal tube position, and aid in tracheal tube exchange.

A limitation of these devices is the need for a video-endoscopy monitoring system, so it may not be suitable for use outside a health care facility. However, most operating suites are equipped with video-endoscopy monitoring systems to which these devices can be connected.

Figure 18.66 GlideScope. Note the 60-degree angulation of the blade. (Courtesy of Saturn Biomedical.)

GlideScope

Description

The GlideScope (Fig. 18.66) has a miniature digital camera on the underside of a plastic blade. A light-emitting device (LED) mounted beside the camera provides illumination. The blade has an embedded antifogging mechanism and a 60ยฐ bend at the midpoint. As a result, the view from the camera is different from the one seen when looking into the mouth. The image is transmitted via a cable to a monitor screen. A portable GlideScope that can operate on battery power and one supplying a color image are available (371). The GlideScope is available in adult and pediatric sizes (neonate, infant, and child).

Use

Immersing the blade in lukewarm water for a few minutes before using it may improve vision (372). It can be used as a curved or straight blade.

The use of a stylet in the tracheal or double-lumen tube is recommended. The angle on the stylet should be at least 50 to 60 degrees (373,374,375,376,377). A malleable stylet whose shape can be changed during use may be helpful (378).

With the head in a neutral position, the GlideScope is inserted in the midline. In patients with limited mouth opening or limited head/neck movement, it may be helpful to insert the laryngoscope upside down and then rotate it counterclockwise (372). It is helpful to identify the uvula and ensure that it is centered on the monitor before advancing the scope around the tongue (379). The blade should be advanced anterior to the epiglottis. After the tip is in the vallecula, the scope is gently elevated.

Intubation occasionally fails despite an excellent laryngeal view (378,379,380). This may be overcome by inserting the tracheal tube upside down, rotating it while it is

inserted, using a tracheal tube with a blunt tip, changing the stylet's curve, slight withdrawal of the laryngoscope, withdrawing the stylet, relaxing the laryngoscope elevation, applying external laryngeal pressure, inserting a tube nasally, or inserting a bougie followed by railroading the tracheal tube over it (363,369,372,379,382).

Figure 18.67 Video Macintosh. The fiberoptic bundle is inserted into the blade. The blade can be removed for cleaning.

If the GlideScope is left inside a patient for an extended period of time, there is a theoretical risk of damage to the tissues, as the glass window will be hotter than 41ยฐC (106ยฐF). Therefore, the GlideScope must be removed after intubation is complete.

Evaluation

Studies show that the GlideScope yields a comparable or superior glottic view compared with direct laryngoscopy (363,371,377,379,383,384,385,386,387). It has been used successfully in both anesthetized and awake patients with difficult airways, including following failed fiberoptic intubation (383,388,389,390,391). It causes less cervical spine movement than the Macintosh blade (42). The learning curve appears to be rapid (379,385,392). However, it may not be suitable for use with neonates (393). In some cases, it may be difficult or impossible to pass the tracheal tube despite a good view of the glottis (61,382).

Video Macintosh Intubating Laryngoscope

The Video Macintosh intubating laryngoscope (Fig. 18.67) has a Macintosh blade attached to the handle and the image-light bundle threaded through a small metal guide in the blade and advanced two thirds of the length of the blade (359). Antifog solution should be placed on the tip of the image-light bundle. It

may provide a better view than a traditional Macintosh laryngoscope (394).

Angulated Video-intubation Laryngoscope

The angled video intubation laryngoscope (AVIL) has a plastic blade whose tip is angulated at approximately 25 degrees (344). The vertical flange is flattened. A thin channel leads from the handle to the blade tip and permits flexible fiberscope insertion. It has proven useful in children requiring manual in-line neck stabilization (362,395).

Tooth Protectors

A tooth protector (mouth guard, mouth protector, dentguard) (Fig. 18.68) is placed over the upper teeth to protect them from the laryngoscope blade. It may also prevent the blade from getting caught in a gap between the teeth. Use of a protector does not guarantee safety from dental trauma (396,397). Although it will prevent direct trauma to the surface of the teeth, it cannot prevent transmission of pressure to the roots.

Tooth protectors are available in different designs (Fig. 18.57) and are fashioned from a variety of materials. A custom tooth protector, professionally made from an impression of the patient's teeth, can provide significant protection (398). A tooth protection device may be attached to the laryngoscope blade (399,400,401).

These devices may make it harder to visualize the larynx and may make tracheal tube insertion more difficult because of lack of space (396). They slightly increase the intubation time (402). Cutting off part of the right side of the protector or using a transparent protector may decrease these problems. It may be necessary to remove the protector before intubation can be accomplished.

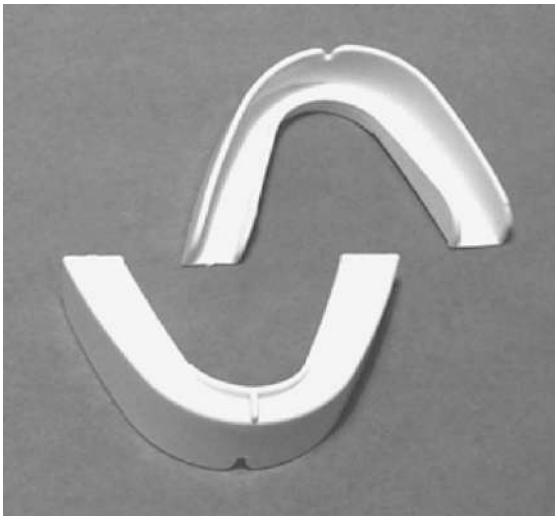

Figure 18.68 Tooth protectors. (Courtesy of Sun Med.)

Complications of Laryngoscopy

Dental Injury

Damage to teeth, gums, or dental prostheses is the most frequent anesthesia-related insurance claim (403,404,405,406,407). In addition to cosmetic disfigurement and discomfort, there may be pulmonary complications if the dislodged tooth or fragment is aspirated. Profuse bleeding may result (408).

A tooth or prosthetic device may be chipped, broken, loosened, or avulsed. The teeth most likely to be damaged are those that have been restored or weakened through periodontal disease, but sound teeth may also be affected (409). The upper incisors are most frequently involved (405,410). This is most often caused by using the teeth as a fulcrum point for the laryngoscope while elevating the epiglottis.

The condition of each patient's teeth should be carefully assessed preoperatively to identify possible problems. Inquiry should be made concerning vulnerable dental repair work or loose or carious teeth. Anatomical conditions in the mouth and pharynx that can cause difficulty should be noted. The patient

should be advised beforehand if there is likely to be a problem. A suture may be placed around a loose tooth to prevent it from entering the airway in the event it becomes dislodged. In patients 4 to 11 years old, the deciduous teeth may be easily dislodged. If such teeth are loose, removal before or during anesthesia may be indicated.

When there are gaps between the upper front teeth, a portion of a tracheal tube or other device may be used to bridge the gap, or a tooth protector may be used. Keeping a partial upper denture in place may prevent the laryngoscope from slipping into gaps between teeth.

If a tooth, fragment, or dental appliance is dislodged, foreign body aspiration should be a major concern. An immediate search should be conducted, starting with an examination of the oral cavity and the area surrounding the patient's head. Chest and neck radiographs must be taken if the fragment is not recovered.

Different types of tooth damage may occur (403). These require different treatments. A qualified dentist or oral surgeon should be consulted. If a tooth is avulsed, immediate replacement in its original position and stabilization will increase the chances of successful reimplantation (411).

Tooth protectors may prevent dental damage. Placing adhesive tape or other materials on the flange of the blade has also been reported to be effective (401,412). Inserting the laryngoscope blade from the left corner of the mouth may spare the incisor teeth (150).

Cervical Spinal Cord Injury

Aggressive head positioning during intubation, especially head or neck extension, has the potential to cause damage in the patient with an unstable cervical spine (413). An unstable cervical spine can be associated with a congenital weakness, malformation, fracture, or dislocation of a cervical vertebra or other conditions such as osteoporosis, connective tissue disease, or tumor (312,414,415). Case reports that describe neurologic deterioration after intubation exist (416,417,418), although the contribution of laryngoscopy to these injuries remains debatable and the overall risk appears to be low (418,419,420,421). It may be advisable to involve the neurosurgeon to witness the intubation so that a maneuver that could cause harm can be

avoided.

There are no data to suggest that any mode of airway intervention is superior in decreasing secondary injury or improving outcome (312,422). Manual in-line immobilization reduces spinal movement and the likelihood of secondary injury (39,312,422,423,424,425,426,427,428,429). A cervical collar should be not be relied on for this purpose.

Damage to Other Structures

Reported injuries to the upper airway include abrasion; hematoma; and lips, tongue, palate, pharynx, hypopharynx, larynx, and esophagus lacerations. A common occurrence is rolling the upper or lower lip between the teeth and the laryngoscope blade as the blade is inserted. Osteomyelitis of the mandible has been reported (430). The lingual and/or hypoglossal nerve may be injured (431,432,433,434,435). Arytenoid subluxation may occur (436). Anterior temporomanidibular joint (TMJ) dislocation may occur (437,438). Patients with TMJ derangements

often state that their problem began following general anesthesia (439).

There is a significant increase in the rate of airway-related complications as the number of laryngoscopic attempts increases (440). The American Society of Anesthesiologists (ASA) Task Force on the Management of the Difficult Airway has recommended limiting to three attempts (441,442).

Shock or Burn

If a laryngoscope light that is left ON contacts the patient, a burn may result (443,444). A short circuit can result in the handle and blade rapidly heating (445,446). The tip of a fiberscope applied directly to the skin may produce a burn (447).

Swallowing or Aspirating a Foreign Body

Cases have been reported in which the bulb or other part of a laryngoscope was aspirated or swallowed (448,449,450,451,452,453). It is important to make every effort to find these foreign bodies. If they cannot be found in the oral cavity or around the patient's head, x-rays of the chest and neck

should be taken. Part of a tumor may be dislodged into the airway and may become implanted (454).

Laryngoscope Malfunction

The most common laryngoscope malfunction is light failure. This may be the result of a defective power source, lamp, or socket; incorrect assembly; or poor contact between the blade and handle. Fiberoptic laryngoscopes are more reliable because the halogen lamp's useful life is longer than an ordinary light bulb, and the lamp is usually in the handle rather than in the blade. Various parts of the blade and handle may break (452,455,456,457,458,459,460,461,462,463,464,465,466,467,468). Misassembly may result in failure (469).

A preuse check will detect most malfunctions. An extra handle and blade should always be immediately available. Neglecting to observe these precautions could spell disaster, especially when a rapid sequence induction is to be performed (470,471).

Circulatory Changes

Laryngoscopy may result in significant increases in blood pressure and heart rate, although these changes are less than those associated with tracheal intubation (219,472,473,474,475,476).

Disease Transmission

The risk of infection transmission, particularly Creutzfeldt-Jakob disease, via laryngoscopes, is unknown but is a matter of concern to anesthesia providers (177,477,478). The use of a disposable blade cover or disposable laryngoscope blade has been encouraged (172,176,479).

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Questions

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

1. The best position for intubating an adult patient when using a rigid laryngoscope is

A. Shoulders elevated

B. Flexion of the lower cervical spine and extension of the head

C. Flat on the bed

D. Pressure exerted on the top of the head

View Answer

2. Techniques for inserting a tracheal tube with a flexible fiberoptic endoscope include

A. Visualizing the larynx with the fiberoptic endoscope, placing the endoscope into the larynx, and sliding the tracheal tube over the endoscope

B. Placing a bougie in the trachea under direct vision by using the fiberoptic endoscope and then inserting the tube over the bougie

C. Placing the tracheal tube into the pharynx as a guide for placement of the fiberoptic endoscope and then advancing the endoscope and then the tube into the larynx

D. Placing the tracheal tube into the larynx with a blind technique and checking its position with the fiberscope

View Answer

3. If the tracheal tube cannot be advanced over a flexible endoscope into the trachea, which of the following maneuvers may be helpful?

A. Withdrawing the tube and rotating it 90 degrees

B. Elevating the mandible

C. Applying external pressure on the larynx

D. Using a rigid laryngoscope to elevate the epiglottis

View Answer

4. Reported complications associated with laryngoscopy include

A. Tooth damage

B. The fiberoptic scope protruding through the Murphy eye

C. Damage to the cervical spinal cord

D. Damage to the recurrent laryngeal nerve

View Answer

5. Which maneuvers are useful for nasal intubation with a fiberoptic scope?

A. Using a nasopharyngeal airway to dilate the nose

B. Introducing the tube through a specially designed mask

C. Using a slit nasopharyngeal airway to introduce the tube

D. Introducing the fiberscope orally and using it to guide the tube from the nose

View Answer

6. In which situations would it be advantageous to use a short rigid laryngoscope handle?

A. When cricoid pressure is being applied

B. When the patient is in a body cast

C. When the patient has large breasts

D. When the neck is frozen in the flexed position

View Answer

7. Techniques that may be helpful to intubate a patient when it is difficult to place a conventional laryngoscope blade in the mouth because of an anatomic abnormality include

A. Inserting the blade into the mouth without the handle attached and then attaching the handle

B. Inserting the blade into the mouth laterally and moving it to the intubating position

C. Inserting the blade with a 90-degree turn and then turning it to the intubating position

D. Inserting the blade 180 degrees from normal and rotating it to the normal intubating position as it is being inserted

View Answer

8. When intubating children,

A. Cervical flexion is frequently not necessary

B. The head should be extended 70ยฐ to 85ยฐ

C. The shoulders frequently need to be elevated

D. It will often be necessary to extend the head over the end of the bed

View Answer

9. Which of the statements below are advantages of fiberoptic intubation?

A. It is easier than rigid laryngoscope intubation

B. There is less cervical spine movement

C. Instruments used are robust

D. It is useful for difficult intubations

View Answer

10. Problems associated with flexible fiberoptic intubation include

A. Cardiac dysrhythmias

B. Greater length of time to perform

C. Hypertension

D. The presence of blood and secretions

View Answer

11. Complications associated with insufflating oxygen through the working channel include

A. Gastric rupture

B. Tension pneumothorax

C. Subcutaneous emphysema

D. Air embolism

View Answer

12. Situations in which the Bullard laryngoscope would be helpful include

A. Limited mouth opening

B. Treacher Collins syndrome

C. Morbid obesity

D. Cervical spine fractures

View Answer

Chapter 19

Tracheal Tubes and Associated Equipment

The tracheal tube (endotracheal tube, intratracheal tube, tracheal catheter) is a device that is inserted through the larynx into the trachea to convey gases and vapors to and from the lungs.

General Principles

Resistance and Work of Breathing

A tracheal tube places a mechanical burden on the spontaneously breathing patient (1,2,3). It adds resistance and is usually a more important factor in determining the work of breathing than the breathing system (4). This is particularly important in pediatric patients (5). Several factors help to determine the resistance to gas flow imposed by a tracheal tube.

Internal Diameter

The single most important factor in determining the resistance to gas flow is the internal diameter (ID) of the tube and its connector. A tube with a thick wall will offer more resistance than a thin-walled tube with the same outer diameter (OD). The wall thickness to tube diameter ratio is greater in small tubes, leading to a greater increase in resistance (6). Resistance will be increased if a suction catheter, fiberscope, or other device is passed through the tube or if secretions line the inner wall.

Length

Decreasing tube length lowers its resistance, but the decrease is much less than could be accomplished by increasing the ID (5,7,8). Most disposable tubes are supplied longer than necessary and may be cut to a more suitable length to reduce resistance.

Configuration

Curves in the tube or connector increase resistance, but if the curve is gentle, the increase is small (5,6). Kinking increases resistance. The resistance of swivel connectors is similar to that of curved connectors (9).

Dead Space

The tracheal tube and connector constitute mechanical dead space, which was discussed in Chapter 7. Because the volume of a tracheal tube and its connector is usually less than that of the natural passages, dead space is normally reduced by intubation. In pediatric patients, however, long tubes and connectors may increase the dead space. Special low-volume pediatric connectors are available.

Tracheal Tube System

Tube

Materials

The material from which a tracheal tube is manufactured should have the following characteristics (10,11):

1. Low cost
2. Lack of tissue toxicity
3. Transparency
4. Easy sterilization and durability with repeated sterilizations (unless disposable)
5. Nonflammability
6. A smooth, nonwettable surface inside and outside to prevent secretion buildup, allow easy passage of a suction catheter or bronchoscope, and prevent trauma
7. Sufficient body to maintain its shape during insertion and to prevent occlusion by torsion, kinking, or compression by the cuff or external pressure
8. Sufficient strength to allow thin wall construction
9. Thermoplasticity to conform to the patient's anatomy when in place
10. Lack of reaction with lubricants and anesthetic agents
11. Latex-free

To date no substance with all of the above traits has been found.

Red rubber tubes are still available. These can be cleaned, sterilized, and reused multiple times. However, they are not transparent, they harden and become sticky with age, have poor resistance to kinking, become clogged by dried secretions more easily than plastic tubes, and do not soften appreciably at body temperature. Latex allergy is another possible problem (Chapter 15).

Polyvinyl chloride (PVC) is the substance most widely used in disposable tracheal tubes. It is relatively inexpensive and is compatible with tissues. Tubes made from PVC are less likely to kink than rubber tubes. They are stiff enough for intubation at room temperature but soften at body temperature, so they tend to conform to the patient's upper airway. Prior to use, a PVC tube may be cooled to make it more firm during intubation or warmed to facilitate placement over a fiberscope (12). PVC tubes have a smooth surface that facilitates passage of a suction catheter or bronchoscope. Their transparency permits observation of the tidal movement of respiratory moisture as well as materials in the lumen.

Silicone is used in some tracheal tubes. Although more expensive than PVC, tubes made from it can be sterilized and reused.

Tube Design

The international/U.S. standard (11) contains requirements and recommendations for tracheal tubes, including the material from which the tube is constructed, the inside diameter, length, inflation system, cuff, radius of curvature, markings, packaging, and labeling (10).

A typical tracheal tube is shown in Figure 19.1. The internal and external walls should be circular. A tube

whose lumen is oval or elliptical in shape is more prone to kinking than one that is round.

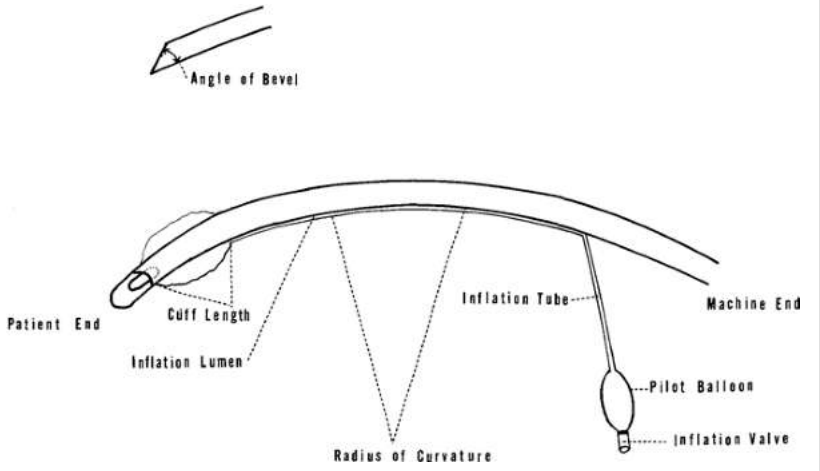


Figure 19.1 Cuffed Murphy tracheal tube.

The machine (proximal) end receives the connector and projects from the patient. It may be possible to shorten the tube at this end. The patient (tracheal or distal) end (tip) is inserted into the trachea. It usually has a slanted portion called the *bevel*. The angle of the bevel is the acute angle between the bevel and the longitudinal axis of the tracheal tube (Fig. 19.1). Most commonly, the opening of the bevel faces to the left when viewing the tube from its concave aspect. This is because the tube is usually introduced from the right, and the larynx is easier to visualize with the bevel facing to the left.

The design or orientation of the patient end is important when the tube is advanced over a fiberscope or introducing catheter. Insertion is easier if the bevel faces backward or the tip is specially designed to minimize the distance between the scope and the tube's leading edge (13,14,15,16,17,18,19,20,21,22,23,24). A hemispherical bevel reduces nasal morbidity during nasotracheal intubation (25). During nasal intubation, turning the tracheal tube so that the bevel faces up may avoid the tip from becoming impinged on the epiglottis (23).

Figure 19.1 shows a hole through the tube wall on the side opposite to the bevel. This is known as a Murphy eye, and a

tube with this feature is called a *Murphy* or *Murphy-type tube*. The purpose of the eye is to provide an alternate pathway for gas flow if the bevel becomes occluded (26,27). Forceps, tube changers, and fiberscopes may inadvertently advance through a Murphy eye and become caught (28,29,30,31). Using a tube with a Murphy eye will reduce trauma during nasal intubation (32). A theoretical disadvantage is that secretions may accumulate in the eye. Some tubes have an additional eye above the bevel. This may provide an additional measure of safety if the tube accidentally advances into a mainstem bronchus.

Tracheal tubes lacking the Murphy eye are known as Magill or Magill-type tubes. If a Murphy eye is not present, the cuff can be placed closer to the tip. This may decrease the risk of inadvertent bronchial intubation.

The American Society for Testing and Materials/International Standards Organization standard (11) requires that a radiopaque marker is placed at the patient end or along the entire length of the tube to aid in determination of tube position after intubation.

Special Tubes

Cole Tube

The Cole tube is shown in Figure 19.2. It is an uncuffed tube. The patient end has a smaller diameter than the rest of the shaft. This provides some protection against inadvertent bronchial intubation. Cole tubes are sized according to the ID of the tracheal portion. The tube should not be inserted far enough for the shoulder to contact the larynx, as this could damage the larynx (33). It has been recommended that this tube is used for neonatal resuscitation but not for long-term intubation (33). The resistance offered by the Cole tube is less than that of a comparable tube of constant lumen (8). A disadvantage is that it cannot be inserted through the nose.

Preformed Tubes

Some tracheal tubes are preformed to facilitate surgery about the head and neck (34). One of these is the Ring-Adair-Elwin (RAE) tube (Fig. 19.3), which has a preformed bend that may be temporarily

straightened during insertion. Frequently, there is a mark at the bend. The external portion of the oral version is bent at an acute angle so that when in place, it rests on the patient's chin with the connector over the patient's chest. The nasal version has an opposite curve from the oral tube so that when in place the outer portion of the tube is directed over the patient's forehead. This helps to reduce pressure on the nares. The oral tubes are shorter than nasal tubes.

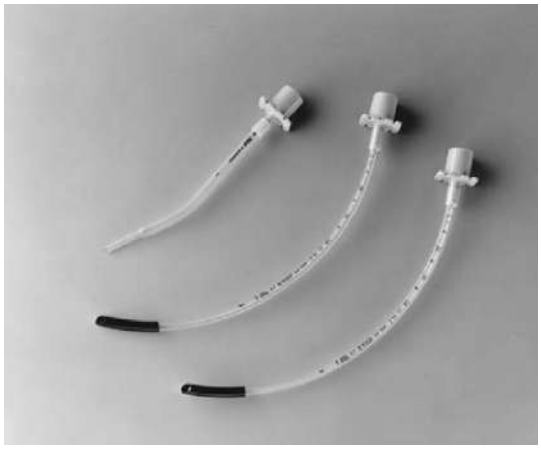


Figure 19.2 Uncuffed pediatric tracheal tubes. The **top** tube is a Cole tube, which is sized by the French scale, according to the intratracheal portion. The **middle** tube is a Magill tube, while the **bottom** tube has a Murphy eye. The dark color is the part of the tube that the manufacturer recommends to be below the vocal cords. (Courtesy of Rusch, Inc.)

The nasal and oral versions are available in various sizes and in cuffed and uncuffed versions. Uncuffed RAE tubes are shorter than cuffed RAE tubes (35). As the diameter increases, the length and distance from the distal tip to the curve also increases. In the majority of cases, when this mark is at the teeth or nares, the tube will be satisfactorily positioned in the trachea if the proper size tube for the patient was selected. This is only a guide and should not be used as the sole criterion for judging correct tube position. Unfortunately, the length from the angle to the tip of the tube varies (36,37).

These tubes are easy to secure and may reduce the risk of unintended extubation. The curve allows the breathing system connection to be placed away from the surgical field during surgery around the head without use of special connectors (38). The long length may make them useful for insertion through a supraglottic airway device (39,40,41) (Chapter 17). The nasal tube may be useful for oral intubation of patients who are to be in the prone position (42) or who are undergoing otolaryngology procedures (43).

A disadvantage of preformed tubes is the difficulty in passing a suction catheter through them. In critical situations, suctioning can be accomplished by cutting the tube at the curvature and then reinserting the connector into the cut end (43). These tubes offer more resistance than comparably sized conventional tubes (6). Since they are designed to fit the average patient, a tube may be either too long or too short for a given patient (35,44). When selecting tube size, reference to height and weight may be more useful than age in years, and the user should always be alert to the possibility of bronchial intubation or accidental extubation.

Spiral Embedded Tubes

The spiral embedded (flexometallic, armored, reinforced, anode, metal spiral, woven, wire-reinforced) tube has a metal or nylon spiral-wound reinforcing wire covered internally and externally

by rubber, PVC, or silicone (Fig. 19.4). The spiral may not extend into the distal and proximal ends. The connector is frequently bonded to the tube.

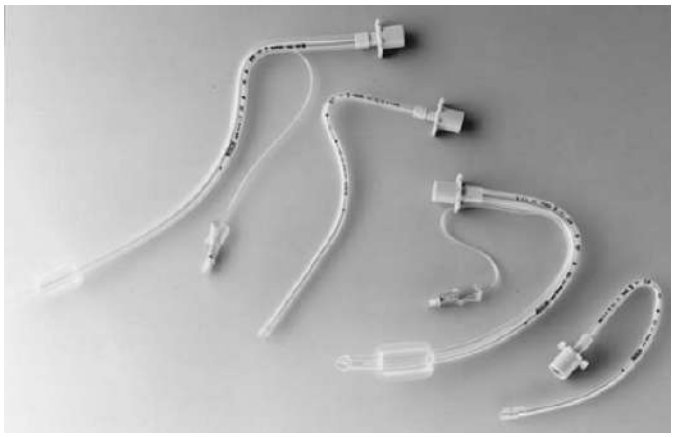
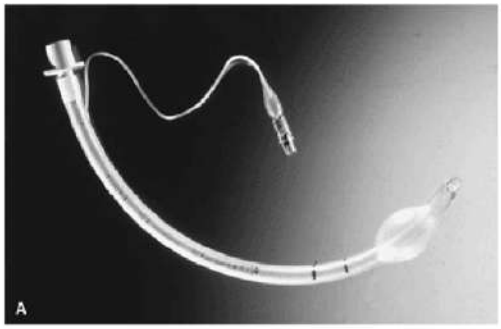


Figure 19.3 Preformed tubes. At **left** are two nasal tubes, one cuffed and one uncuffed; at **right** are two oral tubes. (Courtesy of Rusch, Inc.)



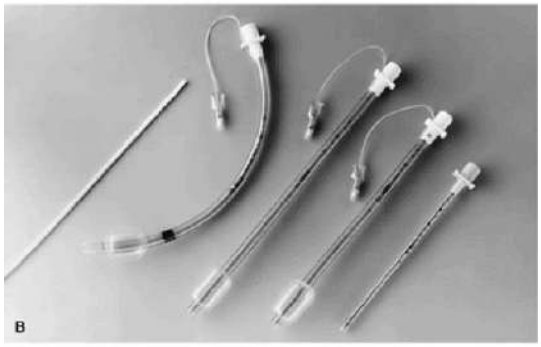


Figure 19.4 Spiral embedded tracheal tubes. **A:** Note the reference marks near the patient end of the tube to aid in positioning with respect to the vocal cords. (Courtesy of Mallinkrodt Medical, Inc.) **B:** Note that the tube on the **left** has a single reference mark. (Courtesy of Rusch, Inc.) **C:** The **middle** tube has a reinforcing covering over the bite area. Note again the referencing marks. (Courtesy of Kendall Healthcare Products Co.)

Spiral embedded tubes are especially useful in situations where the tube is likely to be bent or compressed, as in head and neck surgery. Another use is for surgery on the trachea. The tube can be placed by the surgeon.

The primary advantage of these tubes is resistance to kinking and compression. The portion of the tube outside the patient can be angled away from the surgical field without kinking. This makes them useful for

insertion into the patient with a tracheostomy (45), for submental

intubation (46,47,48,49,50), and retromolar positioning (51). A spiral embedded tube may pass more easily over a fiberscope than a conventional tube (52,53,54,55).

There are a number of problems with these tubes. A forceps and/or a stylet will often be needed for intubation. The tube may rotate on the stylet during insertion. It is difficult and sometimes impossible to pass the tube through the nose. Because of the spiral, these tubes cannot be shortened. The elastic recoil force may increase the tendency to unintentional extubation. They are difficult to insert through the intubating laryngeal mask airway (56). Spiral embedded tubes that have been resterilized have a high incidence of problems (57,58,59). For this reason, reuse is not recommended. Even single-use tubes may develop problems (60). Cases have been reported where a patient bit the tube, causing it to be severed or permanently deformed (61,62,63,64,65,66,67,68). A bite block between the molar teeth, not an oral airway, should be used to prevent this. Some spiral embedded tubes have an external reinforced covering over the bite portion (Fig. 19.4C). Kinking as a result of compression between a retractor and the teeth has been reported (69). The absence of a Murphy eye may result in obstruction if the bevel abuts the wall of the trachea (70).

Hunsaker Mon-Jet Ventilation Tube

The Hunsaker tube (Fig. 19.5) is laser-resistant and designed for subglottic jet ventilation. It is compatible with carbon dioxide, neodymium-yttrium aluminum-garnet (Nd-YAG), and argon lasers. The OD is 3 mm, and it has an integral lumen for monitoring airway pressure and respiratory gases. The patient end has a basket-shaped distal extension designed to center the tube. This tube has been used to administer one-lung ventilation (71).

Laryngectomy Tube

Laryngectomy tubes have a ſ€Jſ€ configuration at the patient end (73) (Fig. 19.6, left). They are designed to be inserted into a tracheotomy. This allows the part of the tube external to the patient to be directed away from the surgical field. The tip may be short and/or without a bevel to avoid advancement into a bronchus.

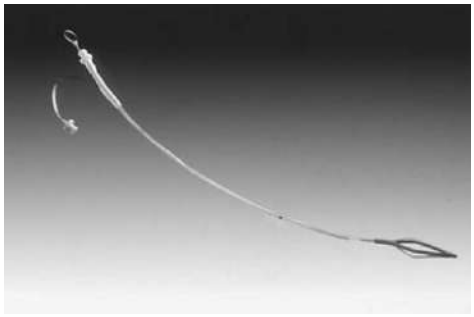


Figure 19.5 Hunsaker Mon-Jet ventilation tube.

Figure 19.6 **Left:** Laryngectomy tube. **Middle:** Injectoflex tube, which is used for procedures on the larynx. The tube has an embedded metal spiral. The insufflation lumen and cuff inflation tube are combined in one sheath with the malleable introducer. **Right:** Spiral embedded tube. (Courtesy of Rusch, Inc.)

The curve may need to be straightened to facilitate insertion. The tube can be secured by suturing or taping it to the chest wall (72).

A case of obstruction of this tube has been reported (73). The soft cuff and short distance between the cuff and distal tip of the tube may cause the bevel to abut the tracheal wall.

Microlaryngeal Tracheal Surgery Tube

The microlaryngeal tracheal surgery (LTS or MLT) tracheal tube (Fig. 19.7) is available with an ID of 4, 5, or 6 mm (74). The large cuff diameter is the same as that found on a standard 8-mm-ID tube. This helps to keep the tube centered in the trachea. One version has a yellow-colored cuff.

This tube is designed for microlaryngeal surgery or for patients whose airway has been narrowed to such an extent that a normal-sized tracheal tube cannot be inserted. The small tube diameter provides better visibility and access to the surgical field. Its length allows it to be used for intubation via a laryngeal mask airway (LMA) or other supraglottic airway device (76). Possible problems with a tube having such a small bore include incomplete exhalation and occlusion. This type of tube is not safe for use with lasers. It can be used for selective bronchial intubation (75) (Chapter 20).

Endotrol Tube

The Endotrol (trigger) tube (Fig. 19.8) has a pull ring loop (trigger) that is connected to the tip of the tube with a cable embedded in the tube wall. Pulling on the ring decreases the tube's inside radius and moves

the tip anteriorly. When used with a stylet, the tip alone can be controlled (77). The Endotrol tube has been used for blind intubations, including blind nasal intubation; intubation utilizing a lighted intubation stylet; and intubation using a laryngoscope (78,79,80,81,82,83,84,85,86).

Figure 19.7 Tubes for microlaryngeal tracheal surgery. **Top:** The cuff on this tube is colored yellow for greater visibility. (Courtesy of Sheridan Catheter Corp.) **Bottom:** Similar tube with an uncolored cuff.

In one reported case, obstruction to gas flow was noted after the tube was inserted nasally (87). The pull ring exerted tension on the pull wire, causing the tip of the tube to abut the tracheal wall. Cutting the pull ring alleviated the tension and the obstruction. Kinking during prolonged intubation has been reported (88).

EndoFlex

The EndoFlex tube is designed to aid intubation when the patient has an anterior larynx. Pulling the white bar toward the connector causes the tube to flex at the cuff and the tip to move anteriorly.

Parker Flex-Tip Tube

The Parker Flex-Tip tube (Fig. 19.9) has a ‘€hooded‘€ curved, flexible tapered tip that points

toward the center of the distal lumen on the concave surface of the tube so that the bevel faces posteriorly during insertion. There are Murphy eyes on the right and left sides of the tube. This tube is fitted with a very thin cuff. This tube is easier to advance over an intubating catheter or flexible endoscope than a

conventional tube (13,19,89,90,91). It is also less likely to impinge on the side of the right vocal cord than is a tube with the point of the bevel on the right. The tube is available in a variety of shapes with and without a cuff.

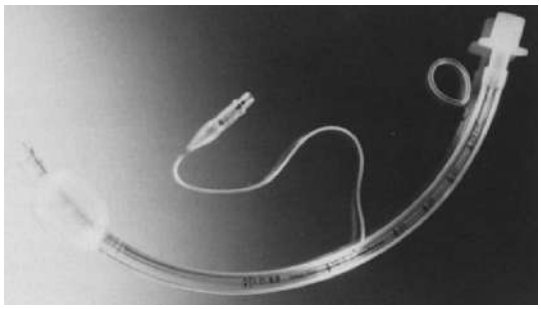


Figure 19.8 Endotrol tracheal tube. The ring is attached to the tip by a cablelike mechanism that allows the tip to be maneuvered. (Courtesy of Mallinckrodt Anesthesiology Division, Mallinckrodt Medical, Inc.)

Figure 19.9 Parker Flex-Tip tracheal tube. Note the two eyes and the ‾€hooded‾€ curved, flexible tapered tip that points toward the center of the distal lumen on the concave surface of the tube so that the bevel faces posteriorly during insertion.

Tubes with Extra Lumen(s)

Tubes with one or more separate lumens terminating near the tip are available (Fig. 19.10). They are useful for respiratory gas sampling, suctioning, airway pressure monitoring, fluid and drug injection, and jet ventilation. A number of problems are associated with these tubes (92). Secretions, blood, or moisture can obstruct the extra lumen. The sampling tube must be securely stabilized to minimize tension on the tube. Moisture may enter the gas lumen and cause problems with the gas monitor (Chapter 22).

The LITA (laryngotracheal instillation of topical anesthesia) (Fig. 19.11) has an additional small-bore channel incorporated within the concave surface of the tube. Ten small holes at the distal 13 cm of the tube allow the injected medication to be sprayed both above and below the cuff. Studies show that this can provide a smooth emergence from anesthesia without coughing in most cases (93).

Tubes with Embedded Fiberoptics

Tubes with fiberoptic channels embedded into the tube wall are available. When connected to a video system, the fiberoptic channel allows the larynx and trachea to be visualized. This type of tube can be used to confirm tracheal intubation and rule out bronchial intubation. These tubes may be useful for difficult intubations.

Laser-resistant Tubes

A number of tracheal tubes have been designed to be used when laser surgery is performed. The manufacturer's instructions should be consulted to determine which tubes should or should not be used with a particular laser. It is important to understand that these tubes are laser-resistant but may catch fire if the laser power is too great or the laser application too long. Lasers and fires are discussed in more detail in Chapter 32.

Laser-Shield II Tube

The Laser-Shield II (Fig. 19.12) is made from silicone with an inner aluminum wrap and an outer Teflon coating (94). It is designed for use with CO_2 and potassium-titanyl-phosphate (KTP) lasers. The cuff is not laser-resistant and contains methylene-blue crystals. It should be inflated with water or a saline solution. There is 1 cm of unprotected silicone tubing above the cuff. The part of the tube distal to the cuff is also unprotected. Cottonoids for wrapping around the cuff are supplied with each tube. These must be moistened and kept moist during the entire procedure.

Studies show that the wrapped portion of the shaft is not penetrated by a CO_2 or Nd-YAG laser, but the overlying Teflon may be vaporized (95). Exposure of the unprotected parts of the tube proximal and distal to the cuff can result in rapid combustion. The methylene-blue crystals may not fully dissolve and may obstruct the pilot tube, making it impossible to deflate (96).

Laser-Flex Tracheal Tube

The Laser-Flex tube (Fig. 19.13) is a stainless steel tube with a smooth plastic surface and a matte finish to reflect a laser beam. It is designed for use with CO_2 and KTP lasers. The wall of the tube is thicker than that of most other tubes (97). The adult version has two PVC cuffs and a PVC tip with a Murphy eye. The two cuffs are inflated by using separate inflation tubes that run along the inside of the tube. The distal cuff can be

used if the proximal one is damaged by the laser. Small uncuffed tubes are available.

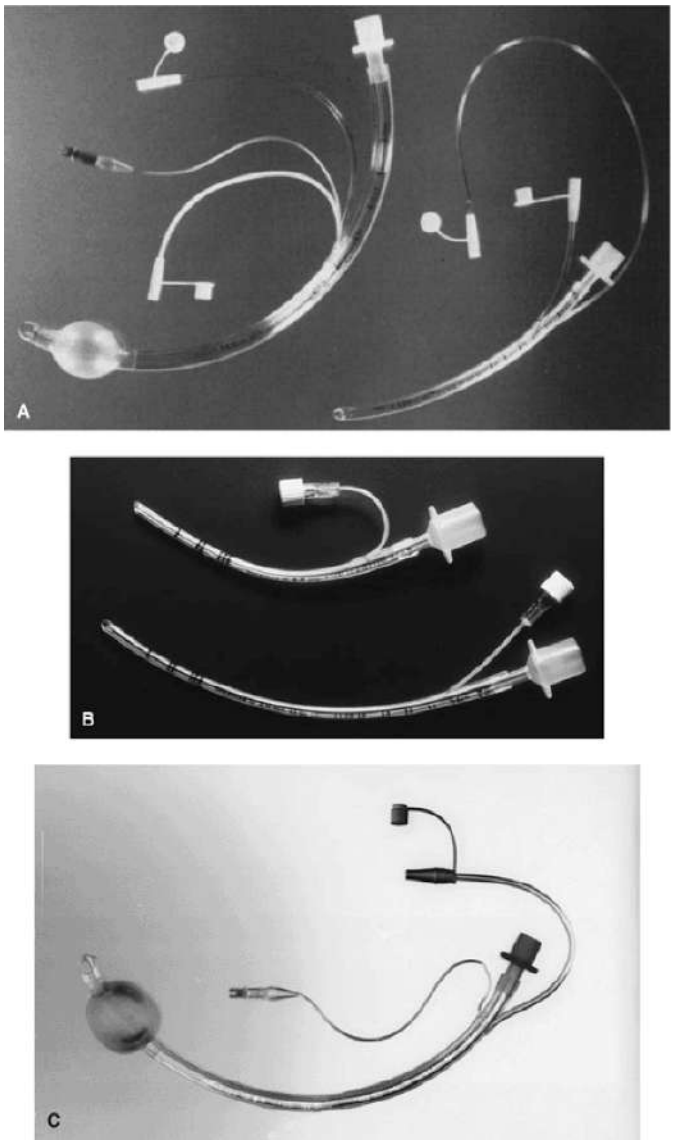


Figure 19.10 Tubes with additional lumen(s). These tubes have a main lumen for ventilation of the patient and one or more additional lumens for monitoring, irrigation, pressure monitoring, suctioning, and/or ventilation. **A:** These tubes have two additional lumens. The clear lumen is used for jet ventilation and administration of oxygen during suctioning and bronchoscopy. The opaque lumen can be used for irrigation and sampling of gases from the trachea. (Courtesy of Mallinckrodt Anesthesiology Division, Mallinckrodt Medical, Inc.) **B:** Pediatric tubes with monitoring lumens. (Courtesy of Kendall Healthcare Products Co.) **C:** Tube with lumen designed for subglottic suctioning. (Courtesy of Mallinkrodt Medical, Inc.)

The cuffs should be filled with saline colored with methylene blue

(98). The distal cuff should be filled first until sealing occurs, then the proximal cuff should be filled.

Studies show that the shaft holds up well when exposed to a CO_2 or KTP laser but not the Nd-YAG laser (97,99,100,101,102). Blood on the outside of the tube renders it less resistant to combustion with the CO_2 laser (103). The cuff and tip are vulnerable to all lasers. This tube is less likely to reflect CO_2 laser radiation than are other tubes (104).

The Laser-Flex tube is somewhat stiff and has a rough surface. The double cuff adds to the time of intubation and extubation. The large external diameter can be a

problem in small patients. In one reported case, great difficulty was experienced in removing the tube because of a subglottic mass (105). In another case, difficulty inserting an airway exchange catheter (AEC) occurred (106). The Laser-Flex tube will not fit over either of the Bullard stylets (Chapter 18), so this laryngoscope cannot be used with this tube. The tube will fit through the Upsher Scope (Chapter 18).

Figure 19.11 LITA (laryngotracheal instillation of topical anesthesia) tube. Small holes at the distal 13 cm of the tube allow the injected medication to be sprayed both above and below the cuff. The *black reference bar* indicates the position of the uppermost opening. (Picture courtesy of Kendall Healthcare Products Company).

Sheridan Laser Tracheal Tube

The Sheridan laser tube (Fig. 19.14) is a red rubber tube wrapped with copper foil tape. This is overwrapped with water-absorbent fabric that should be saturated with water prior to use. There is a copper band at the cuff-tube junction. Radiopaque pledgets that are designed to be moistened and placed above the cuff are provided with each tube. It is designed for use with a CO_2 or KTP laser. A disadvantage is that it has a thick wall (107). It has a high-pressure cuff.

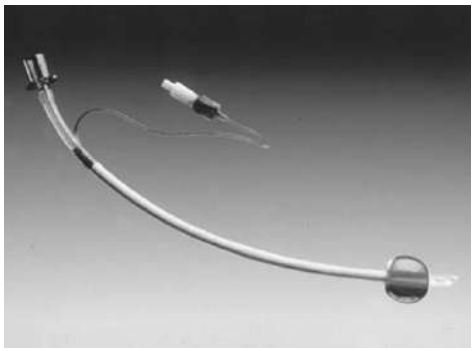


Figure 19.12 Laser-Shield II tracheal tube. (Courtesy of Xomed-Trease.)

Norton Tube

The Norton tube is a reusable, flexible, spiral-wound metal tube with a stainless steel connector and thick walls (108). The exterior of the tube has a matte finish to decrease reflection of the laser beam. It has no cuff. A separate cuff may be attached, or packing around the tube can be used to achieve a seal. Studies show this tube is acceptable for use with KTP, Nd-YAG, and CO_2 lasers (102).

There are a number of problems with this tube. Its flexible coils are not airtight, and angulation can result in a large leak (109). The tube's exterior is somewhat rough and may have sharp edges that could cause tissue damage (110). The large external diameter and stiffness can make surgical exposure difficult (111). The tube tends to twist on a stylet during intubation (102). It requires special ventilating techniques when used without a cuff. If it is used with a cuff, the cuff and its inflating tube can be ignited and may or may not remain attached to the tube.

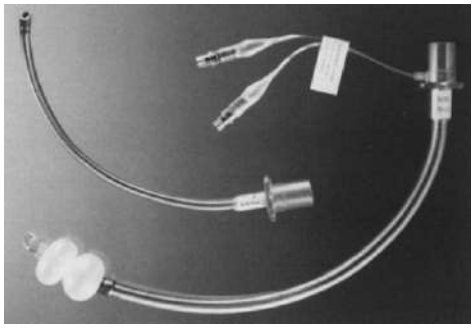


Figure 19.13 Laser-Flex tracheal tubes. The adult tube has two cuffs. The distal cuff can be used if the proximal one is damaged. (Courtesy of Mallinckrodt Medical, Inc.)

Figure 19.14 Sheridan Laser tracheal tube. The outer fabric should be saturated before use. (Courtesy of Kendall Healthcare Products Co.)

Bivona Fome-Cuf Laser Tube

The Bivona Fome-Cuf laser tube (Fig. 19.15) has an aluminum and silicone spiral with a silicone covering. It has a self-inflating cuff that consists of a polyurethane foam sponge with a silicone envelope. The cuff must be deflated before intubation or extubation (112). The cuff should be filled with saline during use. The cuff retains its shape and keeps a seal when it is punctured, but it can no longer be deflated for removal (77,102). The inflation tube runs along the exterior of the tube and is colored black so that it can be positioned away from where the laser will be used (113). It is marketed for use with the CO_2 laser.

The tube is poorly resistant to all lasers (99,100,102). When burned, the silicone covering forms an ash that sloughs off and is left in the trachea, but most of the tube stays intact (102). A high incidence of sore throat has been noted with this tube (114).

Lasertubus

This tube (Fig. 19.16) is made of white rubber and has a cuff-within-a-cuff design. If the outer cuff is perforated by the laser beam, the trachea will still be sealed by the inner cuff. The manufacturer recommends that the inner cuff be filled with air and the outer cuff with water or saline. The shaft above the cuff is covered by a corrugated silver foil, which is covered by a Merocel sponge that should be moistened with saline before use. This tube is recommended for use with argon, Nd-YAG, and CO_2 lasers (115). Bending the tube in the area above the sponge covering can predispose the tube to kinking (116,117).

EMG Reinforced Tracheal Tube

This tube (Fig. 19.17) is designed to monitor recurrent laryngeal nerve electromyogram (EMG) activity during surgery (118). The tube is wire-reinforced and has four stainless steel electrodes above the cuff. The electrodes are connected to a monitor (Fig. 19.18).

Manufacturing defects with this tube have been reported (119,120,121). It should be checked carefully for defects before

use.

Intubating Laryngeal Mask Tracheal Tube and Tube Stabilizer

The intubating laryngeal mask (ILMA, ILM, LMA-Fastrach) tracheal tube (Fig. 19.19) is designed to be inserted through the intubating laryngeal mask (Chapter 17) but can be purchased separately. It is a straight, wire-reinforced silicone tube with a tapered patient end, blunt tip, short bevel, and Murphy eye. It has a high-pressure, low-volume cuff (122,123) (Fig. 19.20). It is reusable and can be autoclaved. It is available in sizes 6, 6.5, 7, 7.5, and 8.

Figure 19.21 shows the tube stabilizer. It is used to stabilize the tube while the LMA is being removed.

This tube has been found to be easier to advance over a fiberscope than a plastic tube during both oral and nasal intubation (14,15,20,21,24). It has been used for submental intubation (124) and tracheal resection and reconstruction after the tip has been removed (125).

Problems reported with this tube include eccentric cuff inflation, internal deformities, and the tip folding during insertion (126,127,128,129). As with other spiral wire-reinforced tubes, biting can deform the spirals or cause

a leak (130). This tube should be used with caution if prolonged intubation is anticipated because of the high-pressure characteristics of the cuff (122,123,125,131). Cuff inflation should be limited to the minimum volume that seals the trachea. When exposed to the magnetic resonance imaging (MRI) environment, the tube poses no direct risk to the patient or other personnel. However, MRI quality may be compromised.

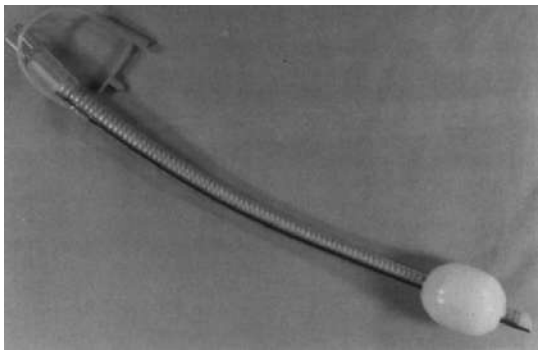


Figure 19.15 Bivona Fom-Cuf laser tube.

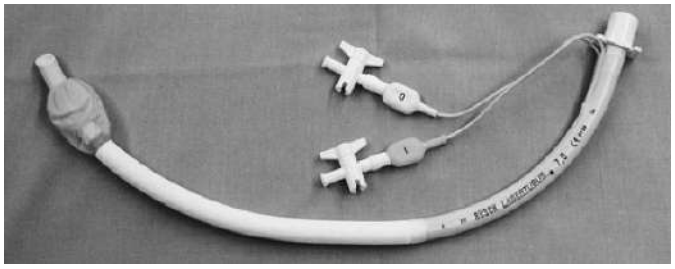


Figure 19.16 Lasertubus. The inflation tubes have stopcocks.

Hi-Lo Evac Tube

The Hi-Lo Evac tube (Fig. 19.22) incorporates a dedicated channel that can be used to clear secretions below the vocal cords but above the cuff. Results were mixed when using this tube to prevent or delay pneumonia (132,133,134,135,136,137,138). The lumen may become blocked by secretions (139).

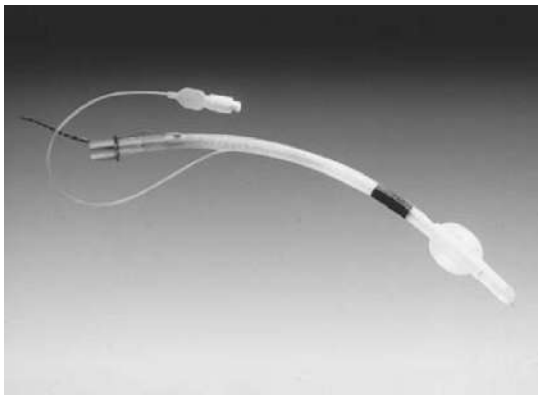


Figure 19.17 Electromyogram reinforced tube. Note the surface electrodes and electrode leads. (Courtesy of Xomed Surgical Products, Inc.)

Hi-Lo Jet Tube

The Hi-Lo Jet tube is an uncuffed tube with an additional lumen that can be used for jet ventilation, monitoring airway pressure, sampling respiratory gases, administering local anesthetics, or irrigating the airway (77,140). One problem with the tube is that a suction catheter may bind in the small tracheal tube lumen (141).

Tube Size

Current standards designate tracheal tube size by the ID in millimeters. The French scale size (three times the external

diameter in millimeters) may still be listed in catalogs and on packages and is used on some tubes (Figs. 19.2, 19.23). Because of variations in wall thickness, tubes having the same ID may have different external diameters (142,143,144). The standards also specify that tubes size 6 and smaller show the external diameter in millimeters (Fig. 19.3B). Many manufacturers also mark this on larger tubes.

The ASTM/ISO standard (11) requires tube size to be marked between the cuff and the take-off point of the inflation tube for cuffed tubes. For uncuffed tubes, the size marking should be toward the patient end. Some manufacturers also put the tube size on the pilot balloon so that the size can be determined when the tube is in place (Fig. 19.24).

Tube Length

The ASTM/ISO standard (11) specifies minimum tube length, which increases as ID increases. Most manufacturers supply tubes longer than the minimum required by the standard. Most tubes can be shortened. The length of a tube may vary (145).

Tube Markings

Typical tracheal tube markings, shown in Figure 19.23, are situated on the beveled side of the tube above the cuff and are read from the patient to the machine end. The following are required by the ASTM/ISO standard (11):

1. The word *oral* or *nasal* or *oral/nasal*.
2. Tube size in ID in millimeters. This may also be marked on the pilot balloon (Fig. 19.24).
3. The OD for tubes size 6 and smaller.
4. The name or trademark of the manufacturer or supplier.

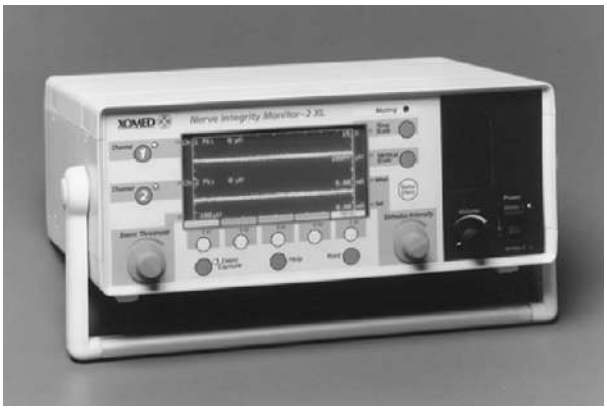


Figure 19.18 Monitor for use with EMG reinforced tube. (Courtesy of Xomed Surgical Products, Inc.)

5. Graduated markings showing the distance in centimeters

from the patient end. These allow the depth of insertion to be determined and monitored. On some tubes, the name of the manufacturer may replace the length markings (146). This can lead to problems with correct placement.

6. A cautionary note such as ‘€Do not reuse‘€ or ‘€Single use only‘€ if the tube is disposable.
7. A radiopaque marker at the patient end or along the full length.

Other markings not in conflict with those mentioned in the list may be applied.

Some tubes have markings (guide marks) to help position the tube with respect to the vocal cords (147,148,149,150,151,152,153,154) (Figs. 19.2, 19.4, 19.23).

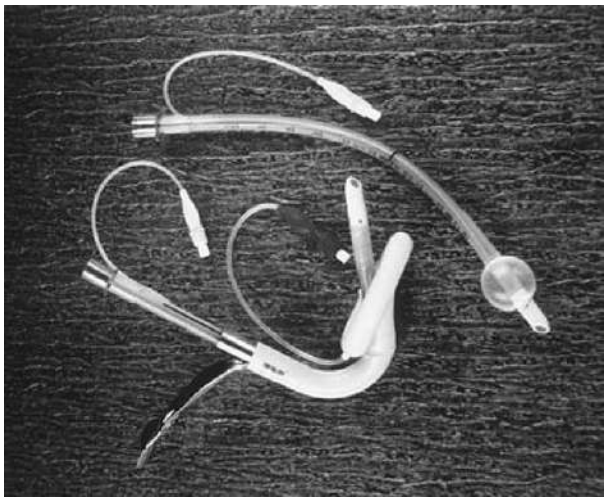


Figure 19.19 ILM-ETT. The *black circle* near the middle of the tube will be at the end of the connector when the tip of the tube is at the entrance to the bowl of the mask. (Courtesy of LMA North America.)

Cuff Systems

A cuff system consists of the cuff plus an inflation system, which includes an inflation tube, a pilot balloon, and an inflation valve (Fig. 19.1). An inflation lumen in the tube wall may also be present. The purpose of the cuff system is to provide a seal between the tube and tracheal wall to prevent passage of pharyngeal contents into the trachea and ensure that no gas leaks past the cuff during positive-pressure ventilation. The cuff also serves to center the tube in the trachea.

Cuff

The cuff is an inflatable sleeve near the patient end of the tube. The cuff material should be strong and tear-resistant as well as thin, soft, and pliable. Cuff materials are subject to the same

tissue-testing requirements as the tube itself.

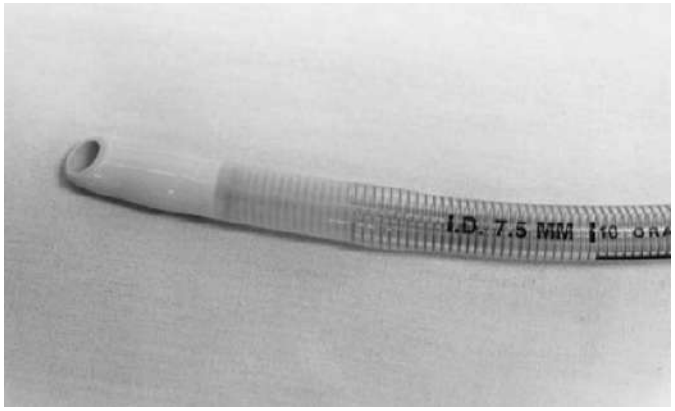


Figure 19.20 Tip of ILM-ETT. Note how the high-pressure cuff lies flat against the tube.

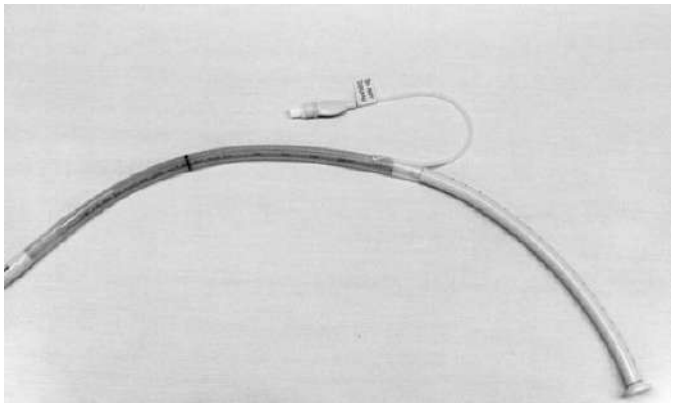


Figure 19.21 ILM-ETT with Stabilizer.

The ASTM/ISO standard (11) specifies the maximum distance from the tip of the tube to the patient end of the cuff. This varies with tube size. It also requires that the bonded edge of the cuff does not encroach on the Murphy eye, if present; that the cuff does not herniate over the tube tip under normal conditions of use; and that the cuff inflates symmetrically.

Cuff Types

The cuff type depends on its construction. The construction largely determines if the pressure needed to inflate the cuff is high or low.

Low-volume, High-pressure Cuff

Description

The low-volume, high-pressure (small resting diameter, low residual volume, lowÎ€“volume, small, standard, conventional, low-compliance, high-pressure) cuff has a small diameter at rest and a low residual volume (the amount of air that can be withdrawn from the cuff after it has been allowed to assume its shape with the inflation tube exposed to atmospheric pressure). It requires a high intracuff pressure to achieve a seal with the trachea. It has a small area of contact with the tracheal wall and distends and deforms the trachea to a circular shape (Fig. 19.25).

Figure 19.22 Hi-Lo Evac tube. (Picture courtesy of Tyco Healthcare.)

Most of the pressure inside this type of cuff is used to overcome cuff wall compliance. The pressure exerted laterally on the tracheal wall will be less than the intracuff pressure. The intracuff pressure does not change when the tracheal wall is contacted and does not bear a consistent relationship to tracheal wall pressure.

Advantages

These cuffs offer better protection against aspiration and better visibility during intubation than low-pressure cuffs. They may be associated with a lower incidence of sore throat (114,155). Because they are usually reusable, they are less expensive. They have been recommended for use in adolescent patients (156).

Disadvantages

The pressure on the tracheal wall exerted by such a cuff is difficult to determine but will likely be well above mucosal perfusion pressure (157). Intracuff pressure and the lateral pressure on the tracheal wall increase sharply as increments of air are added to the cuff. If the largest tracheal tube possible is used, the cuff will be minimally inflated when a seal is created.

The most serious risk associated with high-pressure cuffs is ischemic damage to the tracheal wall mucosa following prolonged use. Whether they should be used for short periods of general anesthesia is more controversial. If a tube with a high-pressure cuff is used intraoperatively and the tube must be left in place following surgery or the surgery is expected to last more than a few hours, it should be replaced with a tube with a low-pressure cuff.

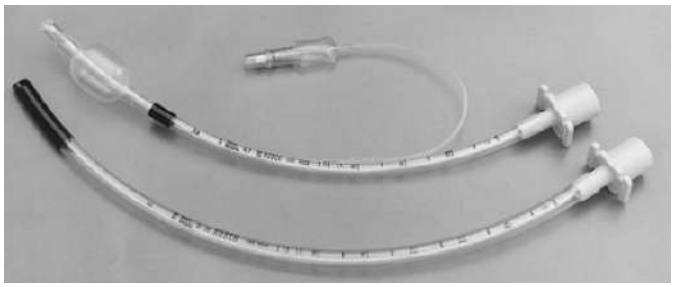


Figure 19.23 Typical tracheal tube markings. The dark marking at the patient end of the bottom tube and the mark above the cuff on the top tube are to aid in proper placement with respect to the vocal cords.The internal and external diameters as well as the size in French scale are shown. For example, on the **top** tube, the ID is 5.0, the external diameter is 6.7, and the French scale size is 20). Z-79 and IT both indicate that the tube material has passed the tissue toxicity test. Length from the patient tip is marked in centimeters. (Picture courtesy of Rusch, Inc.)

Figure 19.24 The tracheal tube size is marked on the pilot balloon.

High-volume, Low-pressure Cuff

Description

A high-volume, low-pressure (large resting diameter; large residual volume; large; high-volume; high-compliance, low-pressure; floppy; low-pressure, HVLP) cuff has a large resting volume and diameter. A thin compliant wall allows a seal with the trachea to be achieved without stretching the tracheal wall. As the cuff is inflated, it first touches the trachea at the widest part of the cuff or the narrowest point in the trachea under the cuff. As the cuff continues to inflate, the area of contact becomes larger and the cuff adapts itself to the tracheal surface (Fig. 19.25). If cuff inflation is continued, the area in contact with the cuff will be subject to increasing pressure, and the trachea will be distorted.

Different shapes have been used for the low-pressure cuff (158). A cuff with a short tracheal contact area may have fewer folds and wrinkles when inflated and may be associated with a lower incidence of postoperative sore throat. When high airway pressures must be used, a short cuff requires higher intracuff pressures than a cuff with a larger volume. The larger volume provides a greater reservoir of gas within the cuff, allowing additional gas to be ‘€milked‘€ into the proximal end of the cuff without increasing the resting cuff pressure (158).

The intracuff pressure varies during the ventilatory cycle. During spontaneous breathing, airway (and cuff) pressure will be negative during inspiration and positive during exhalation. With controlled ventilation, when airway pressure exceeds intracuff pressure, positive pressure will be applied to the lower face of the cuff. If the cuff wall is pliable, it will be unable to resist this pressure and will be deformed into a cone shape as the distal

portion is compressed and the proximal portion is distended (158). The air in the cuff will be compressed until intracuff pressure equals airway pressure. During exhalation, the intracuff pressure will decrease until its resting pressure is reached. A leak will develop if the diameter of the expanded trachea becomes greater than the diameter of the proximal end of the cuff. At that point, more gas must be added to the cuff to abolish the leak. Unfortunately, this additional cuff inflation will elevate the baseline cuff pressure.

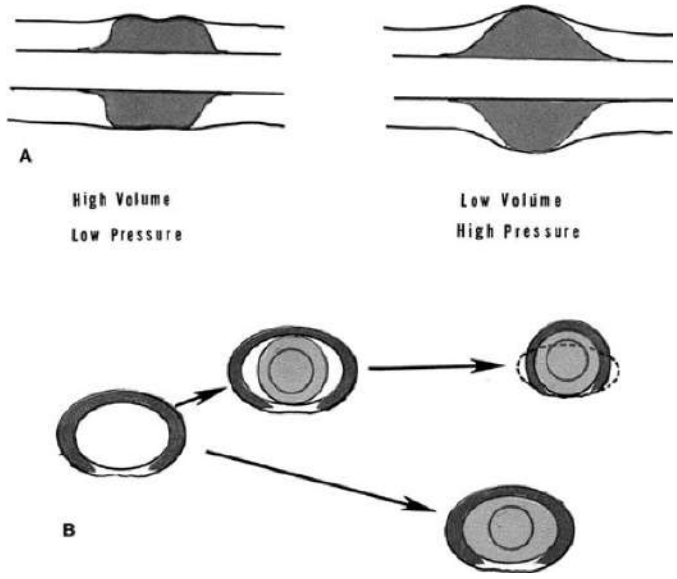


Figure 19.25 Relation of different types of cuffs to the trachea. **A:** Side view. At the **left**, the high-volume, low-pressure cuff has a large area of contact with the trachea. The cuff adapts itself to the irregular tracheal wall. At the **right**, the low-volume, high-pressure cuff has a small area of contact with the trachea. It distends the trachea and distorts it to a circular shape. **B:** Cross-sectional view. At the **left** is the normal trachea. At the **top**, the low-volume, high-pressure cuff distorts the trachea and makes the tracheal contour the same as the shape of the cuff. At the **bottom**, the soft high-volume, low-pressure cuff conforms to the normal tracheal lumen.

Inserting a gastric tube or esophageal stethoscope may increase intracuff pressure (159,160).

It is desirable that cuff circumference at residual volume be at least equal to the circumference of the trachea (161,162). If the cuff is smaller, it must be stretched beyond its residual volume to create a seal. At this point, it will act like a high-pressure cuff (158). On the other hand, if the residual cuff diameter is much greater than the diameter of the trachea, cuff infolding may occur, with the possibility of aspiration along the folds.

Advantages

A significant advantage of high-volume, low-pressure cuffs is that provided the cuff wall is not stretched, the intracuff pressure closely approximates the pressure on the tracheal wall (162). Thus, it is possible to measure and regulate the pressure exerted on the tracheal mucosa. With proper use, the risk of significant cuff-induced complications following prolonged intubation is reduced.

Disadvantages

Tubes with these cuffs may be more difficult to insert, as the cuff may obscure the view of the tube tip and larynx. The cuff is more likely to be torn during intubation, especially if forceps are used. There may be a greater likelihood that the tracheal tube with this type of cuff will be dislodged (163).

The incidence of sore throat may be greater with low-pressure than with high-pressure cuffs, unless the cuff is specially designed so that the tracheal contact area is small (114,155).

A major drawback of this type of cuff is that it may not effectively prevent fluid from leaking into the lower airway even at cuff pressures as high as 60 cm H_2O (157,164,165,166,167,168,169). Fluid leakage is increased with spontaneous respiration and is reduced with continuous positive airway pressure, positive end-expiratory pressure (PEEP), and pressure-supported ventilation (166). Intermittent positive-pressure ventilation adds some protection. Lubrication with a water-soluble gel will reduce fluid leak for a limited period of time (166,170,171,172). It has been shown that a silicone cuff without folds prevents the leakage of fluid when used with a constant-pressure inflation system (168,169,173,174,175).

It is relatively easy to pass devices such as esophageal stethoscopes, temperature probes, and enteric tubes around low-pressure cuffs (176,177,178,179,180). Suction applied to the gastric tube will result in negative pressure in the lungs.

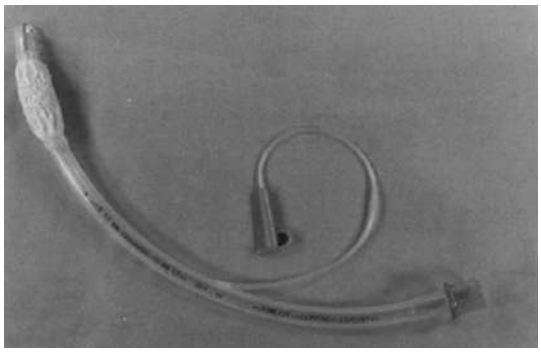


Figure 19.26 Tube with deflated foam cuff.

A problem with low-pressure cuffs is the belief that simply using this type of cuff will prevent high pressures from being exerted on the tracheal wall. Any cuff can be overfilled or the volume

and pressure can increase during use, resulting in high intracuff and tracheal wall pressures. Indeed, tracheal injury can occur even when these cuffs are used properly. When nitrous oxide is used, it will diffuse into the cuff. This added volume will increase the pressure on the tracheal mucosa (181,182,183,184,185,186,187).

Foam Cuff

The foam (sponge, Fome, Kamen-Wilkinson) cuff has a large diameter, residual volume, and surface area (182,188) (Figs. 19.15, 19.26). It is filled with polyurethane foam that is covered with a sheath. Applying suction to the inflation tube causes the foam to shrink. When the negative pressure is released, the cuff expands.

The tube is supplied with a T-piece to fit between the connector and the breathing system (Fig. 19.27). When the inflation tube is connected to this T-piece, the pressure inside the cuff will follow proximal airway pressure during the ventilatory cycle (182,188). Before extubation, the cuff should be collapsed by aspirating and then clamping the inflation tube.

When in place in the trachea, the amount that the foam expands determines the pressure exerted laterally on the tracheal wall. The more the foam expands, the lower the pressure (188). Thus, the pressure on the tracheal wall depends on the relationship between cuff diameter at residual volume and the diameter of the trachea. If too large a cuff is used, the cuff:tracheal wall pressure ratio will be high. If too small a cuff is used, there will not be a seal. The risk of fluid leaking past the cuff is similar to that with most high-volume, low-pressure cuffs (166).

Diffusion of anesthetic agents into the cuff can occur but will not cause an increase in pressure if the inflating channel is open to atmosphere (182,189). It is not necessary to monitor cuff pressure with this device. It can provide a seal at a low tracheal wall pressure, provided the relationship between the cuff and tracheal diameters is optimal (112,188). A reduced incidence of tracheal dilatation has been reported with its use (190).

One study found a high incidence of sore throat associated with its use (114), while another found a low incidence compared with air-filled cuffs (191). In two reported cases, the inflation tube was accidentally pulled out at the point of insertion on the tube, making cuff deflation impossible (192,193).

Lanz Cuff

The Lanz pressure-regulating valve (McGinnis balloon system) (194,195,196) consists of a

very compliant latex pilot balloon inside a transparent plastic sheath with an automatic pressure-regulating valve between the balloon and the cuff (Fig. 19.28). The pilot balloon has three functions: (a) an indication of cuff inflation, (b) an external reservoir for the cuff, and (c) a pressure limiting device. It is designed to maintain an intracuff pressure of 20 to 25 torr at end expiration while preventing overinflation of the cuff.

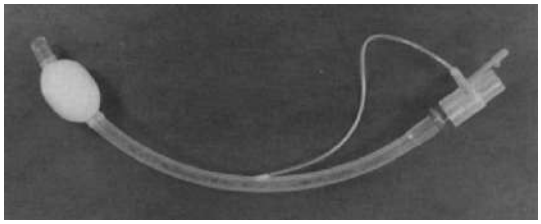


Figure 19.27 Tube with inflated foam cuff and a T-piece.

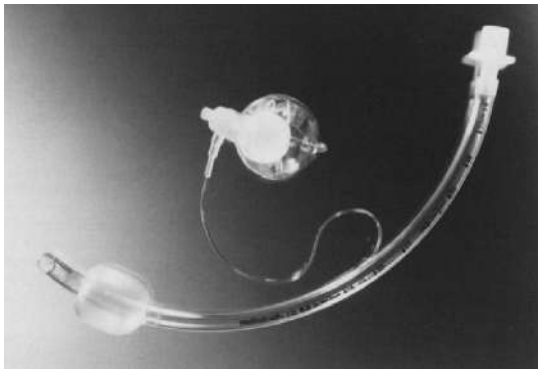


Figure 19.28 Lanz pressure-regulating valve. The pilot balloon is confined inside a transparent plastic sheath. There is a pressure-regulating valve between the pilot balloon and the cuff. Air should be injected into the cuff until the pilot balloon is stretched, but it should be smaller than the confining sheath.

The pressure-regulating valve permits rapid gas flow from the balloon to the cuff but only slow flow from the cuff to the balloon. This prevents gas from being squeezed back into the balloon when the airway pressure rises rapidly, so there is no gas leak around the cuff during positive-pressure ventilation. It also prevents increases in cuff volume and pressure caused by diffusion of nitrous oxide and other gases into the cuff.

As air is injected, the cuff and balloon are inflated in parallel. When the balloon has a stretched appearance, a pressure of approximately 26 to 33 cm H_2O will be present in the cuff. As injection continues, the pilot balloon fills preferentially. The intraballoon pressure remains constant and will not increase until it strikes the confining sheath. Should the trachea expand, air will slowly flow from the balloon into the cuff. The pressure-regulating valve protects against rapid loss of cuff volume into the balloon during inspiration.

This valve has been found by several investigators to be effective in keeping lateral tracheal wall pressure low and

preventing increases in cuff pressure due to nitrous oxide (189,194). It eliminates the need to measure cuff pressure.

For patients requiring high airway pressures, this system may fail to form a seal (197). The cuff may leak, particularly after prolonged use (198). If the balloon is compressed or overinflated, the intracuff pressure will rise.

Cuff Pressures

Intracuff Pressure

A high cuff pressure prevents aspiration, ventilatory leaks, and eccentric tube positioning in the trachea but can cause damage to the trachea. A low cuff pressure minimizes tracheal damage and can act to relieve excessive airway pressure but may result in aspiration, leaks, and eccentric tube positioning.

It is desirable that the cuff seal the airway without exerting so much pressure on the trachea that its circulation is compromised or the trachea is dilated. Most authors recommend that the pressure on the lateral tracheal wall measured at end expiration is between 25 and 34 cm H_2O (18 to 25 mm Hg) in normotensive adults (77,157,199,200,201,202). A patient who requires high peak inflation pressures will need a higher cuff pressure to prevent leaks (minimum occlusive pressure), increasing the risk of ischemic tracheal injury (202).

For children, no firm recommendations for cuff pressure have been reported, but it seems logical that lower pressure should be used because of their lower arterial pressures (203).

Changes in Intracuff Pressure

The intracuff pressure and volume of a cuff inflated with air rise when nitrous oxide is administered (181,182,183,184,185,186,187). The increase varies directly with the partial pressure of the nitrous oxide, the permeability of the cuff wall, and time. Heated humidification slows diffusion of nitrous oxide into the cuff (204). When nitrous oxide administration is discontinued, the pressure in the cuff decreases rapidly (205).

There are a number of other reasons why cuff pressure will vary. Cuff pressures are lower during hypothermic bypass (206,207). Increases in cuff pressure may result from pressure from nearby surgical procedures (208), increases in altitude (209), diffusion of oxygen into the cuff (210), and changes in head position away from the neutral position (211). Cuff pressure will also be affected by coughing, straining, and changes in the muscle tone. Foam-filled cuffs do not exhibit these fluctuations (191). During aeromedical transport, cuff pressure rises when altitude increases (212). Certain topical anesthetics can increase the cuff pressure with some tracheal tubes (213).

Means to Limit Cuff Pressure

1. Cuff pressure can be measured continuously or at frequent intervals and altered by inflating or deflating the cuff as needed. This is the only way to ensure adequate protection

from the threats of aspiration and tracheal ischemia (214). Measurement is easy, and cuff monitors are inexpensive. Pressures higher or lower than recommended are common when the cuff pressure is not measured.

Four hours may be needed to stabilize cuff pressure when using nitrous oxide (215,216). If the tracheal tube is to be left in place and nitrous oxide has been in use, the cuff should be evacuated and filled with air to avoid a leak in the postoperative period (217).

Several methods have been used to monitor intracuff pressures continuously or intermittently (197,198,199,200,201,202,203,204,205,206,207,208,209,210,211,212,213,214,215,216,217,218,219). Devices for this purpose are available commercially (Fig. 19.29). Cuff pressure can be measured by connecting the inflation tube to the pressure channel of a monitor by using an air-filled pressure transducer (220,221,222,223) or directly to a manometer (224).

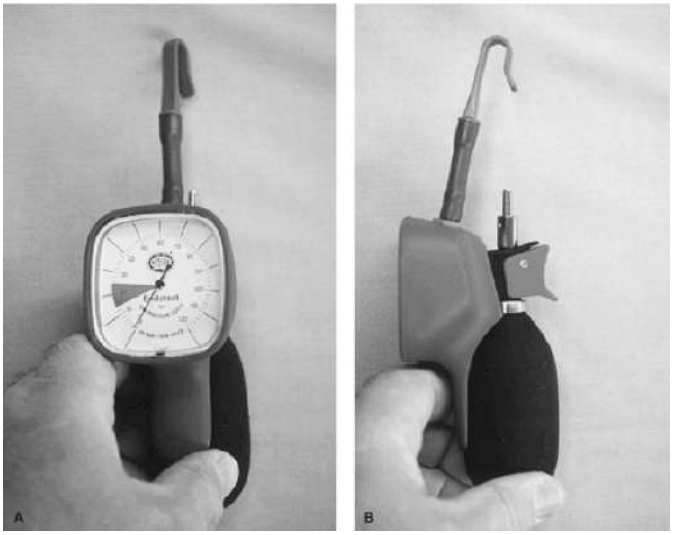


Figure 19.29 Device to measure intracuff pressure. **A:** Frontal view. **B:** Side view showing valve used to reduce the pressure. (Courtesy of Rusch, Inc.)

2. The cuff can be filled with a gas mixture containing oxygen and nitrous oxide or nitrous oxide alone (183,225,226,227,228). This is awkward to perform. A cuff inflated with nitrous oxide will lose volume and may allow a leak when nitrous oxide administration is discontinued or during extracorporeal circulation (205,217,229).
3. The cuff can be filled with water or saline (184,209,229,230,231,232). This results in a more stable pressure. However, the initial adjustment of cuff pressure is more difficult. Fluid-filled cuffs cannot be deflated rapidly.
4. The syringe may be left attached to the inflation tubing.

This has not been found to be effective in limiting pressure increases in the cuff (233,234,235).

5. Using a cuff designed to reduce diffusion of nitrous oxide, a cuff with a high compliance, or a cuff with a large thin-walled pilot balloon has been recommended (185,186,236,237,238,239,240,241,242).
6. Specialized balloon systems such as the Lanz pressure-regulating valve (see above) and various other devices for controlling cuff pressure have been developed (199,219,242,243,244,245,246,247,248).
7. Pressure may be assessed by manual palpation and pinching the pilot balloon. These methods do not give consistently accurate assessments of cuff pressure (249,250,251,252).
8. Using a minimal leak volume, minimal occlusive volume, or a predetermined volume to inflate the cuff has been found to be unsatisfactory (252).

Inflation System (Fig. 19.1)

Inflation Lumen

The inflation lumen, which connects the inflation tube to the cuff, is located within the wall of the tracheal tube. The ASTM/ISO standard (11) requires that it does not encroach on the tracheal tube lumen and recommends that it does not bulge outward.

External Inflation Tube

The external inflation tube (cuff tube, pilot tube or line, pilot balloon line, inflating tube, tail) is external to the tube. The ASTM/ISO standard (11) requires that its external diameter does not exceed 2.5 mm and recommends that it be attached to the tube at a small angle. The standard also specifies the distance from the tip of the tube to where the inflation tube is attached and requires that there is at least 3 cm between the machine end of the inflation tube and the pilot balloon or inflation valve.

The inflation tube can become obstructed by kinking, crushing from a clamp or external fixation device, methylene-blue crystals, or the tracheal tube connector (96,253,254,255).

Pilot Balloon

The pilot balloon (bulb, external reservoir, external balloon) may be located near the midpoint of the inflating tube or adjacent to the inflation valve. Its function is to indicate cuff inflation.

Inflation Valve

The inflation valve is designed so that when the tip of a syringe is inserted, a plunger is displaced from its seat and gas can be injected into the cuff. Upon removing the syringe, the valve seals so that gas cannot escape from the cuff. Some tubes may lack an inflation valve. If a valve is not present, cuff inflation is maintained by applying a clamp to the external inflation tube or by placing a plug in its free end.

Tracheal Tube Connector

The tracheal tube connector (union) serves to attach the tube to the breathing system. It may be made of plastic or metal. The dimensions of the connector are set by an ASTM/ISO standard (11).

The end that fits into the tube is called the *patient end*, and the size of the connector is designated by the ID of this end in millimeters. The end that connects to the breathing system is called the *machine end* and has a 15-mm male fitting. The connector should be the same size as the tube with which it is intended to be used. This will result in minimal reduction of the lumen and make separation unlikely.

The most commonly used connectors are the straight and 90ยฐ curved (right angle). Acute angle connectors with less than a 90ยฐ curve (Fig. 19.30) and flexible connectors are available. A curved or flexible connector may facilitate positioning the breathing system away from the surgical field but increases resistance and must be removed from the tube when it is desired to insert a stylet or suction catheter.

The connector may have protrusions, lugs, or other features to which elastic bands or other devices may be attached to prevent accidental disconnection from the breathing system. There is controversy as to their desirability, as they may increase the risk of accidental extubation. Some connectors have a port for respiratory gas sampling. Some have flanges to aid in holding the connector.

Many disposable tracheal tubes come with the connector only partly inserted. This is done by the manufacturer to prevent the tube from dilating and the connector from falling out. Before use, the connector should be fully inserted. Removing it from the tube and wiping the tube end with alcohol will facilitate full insertion and bond the connector with the tube. A towel clip may be used to remove a connector from the tracheal tube (256).

Occasionally, when the connector is firmly seated, the pilot tube may be occluded, blocking the inflation tube (253). This only occurs when the pilot tube enters the tracheal tube at the end where the connector is inserted.

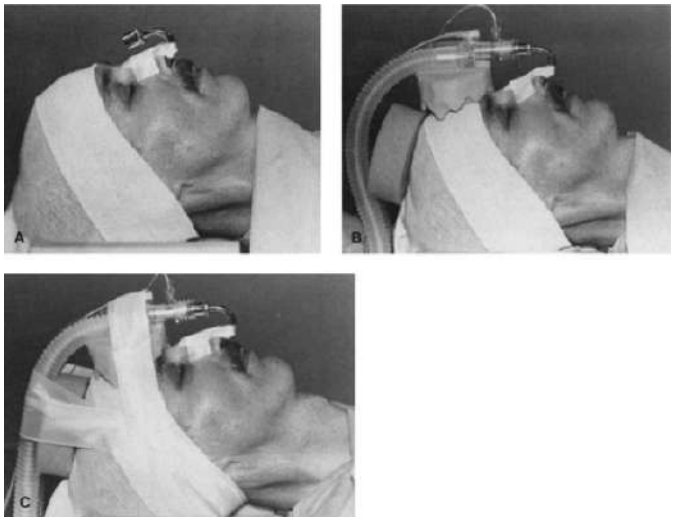


Figure 19.30 Method of securing a nasotracheal tube. **A:** A skull cap is placed around the head. An acute-angle connector is used and taped so that it does not exert pressure on the nasal ala. **B:** Foam padding is used to keep the breathing system from exerting pull on the tracheal tube. **C:** Tape is added to keep the breathing system firmly in place.

Laser-resistant Tracheal Tube Wraps

The only product approved by the Food and Drug Administration (FDA) for laser protection is a two-layered sheet of synthetic surgical sponge and adhesive-backed corrugated silver foil (Merocel Laser-Guard), which is available in several sizes. It can be used on rubber or PVC tubes but should not be used on a silicone tube. Before use, the tube with wrap is saturated with saline. When wet, the sponge and reflective foil act as a heat sink and disperse argon, CO_2, Nd-YAG, and KTP laser beams (102,104,247,248,249,250,251,252,253,254,255,256,257,258,259). The wrapped tube should not be used with Nd-YAG contact fiber tips, which may puncture and damage the wrap. Blood on the coating does not reduce its protective effect (103). It is important that the wrapping procedure recommended by the manufacturer is followed carefully and that the sponge material is kept moist during use. The cuff and the area below the cuff are not protected by the wrap. The cuff should be inflated with water or saline and methylene blue and protected by moistened cotton patties supplied with the tube. Breaks in the silver foil wrap when the tube was manipulated have been reported (260).

Other products including aluminum foil and tape and copper tape have been used to wrap tracheal tubes. These products are not approved for protecting tracheal tubes from lasers. These wraps have a number of disadvantages. They reduce tube flexibility, can predispose to kinking, and may create a rough surface (102,261,262). The OD of the tube is increased. Reflection of the laser beam from metallic tape may cause damage to non-targeted tissues (104). The wrapping material may come off and

obstruct the airway (263). Errors in wrapping or sharp bends could expose the tube to the laser beam (102,264,265).

Tube wrapping, fires, and lasers are discussed in more detail in Chapter 32.

Use of the Tracheal Tube

Tube Choice

Cuffed versus Uncuffed

Cuffed tubes are routinely used in adults (266,267,268,269,270,271). Traditionally, uncuffed tracheal tubes were routinely used in

young children, with the practice of adding a cuff beginning at 6 to 10 years of age (156). In recent years, cuffed tracheal tubes have been used more often in small children.

Advantages of cuffed tubes include improved accuracy of monitoring end-tidal gases, tidal volume, compliance, and oxygen consumption; decreased risk of aspiration; ability to use high inflation pressures and low fresh gas flows; less operating room (OR) pollution; decreased risk of fire; and fewer tube changes (269,272,273,274,275,276). There is a theoretical risk that infectious droplets will be dispersed when ventilating with an uncuffed tube (271).

Drawbacks of using a cuffed tube in children include the need to choose a slightly smaller tube (which makes suctioning more difficult and tube obstruction more likely and increases resistance and work of breathing); the risk that overinflation of the cuff will result in excessive pressure against the mucosa; the risk of injury to the vocal cords; and a reduced margin of safety (the need to avoid the cuff impinging on the glottis, yet avoiding bronchial intubation) (272,277,278,279,280). Relatively small amounts of inflated air lead to rapid increases in cuff pressure and volume (280). The larger external diameter of the cuffed tube may lead to problems with extubation (281). If a cuffed tube is inserted through a pediatric supraglottic device such as an LMA, it may be impossible to remove the supraglottic device after intubation (282).

Studies indicate that using cuffed tubes in children is not associated with increased complications (273,283,284,285,286,287,288). A cuffed tube may be used to occlude a tracheo-esophageal fistula (288,289,290).

Studies indicate that an ultrathin high-volume, low-pressure polyurethane cuff results in lower sealing pressures than conventional cuffs (203,291,292).

Size

Smaller-diameter tubes are easier to insert and require less reshaping force to adapt to the patient's airway but are associated with higher resistance, difficulty passing a fiberscope or suction catheter, and increased risk of occlusion and kinking (293). Larger tubes are associated with less risk of occlusion and lower resistance but are linked with a higher incidence of postoperative sore throat and are more difficult to insert.

Because no system of choosing the correct size tube is foolproof, the user should always have readily available tubes that are larger and smaller than the tube chosen. A smaller tube should be used when a difficult intubation is anticipated.

Cuffed Tubes

With cuffed tubes, the cuff circumference should equal that of the tracheal lumen. If the tube is too small, a high cuff pressure will be needed to achieve a seal, increasing pressure on the mucosa. If the cuff is too large in relation to the tracheal lumen, it will have folds when inflated to occlusion. Aspiration may occur along those folds.

TABLE 19.1 Recommended Tube Sizes for Children

Age	*Normal Size*
14 y	7.5Ĺ€“8
12Ĺ€“13 y	7Ĺ€“7.5
10Ĺ€“11 y	6.5Ĺ€“7
8Ĺ€“10 y	6Ĺ€“6.5
6Ĺ€“7 y	5.5Ĺ€“6
4Ĺ€“5 y	5Ĺ€“5.5
1.5Ĺ€“4 y	4.5Ĺ€“5
9Ĺ€“18 mo	4Ĺ€“4.5
Full term to 9 mo	3.5Ĺ€“4
Premature	2.5Ĺ€“3

One study found that the ideal tube in the average adult is a 7.5-mm-ID tube for females and an 8.5-mm-ID tube for males (294). However, there is great variation in sizes and shapes of tracheas in adults. The transverse dimensions increase with age, but in general, the correlation between age, race, height, weight, body surface area, and tracheal shape or size is poor. There is considerable variation in the cuff circumference of tracheal tubes with identical IDs.

Age is recognized as the most reliable indicator of the appropriate tracheal tube size for children (Table 19.1).

For cuffed tubes in children, the following formula may be used: ID in mm = age/4 + 3 (273). Alternately, a tube 0.5 to 1 mm smaller than that calculated for an uncuffed tube may be used. However, there are considerable differences in outer tube

diameters for a given ID cuffed tube from different manufacturers (278).

A child with Down syndrome has a smaller trachea, so a tracheal tube at least two sizes smaller than usual should be used (295). Premature babies have relatively elastic laryngeal structures that may allow a large tube to be inserted (296). This may result in injury to the posterior part of the glottis.

Uncuffed Tubes

With uncuffed tubes, the size should be large enough to provide effective ventilation but not so large as to cause pressure on the mucosa. This is commonly achieved by allowing a leak between the tube and the wall of the trachea at high peak airway pressures (20 to 25 cm H_2O) (143,297,298,299,300). Many factors influence the leak pressure, and these should be borne in mind when performing the leak test (268). Measuring the leak when the child's head is turned to one side or when he is not paralyzed increases the pressure required to cause the

leak. The importance of the presence of a leak has been challenged (301).

The following have been used as general guidelines for selecting the proper size tube in children. There is considerable variation in subglottic size in children and in the external diameters of pediatric tracheal tubes (143,302,303).

1. For children below 6 years: age in years/3 + 3.75

   For children older than 6 years: age in years/4 + 4.5 (277,304),
2. ID = age in years/4 + 4 or 3.5 (153,273)
3. ID = 3 mm for those 3 months of age and younger

   = 3.5 mm for those from 3 to 9 months of age

   = (age in years + 16)/4 over 9 months of age (298,305)
4. (age in years + 16)/4 (306)
5. Use of a measure based on body length (305,307,308,309).
6. Choosing a tube whose external diameter is the same width as the distal phalanx of the little or index finger. Studies indicate this may be less accurate than other methods (298,304) but may be useful when the child's age is unknown.
7. ID = 2.44 + (age ร— 0.1) + (height in cm ร— 0.02) + (weight in kg ร— 0.016) (310).

Checking the Tube

Before insertion, the tube should be examined for defects such as splitting, holes, and missing sections (311,312,313,314). The tube should also be checked for obstructions. With transparent tubes, simple observation will suffice (315). With other tubes, the user should look into both ends and/or insert a stylet.

The cuff, if present, should be inflated and the syringe removed to check for leaks in the inflation valve. If the syringe remains in the valve, the valve housing may crack and leak (316). The cuff should be inspected to make certain that it inflates evenly and does not cause the tube lumen to be reduced. It should be left inflated for at least 1 minute to check for a slow leak.

If the tube has a sponge cuff, all the air should be aspirated. The inflation tube should then be closed or clamped. The cuff should remain collapsed. If it fills, there is a leak, and the tube should be discarded.

Preparing the Tube

After the sterile wrapping is opened, the tube should be handled only at the connector end. The connector should be inserted as far as possible. Removing the connector from the tube and wiping the tube end with alcohol will make it easier to insert the connector into the tube and will allow it to bond to the tube. Using sterile lubricant jelly on a low-pressure, high-volume cuff may decrease aspiration by filling in the folds (166,170). For oral intubation, only the cuff should be lubricated. If nasal intubation is planned, lubricant should be placed along the entire length of the tube.

If a fiberoptic intubation or nasal intubation using a standard tube is intended, the tube should be warmed to increase flexibility (317).

Inserting the Tube

Techniques

Oral Intubation

Direct Laryngoscopy

Oral intubation is generally preferred for general anesthesia and in emergencies because it can be performed more quickly and easily than nasal intubation. It allows use of a wider and shorter tube than can be used for nasal intubation. Disadvantages include the possibility of oropharyngeal complications. Oral intubation is usually not well tolerated by the conscious patient. The patient with an oral tube has difficulty swallowing. Significant cervical spine motion may be associated with direct laryngoscopy (318,319).

Obstruction from biting can occur with oral intubation. A bite block, rolled gauze, or oral airway should be placed between the teeth to prevent the patient from biting the tube and occluding the lumen.

Inserting the tube is usually easy once the vocal cords are exposed. The tube should be introduced into the right corner of the mouth and directed toward the glottis with the bevel parallel to the vocal cords. If there is cord movement, the tube should be inserted during maximum abduction. Gripping the tube as shown in Figure 19.31 may facilitate anterior movement of the patient end of the tube during insertion (320).

Blind Oral Intubation

A blind oral technique is performed with the head flat, then tilted back in maximum extension (321,322). A stylet with a bend is inserted into the tracheal tube. The intubator applies pressure to the cricoid cartilage with one hand while the tracheal tube is introduced into the mouth with the other, following the curve of the tube. The tube is advanced until the intubator feels the tip or feels the tube advance into the trachea. It may be necessary to manipulate the larynx to the right or left to advance the tube into the trachea. The Endotrol tube may be useful in blind oral intubations (82,83). If the patient is breathing spontaneously, blind intubation may be performed by using capnography to obtain the optimal CO_2 waveform (323,324) or a whistle-type device such as the Beck Airway Airflow Monitor (BAAM) may assist placement (83). The tracheal tube with disposable whistle attached is passed blindly into the oropharynx and advanced slowly. When the whistle sounds loudest, the tracheal tube is advanced. As with any blind technique, bleeding may occur. This will make

fiberoptic techniques more difficult if the blind intubation is not successful.

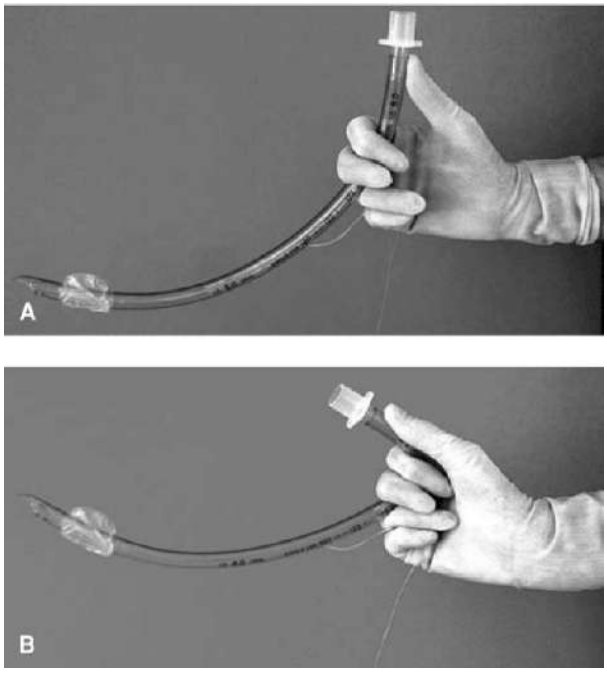


Figure 19.31 A: The tracheal tube is gripped as shown in the picture with the thumb on the shaft near the connector and two fingers around the tube. **B:** Pushing forward with the thumb will cause the tip to move forward.

Digital Technique

In a digital (tactile) technique, one hand is placed in the patient's

mouth, and the fingers are slid posteriorly along the tongue. The other hand introduces the tracheal tube into the mouth, and the intraoral hand is used to guide the tracheal tube tip. Several variations of this technique have been described (325,326,327,328,329,330,331).

Nasal Intubation

The nasal route is commonly used for surgical procedures involving the oral cavity, oropharynx, and face where an oral tube would hinder the surgeon's access to the operative field (332,333). Other indications may include a fractured mandible, limitation of movement at the temporomandibular joints, a patient with a neck injury or cervical spine disease, intra-oral pathology including mechanical obstruction, and patients who will not tolerate direct laryngoscopy.

Intubation by the nasal route has many advantages. Securing the tube is easier. The nasal route eliminates the possibility of the tube being occluded by biting. Nasal intubation may cause less cervical spine movement than oral intubation (318,334,335). Disadvantages include the fact that a smaller tube must be used, resulting in increased resistance and difficulty in suctioning or endoscopy. Intubation usually takes longer. Severe bleeding may occur (336). Nasal intubation has been shown to result in a high incidence of bacteremia, sinusitis, and otitis (337,338,339,340,341,342,343).

Contraindications to nasotracheal intubation include coagulopathy and any mechanical impediment of the nasotracheal route, including polyps, abscesses, foreign bodies, and possibly epiglottitis (344). A fracture at the base of the skull is usually considered a contraindication to nasotracheal intubation (345), although it has been safely used in this situation (346,347,348,349). Fiberoptic-guided intubation should be used (350). Pneumocephalus has been reported after nasal intubation in a patient who had had a repair of the cribiform plate (351). Trans-sphenoidal surgery can leave a bony defect in the skull that is susceptible to perforation by a nasal tube (352).

A tracheal tube one size smaller than would be considered optimal for oral intubation is preferable to minimize trauma. It should be thoroughly lubricated along its entire length with a sterile, water-soluble lubricant. The cuff should be fully deflated.

If possible, a fiberscope should be passed through the nostrils to determine the presence of abnormalities (349,353,354). Clinical tests such as estimating the rate of airflow by palpation when the contralateral nostril is occluded or asking for the patient's assessment of airflow through the nostrils does not correlate with nasal abnormalities (355). Inserting progressively larger lubricated nasal airways will test the patency of the nostril and dilate it. Other methods to decrease trauma include applying a vasoconstrictor; using a Magill-tipped tube; using a silicone tube with a hemispherical bevel; thermosoftening the tube; passing the tube through a nasal airway; using an intraluminal balloon or esophageal stethoscope; slipping the end of a catheter or glove finger over the tip of the tracheal tube; and inserting the tube over a bougie, stylet, or catheter (25,32,356,357,358,359,360,361,362,363,364,365,366,367,368,369,370,371,372). Using a bougie or stylet with an anterior curve will facilitate

intubation. Nasal treatment with mupirocin is effective in preventing bacteria from being carried into the trachea (373).

When the tube is inserted, the bevel opening should face laterally (374,375). It should be advanced along to the floor of the nose while slightly lifting the tip of the nose (375,376). The tube should be pulled cephalad as it is passed posteriorly until it contacts the posterior pharyngeal wall. From this point, the natural curve of the tube and the anterior body of the cervical spine will usually direct it anteriorly. Only gentle pressure should be used. If excessive resistance is encountered, the other nostril or a smaller tube should be tried (376).

Sometimes, the tube will impact the posterior pharyngeal wall and resist attempts to advance it farther. The tube should be pulled back a short distance and the patient's head extended to facilitate passage beyond this point. It may be useful to withdraw the tube and place a stylet with an acute bend in the distal 1.5 cm into the

tube. The tube is then inserted until it passes the posterior nasopharynx, then the stylet is withdrawn. Another technique is to pass a suction catheter through the tube and into the oropharynx. The tip of the catheter can be brought out through the mouth. A forward pull on the catheter will usually bring the tip of the tracheal tube forward. Anticlockwise rotation may assist passage at this point (332,377). If the tube deviates laterally, it should be withdrawn to the upper part of the oropharynx and redirected after a rotation of 30ยฐ or more (333). Tilting (not rotating) the patient's head toward the side of the intubation may also be helpful (378).

Direct Laryngoscopy

After the tube is in the pharynx, the larynx is exposed by using a rigid laryngoscope. If the tube impinges on the anterior commissure, it should be twisted while applying gentle downward pressure (379). The position of the larynx relative to the tube tip may be altered by flexing or extending the neck and/or external pressure on the larynx. If these manipulations do not align the tube and laryngeal opening, forceps can be used to grasp the tip and direct it through the vocal cords. The cuff should not be grasped, as it may be damaged by the forceps.

An alternative to grabbing the tube with a forceps is to add 10 to 15 mL of air to the tracheal tube cuff (380). This may cause the tip to align itself with the vocal cords. The tube tip is then pushed into the trachea until the cuff contacts the vocal cords, at which point the cuff is deflated and the tube is inserted into the trachea.

If the tip passes through the vocal cords but then encounters resistance, it is likely that the curve of the tube is directing the tip into the anterior wall of the larynx. Withdrawing the tube slightly and flexing the neck will usually allow the tube to advance into the trachea. Other techniques include rotating the tube 180ยฐ, passing a suction catheter or bougie through the tube into the larynx as a guide, and inserting a stylet with an anterior bend near the tip.

Flexible Fiberoptic Laryngoscopy

This method is often preferred. Blind nasal intubation may stir up bleeding and ruin the chance to view the larynx through a fiberscope. The technique is described in Chapter 18. A wire-reinforced, Parker Flex-Tip, or warmed standard tracheal tube may facilitate intubation with a fiberscope (13,19,52,53,54,55,317). Passage beyond the epiglottis may be facilitated if the tube is rotated so that the bevel is facing up (23).

Blind Nasal Intubation

The blind technique may be useful when direct laryngoscopy or fiberoptic intubation would be difficult. There are instances where blind nasal intubation may prove life saving, and the technique is well worth learning (381,382,383).

Blind nasal intubation may be performed under general or local anesthesia. A tracheal tube with directional tip control may improve the success rate (84,86). The classical technique of blind nasal intubation requires a spontaneously breathing patient and uses breath sounds to guide placement. The patient is placed in the classical intubating position with the neck flexed and the head extended. After the tube is inserted through the nostril, it is advanced blindly. If the patient is breathing spontaneously, breath sounds can be heard as the tip approaches the larynx. When the sounds are at maximal intensity, the tube is gently but swiftly advanced during inspiration. If the sounds suddenly cease but the patient continues to breathe, the tube has passed into a location other than the trachea.

Various modifications of this technique have been described (384,385,386,387,388,389,390,391,392). The BAAM and other whistle devices have been used to facilitate detecting airflow during intubation (330,393,394,395,396,397). These devices are attached to the machine end of the tracheal tube and make a sound as air passes through the tube.

The presence of end-tidal CO_2 can also be used as a guide to blind intubation (398,399,400,401). If CO_2 ceases to be detected, the tube has entered the esophagus.

If the patient is not breathing, certain landmarks on the front of the neck (hyoid bone, notch of the thyroid cartilage, and the cricoid cartilage) can be observed. As the tube moves anteriorly, the tip moves these landmarks. The object is to move the tip to the midline at the thyroid angle, where it should enter the larynx. If the tip is above the thyroid cartilage, flexing the head will move the tip caudally. If the tip is below the thyroid cartilage, neck extension will move it cephalad. If the tip is observed laterally, the tube should be withdrawn and twisted to direct it toward the midline. If the tube tip passes the laryngeal inlet but impinges on the anterior trachea, increasing cervical flexion or rotating the tube through 180ยฐ may allow it to pass into the trachea.

Other maneuvers may be employed to aid blind nasal intubation. Flexion or extension of the head or manipulating the larynx by external pressure may line up the tube and larynx (402).

Rotating the tube may be helpful (332,403). A stylet can be inserted into the tube to help to advance the tip through the vocal cords. The cuff may be partially inflated in the oropharynx to elevate the tip from the posterior pharyngeal wall and center it (380,402,404,405,406,407,408). The cuff is deflated before the tube is advanced into the trachea. A suction catheter or nasogastric tube that is inserted through the tube may facilitate passage through the larynx (409,410,411). A bougie can be used (412). Blind nasotracheal intubation facilitated by continuous fluoroscopy has been described (413).

Depth of Insertion

In adults, the tube should be inserted until the cuff is 2.25 to 2.50 cm below the vocal cords (147,414). This should be regarded as a starting position, as there is great variation in the length of the trachea. Some manufacturers

place a mark above the proximal end of the cuff and recommend that the tube is advanced until this mark lies at the vocal cords. If no cuff is present, the tube tip should be inserted not more than 1 cm past the cords in children under 6 months, not more than 2 cm past the cords for patients up to 1 year, and not more than 3 to 4 cm past the cords in larger patients.

In average-size adult patients, securing the tube at the anterior incisors at 23 cm in males and 21 cm in females has been shown to be a reasonable starting point for tube placement (415,416). For nasal intubations, 5 cm should be added to these lengths for positioning at the nares (417). However, caution should be exercised in using routine depth of insertion, as tracheas vary in length (418,419,420,421).

Formulas based on the subject's height or other measurements may be used (422,423,424), or the correct length can be estimated by aligning the proximal end of the cuff externally at the level of the cricoid cartilage and angling the tube anteriorly toward the level of the upper incisors or gums (425).

Checking Tube Position

After the tube has been inserted, its position should be checked to be certain that it is in the tracheobronchial tree and that it is neither too deep nor too shallow. Methods to detect bronchial or esophageal intubation are discussed in the Perioperative Complications section later in this chapter. After correct placement is confirmed, the portion of the tube external to the patient may be shortened to prevent kinking (426).

Inflating the Cuff

Low-volume, High-pressure Cuff

A high-pressure cuff should be inflated with the minimal amount of gas that will cause it to seal against the trachea at peak inspiratory pressure. Listening with the unaided ear will often miss small leaks. These can be detected by palpation or auscultation of the pretracheal area. Inflation until the pilot balloon is tense and/or inflating beyond seal will result in unnecessarily high cuff volume and pressure.

Low-pressure, High-volume Cuff

With a low-pressure, high-volume cuff, the cuff should be inflated to a pressure of 25 to 34 cm H_2O (18 to 25 mm Hg) at end-expiration in adults (77,157,197,200,201,202). No data exist in children about cuff pressure limits, but lower cuff pressures are preferable. The pressure should be measured (Fig. 19.29) and adjusted approximately 10 minutes after the tube has been inserted. This delay is necessary to allow for softening of the cuff material at body temperature and for the patient to become settled, because the volume necessary for occlusion will vary with muscle tone. Not measuring the pressure will usually result in a pressure well above that recommended (139).

After cuff pressure has been adjusted, a check should be made to make certain that there is no leak at peak airway pressure. A leak can be detected by a difference between inhaled and exhaled volumes, a noise heard with a stethoscope around the cuff, or by monitoring for CO_2 in the upper airway (139).

Cuff pressure should be measured and adjusted frequently. Changes in muscle tone in the trachea and diffusion of gases across the cuff may result in large cuff pressure changes. The peak inspiratory pressure may also change, so frequent checks for leaks should also be performed.

When a tracheal tube with a Lanz pressure-regulating valve is used, the cuff should be inflated until a seal is achieved during peak inspiration. The pilot balloon should be distended but smaller than the confining sheath.

Sponge Cuff

After intubation, the inflation tube should be opened to atmosphere and the cuff allowed to fill with air. The amount of air in the cuff should be determined by withdrawing the air with a syringe. The ability to remove 2 to 3 mL from the smallest cuff or 5 to 6 mL or more from the largest cuff usually signifies that the cuff:tracheal wall pressure ratio will allow adequate mucosal perfusion. If little or no air can be aspirated, the cuff may be too large.

If a leak is present after the cuff has been allowed to expand, wrinkles in the cuff may be present and may be straightened out by injecting 2 or 3 mL of air into the cuff and then allowing it to deflate. If the leak persists, a larger tube may be needed.

Securing the Tube

A securely positioned tracheal tube is essential for safe anesthesia. If the tube is not well fixed, there is danger of accidental extubation, or the tube may advance into a bronchus. The technique used to fix the tube must be appropriate for the nature of the surgery and allow access to the tube. Gently pressing the chin toward the maxilla will help to keep the tube in position while it is being secured (427).

Adhesive tape is most commonly used to maintain the tube in the desired position. A variety of taping methods have been used (428,429,430,431,432,433). The part of the tube to which the tape is to be applied should be thoroughly dried. All tapes do not adhere to all tracheal tubes equally well (429,433), so it is

advisable to test available tapes to determine which works best for the chosen tube. Adhesion to both the patient and the tube may be

improved by using a transparent adhesive dressing (434,435,436) or an adhesive such as tincture of benzoin (434,437). If possible, the tape should not be placed across the connector, because it may obscure a disconnection and hinder rapid reconnection (438,439). Securing the edges of the tape with tape at a right angle will prevent loosening at the edges (437). A clear adhesive dressing placed over the tape will protect it from oral secretions, blood, or prep solutions (440). A gauze pad may be used to protect the patient's face from the connector, especially when the patient is in the prone or lateral position (441).

Many patients have beards or mustaches, making it difficult to attach the tape. For patients with sufficiently long mustache hair, this can be taped to the tracheal tube (442). If a mustache interferes with proper fixation, the patient should be informed preoperatively that trimming or even shaving may be necessary. Because hair is an insecure medium for fixing a tube, a close-fitting skull cap, elastic net, or a towel taped around the head may be used to provide a structure to attach tape or ties (Fig. 19.30). Another method is to use double-sided tape to attach an elastic strap (443).

Some patients have cutaneous responses to adhesive tape (444,445,446). Fragile skin is commonly present with prematurity, chronic steroid treatment, zinc deficiency, amyloidosis, epidermolysis bullosa and patients receiving cosmetic skin exfoliants. In these patients, other materials such as a tie should be used to anchor the tube (428,447,448,449,450,451,452).

Special devices (tube holders, fixation devices) for securing tracheal tubes without use of adhesives or ties are available commercially (453,454,455,456). A tube holder may be combined with a bite block and/or nasogastric tube holder (457,458).

Special methods for securing the tracheal tube in patients with trauma or facial burns have been described (448,459,460,461,462,463,464,465,466,467,468). Complicated craniofacial procedures and reconstructive surgery may require securing the tracheal tube to a stable tooth by using a wire, suture, or dental floss (448). The tube may also be sutured to the tongue, between the teeth, to a mandibular structure, or to the nasal septum (469,470,471).

A nasal bridle may be used for fixation of a nasotracheal tube (472,473,474,475). A section of material (e.g., feeding tube or umbilical tape) is looped around the nasal septum. The three tubes (nasotracheal and two ends of the fixation material) are then secured together close to the external nasal septum. This may be especially useful in patients with tape allergies or excessive secretions.

Changing the Tube

Replacing a tracheal tube may be necessary if the tube is damaged or obstructed or a larger tube is required (476,477). It

may be necessary to change from an oral to a nasal tube or vice versa. There are several techniques: direct laryngoscopy, using a flexible endoscope, using a laryngeal mask, and using a tube changer (discussed later in this chapter). Combining these methods may confer additional safety (478,479,480,481,482).

Changing an oral tube to a nasal tube by using an AEC is discussed later in this chapter. Another technique is to insert a fiberscope loaded with a tracheal tube through the nostril and then insert the tip into the trachea beside the oral tube. The oral tube is then withdrawn and the nasal tube advanced into the trachea. Alternately, a fiberscope may be inserted through the nostril, retrieved orally, then passed through the existent oral tracheal tube (483). The fiberscope and tube are then withdrawn retrograde through the nasal passage.

Removing the Tube

The oral airway or bite block should be left in place until after extubation to avoid biting on the tube (67,484,485,486,487). Lidocaine sprayed down the tracheal tube will attenuate the airway and circulatory reactions during emergence and extubation (488,489). Respiratory and cardiovascular complications that are commonly associated with extubation can be decreased by inserting a supraglottic airway device (Chapter 17) before or just after removal of the tracheal tube (490,491,492,493,494,495,496,497,498,499,500,501,502).

Extubating a patient in whom it may be difficult to re-establish an airway is best carried out in a staged or ĩ€reversibleĩ€ manner, permitting reintubation while allowing oxygen administration by insufflation or jet ventilation while the airway is being secured (503,504,505,506,507,508,509,510). An AEC that can be connected to the breathing system or other oxygen source may be useful for this purpose. In the very small patient, a guide wire may be used (509).

Before extubation, the mouth and pharynx should be suctioned and the tape or other fixation device removed. Withdrawing the tube until resistance is met before deflating the cuff may push material that has accumulated above the cuff into the pharynx, where it can be removed by suctioning. A large sustained inflation should be administered (504,511). Alternately, the adjustable pressure limiting (APL) valve can be closed and airway pressure allowed to rise to 5 to 10 cm H_2O (512). While the lung is near total capacity, the cuff should be deflated and the tube removed. If a syringe cannot be located, the tip of a pen can be inserted into the valve assembly to deflate the cuff (513). The practice of pulling the pilot balloon and inflation valve from the inflation tube to deflate the cuff should be discouraged, as this can cause the inflation tube to seal (514,515,516). Suction should not be applied to the tube during extubation, as this will cause oxygen desaturation (511,517).

If the tube cannot be easily removed, the inflating tube should be checked for obstruction, especially at the

point where tape was used to hold the tube in place. If the surgery has involved the mouth, neck, or thorax, a suture may have been placed through or around the tube. If the tube is

forcibly removed in these circumstances, the surgical site may be disrupted.

Using Open but Unused Tubes

Many clinicians feel that it is necessary to open one or more tubes of different sizes. This raises the question as to whether it is safe to store these tubes for another day. Studies indicate that tracheal tubes can be used up to 14 days after being opened (518,519). However, if a lubricant has been used, it may dry out and form flakes (520).

Perioperative Complications

Failure of the Tube to Pass into the Trachea over an Intubating Device

It is sometimes difficult to pass (railroad) a tracheal tube over a fiberscope, lighted stylet, bougie, or airway exchange catheter (AEC) and through the glottic opening. When using a flexible endoscope, this can often be prevented by using the largest scope that fits easily inside an appropriate size of tracheal tube and keeping the fiberscope in the midline (521,522,523,524,525,526,527). A tube with a tip designed to minimize the distance between the fiberscope and the leading edge of the tube may pass more easily than a standard tube (14,15,18,19,20,21,24,90,91,528). A spiral embedded tube may pass more easily over a fiberscope than a tube with a preformed curve (53,54,55,529,530). Warming a standard tracheal tube may facilitate its passage (55,317). The tube may pass more easily if it is reverse loaded (upside down from its natural curvature) (527,531).

Other maneuvers can be taken to facilitate passing a tracheal tube into the trachea (532). A supraglottic device such as an LMA may facilitate intubation (533). Rotating the tracheal tube 90ยฐ counterclockwise may be helpful (18,277,505,524,526,534,535,536,537). Other helpful maneuvers are neck extension, using a rigid laryngoscope to open up the airway, applying a jaw thrust, and applying external pressure to the larynx (521,538,539,540,541). Another method is to insert a smaller tracheal tube beyond the tip of the tracheal tube (529,533,542,543). A stylet may be placed within the tube with the fiberscope (544). Still another technique is to pass an AEC via the tracheal tube beside the flexible scope until the tip of the catheter is visualized near the carina (545). A sleeve may be placed on the fiberscope to increase its diameter (522,546). If the patient is awake, he can be asked to take a deep breath or in the sitting patient to look upward (547).

Trauma

Intubation is often associated with trauma to the structures in the upper and lower airways. One study found that 86% of patients had occult or visible blood after extubation (548). Airway injury forms a major subgroup of malpractice claims (549,550). Trauma is often associated with use of excessive force or repeated attempts at intubation. It varies with the skill of the operator, the difficulty of the intubation, and the amount of muscle relaxation. Damage may be increased if the stylet protrudes beyond the end

of the tube or through the Murphy eye. Mucosa can be torn when a metal or foil-wrapped tube is used. A defective tube may have a barb.

Reported injuries to the larynx include hematomas, contusions, lacerations, puncture wounds, cord avulsions, and fractures (550,551). Arytenoid cartilage dislocation may occur (550,552,553,554,555,556,557,558,559).

With nasotracheal intubation, abrasion or laceration of the nasal mucosa is common (560). The nasal septum may be dislocated or perforated. Fragments of adenoid tissue, nasal polyps, or turbinates may be dislodged (375,561,562,563,564,565,566). Blood clots from epistaxis may enter the trachea and block a bronchus (567,558).

Cases of tracheal, bronchial, pharyngeal, nasal fossa, hypopharyngeal, pyriform sinus, esophageal, and laryngeal perforation have been reported, sometimes with fatal consequences (550,569,570,571,572,573,574,575,576,577,578,579,580,581,582,583,584,585,586,587,588,589,590,591,592,593,594,595). Esophageal perforation can occur (550,596,597,598,599,600,601,602,603,604).

The best way to avoid trauma is to never use more than gentle pressure. A stylet should be flexible and not extend beyond the tip of the tube. Methods to decrease trauma to the nose were discussed in the Nasal Intubation section.

Esophageal Intubation

Esophageal intubation can occur even with an experienced anesthesia provider (605,606,607,608,609,610). Recognition and prompt correction are necessary to prevent dire consequences. In most patients, recognizing esophageal intubation is not difficult. But in some, the signs so closely resemble tracheal placement that they can deceive even a careful, experienced individual. In many of the reported cases of esophageal intubation, one or more of the following tests were performed and were misleading.

Direct Visualization

Directly visualizing the tube passing between the vocal cords is one of the most reliable methods. Unfortunately, the glottis often cannot be seen well. The tracheal tube may be posteriorly displaced with the laryngoscope blade still in the mouth, bringing the larynx into view (611). However, even after the tube is

visualized between the cords, it may slip out as the laryngoscope or stylet is removed or the tube is secured.

Feel of the Reservoir Bag

Normal reservoir bag compliance and refilling with manual ventilation is another method to determine correct tracheal tube placement. This test is unreliable (605,606,612). It may be more reliable if performed with no fresh gas flow (613).

A related test is seeing movement of the reservoir bag in time with the patient's spontaneous respiratory efforts. However, tidal volumes have been noted with the tube in the esophagus

(605,614).

Chest Wall Motion

Some users rely on visual and/or manual evidence of chest wall movement during ventilation. Unfortunately, movement of the chest wall simulating lung ventilation can occur with the tube in the esophagus, especially in patients whose respiration is primarily abdominal (606,614,615,616). Chest wall movement may be difficult to assess in the obese patient or in the patient with large breasts. Low lung or chest wall compliance may result in little chest movement, even when the tube is in the trachea. Listening through the open end of the tracheal tube while the sternum is abruptly depressed can also be misleading (606).

Auscultation

Auscultation should be performed high in each midaxillary area, not just the anterior chest region. The quality of the sounds is important. A gurgling sound (death rattle) suggests esophageal placement. This test is not always reliable (605,606,614,615,617,618,619). Auscultating the upper abdomen as well as the lungs may increase the reliability of auscultation (615,620). These sounds may be confused with breath sounds that are often heard in the epigastric area in thin individuals and pediatric patients (605,618).

Another method of determining tracheal tube location is breathing system auscultation (621). A stethoscope is attached to an adaptor in the breathing system adjacent to the tracheal tube. If the tube is in the trachea, loud breath sounds are heard. If the tube is in the esophagus, squeaks or flatus-like sounds are heard. This test is not totally reliable.

Epigastric Distention

The abdomen can be observed for gastric distention. Unfortunately, the abdomen does not always distend with intermittent gastric inflation, and gastric distention can result from mask ventilation before intubation is attempted (606). The presence of a hiatal hernia or intrathoracic gastrointestinal contents may result in the absence of abdominal distention with esophageal intubation (614). The presence of a nasogastric tube may make gastric filling difficult to distinguish from normal abdominal movements during ventilation.

Moisture Condensation in the Tracheal Tube

Moisture condensation in a transparent tracheal tube is not reliable, because moisture can appear with esophageal intubation (605,606,615,622,623). But if no condensation is seen, the tube is almost always in the esophagus.

Gastric Contents in Tracheal Tube

Gastric contents in the tube lumen may indicate misplacement. However, gastric fluid may not appear with esophageal placement and/or may be difficult to distinguish from secretions from the trachea (605,606).

Oxygenation

Good patient color or satisfactory pulse oximeter readings have been advocated as a means to confirm tracheal placement. However, hypoxemia may be delayed a number of minutes with esophageal intubation if preoxygenation has been performed. Later onset of hypoxemia may occur from other causes beside esophageal intubation and must be ruled out. By that time, esophageal intubation may not be suspected. If oxygen saturation improves after intubation, it is likely that the tube is in the tracheobronchial tree (624). The patient can be ventilated by using a mask placed over the open tube and mouth. Cyanosis relieved by this maneuver is evidence of tube misplacement.

Chest X-ray

Chest radiography is time consuming and expensive and may not be definitive in determining if the tube is in the esophagus (605,606,625,626,627).

Palpation

During intubation, a washboardlike sensation can often be felt by the individual who is manipulating the tube or applying cricoid pressure as the tube passes over the tracheal rings. After tube placement, maneuvers such as inflating and deflating the cuff rapidly, squeezing the pilot balloon, or moving the tube in and out may be felt when the neck is palpated at the suprasternal notch (628). The Ĩ€roll testĨ€ involves gentle backward pressure on the cricoid cartilage and simultaneous side to side displacement of the cartilage in an attempt to detect a tracheal tube lying behind in the esophagus (629). None of these tests is always reliable (605,629,630).

Cuff Inflation Needed to Produce a Seal

Another method is to note the amount of air required to cause the cuff to form a seal. An excessive amount may indicate esophageal placement. If the cuff is at or

just above the vocal cords or is torn or fails to expand uniformly, there will also be a need for high volumes of air to be added to the tracheal tube cuff.

Figure 19.32 Adaptor to allow a fiberscope to be inserted without interrupting ventilation.

Fiberscopic View

The tracheal rings can be visualized by using a fiberscope or an optical stylet. A special adaptor (Fig. 19.32) with a port will allow ventilation while the examination is carried out. Thin optical fibers passed through or incorporated into a tracheal tube can be used to confirm the proper placement of the tracheal tube when a fiberoptic scope is too large to pass through the tube (631,632,633).

This is a reliable method but requires special instrumentation, skill, and time. If the tip of the tube hangs up on the anterior commissure, it may be possible to visualize the trachea, even though the tube is not in the trachea (634,635).

Tactile Confirmation

Tactile confirmation involves placing one hand inside the patient's mouth and the other hand on the neck and confirming that the tube lies immediately anterior to the interarytenoid groove. This test is not totally reliable (636,637).

Intentional Bronchial Intubation

The tracheal tube may intentionally be advanced into a mainstem bronchus (638,639). The chest is then auscultated during positive-pressure ventilation. If breath sounds can be heard on only one side, bronchial intubation has been achieved. With esophageal intubation, the breath sounds are either equal bilaterally or equally diminished or absent on both sides of the chest. This test is not foolproof (638).

Passing a Device through the Tracheal Tube

A nasogastric tube, introducer, or other device can be passed down the tracheal tube (605,640). If the tube is in the trachea, it will abut the carina at 28 to 32 cm in adults. If the tube is in the esophagus, this resistance will not be felt. Other criteria indicating tracheal intubation include the ability to maintain air entrainment through the open end of the tracheal tube while suction is applied to the tube, the ease of withdrawing the tube with suction, and the absence of bile or gastric contents in the aspirate.

Tracheal Illumination

A lighted intubation stylet, discussed later in this chapter, can be passed through the tube and the intensity of the illumination used to differentiate tracheal from esophageal intubation (641). Obesity and swelling of the neck make use of this technique difficult, and it can only be used with tubes larger than 6.5 mm ID (642). This test has limited reliability (619,643).

Pressure- and Flow-volume Loops

Pressure- and flow-volume loops are discussed in Chapter 23. If the tracheal tube is in the esophagus, the loops will not have

their characteristic shapes. The loop will probably be open. Although it will not detect all esophageal intubations, this test has a high likelihood of success.

Esophageal Detector Device

The esophageal detector device (EDD) (Fig. 19.33) consists of an aspirating component (a large syringe or self-inflating compressible bulb) attached to the tracheal tube using an adaptor (642,644,645,646,647,648,649). The plunger is withdrawn, or the compressed bulb is released. If the tube is in the trachea and an airtight seal has been achieved,

gas will be aspirated from the patient's lungs without resistance. However, if the tube is in the esophagus, apposition of the esophageal walls around the tube tip will occlude the lumen and cause a negative pressure or resistance. As a confirmatory test, the device can be used to inject a bolus of air into the tube while listening over the epigastrium. This test will also detect a blocked tracheal tube (646). The EDD should be used immediately after tube placement, prior to delivering the first breath (608).

Figure 19.33 Esophageal detector device attached to a tracheal tube.

Most studies show that this test has a high degree of accuracy in identifying esophageal intubation even with inexperienced users (619,642,646,650,651,652,653,654,655,656,657,658,659,660,661,662,663,664,665), but one showed poor sensitivity (666). It can be used to detect the position of the Combitube (667). The presence of a nasogastric tube or tracheal tube cuff deflation does not limit its efficacy (668). Its accuracy is not affected by lack of pulmonary perfusion. It is faster than most other methods. This device may be better than exhaled CO_2 in the cardiac arrest patient (663,669).

There are a number of false-negative results in which the tube is in the trachea but the bulb expands too slowly or not at all (670,671). Some investigators found that there were fewer false-negative results if 10 seconds were allowed for reinflation (656). There are situations where this device may not confirm placement in the trachea (646,672). The bulb will not re-expand rapidly in patients with decreased expiratory reserve volume as with the morbidly obese or pregnant patient, patients with

bronchospastic disease, tracheomalacia, pulmonary edema, bronchial intubation, and upper or lower airway obstruction (642,656,659,673,674,675,676,677,678,679,680). Patients having cesarean sections have been investigated by using this test, and a high number of false-positive and false-negative results were found. The incidence of false negatives is reduced if the bulb is compressed after connection to the tracheal tube. Another source of a false negative is the bevel lying against the tracheal wall. This device is unreliable in patients under 1 year of age (681). If the tip of the tracheal tube is above the cords, a false-negative test can occur (663).

False positives have been reported where the tracheal tube was not in the trachea but the device suggested that it was (656,676,679,682,683). These may be related to an incompetent gastroesophageal junction (obesity, pregnancy) or gastric inflation.

Ultrasound

Ultrasound imaging of the diaphragm just beneath the xiphoid process can identify most esophageal intubations (684).

Exhaled Carbon Dioxide

In most cases, an esophageal intubation can be rapidly and reliably determined if CO_2 is not present in the exhaled gases (605,606,619,685). Carbon dioxide monitoring is discussed in detail in Chapter 22. Although not foolproof, this is generally considered the most reliable method of detecting esophageal intubation. The American Society of Anesthesiologists (ASA) Standards for Basic Anesthetic Monitoring and the American Association of Nurse Anesthetists (AANA) require that when a tracheal tube is inserted, its correct positioning must be verified by identification of CO_2 in the expired gas (686). It has been found to be reliable in circumstances where the esophageal detector device was unreliable (687).

Carbon dioxide may not be detected despite correct placement with severe bronchospasm, cardiac arrest, no pulmonary blood flow from problems such as pulmonary embolism, or a one-way obstruction in the tracheal tube (612,660,688,689,690). The EDD may be a more reliable device in these circumstances (669). In the prehospital setting, colorimetric end-tidal CO_2 (Chapter 22) may be difficult to use because of inadequate light. Carbon dioxide may be detected when the tube tip is above the vocal cords (691,692,693).

There are some circumstances in which CO_2 may be detected if the tube is in the esophagus (694,695). Exhaled gases may have been forced into the stomach during mask ventilation before intubation (660,696). Carbon dioxide can be in the stomach as a by-product of antacids that have reacted with gastric acid or from ingestion of carbonated beverages. In these cases, the end-tidal CO_2 will be low. The capnogram (Chapter 22) will have an abnormal configuration and be irregular. In this situation, the CO_2 levels will rapidly diminish with repeated ventilation (697).

Inadvertent Bronchial Intubation

Bronchial intubation is a relatively common problem (618,698,699). It occurs more frequently with emergency intubations and in pediatric and female patients (700,701). A short trachea is associated with a number of pediatric syndromes (702). One study showed that RAE tubes (discussed previously in this chapter) were too long in 32% of children, and bronchial intubation occurred in 20% (44).

Bronchial placement can lead to atelectasis in the nonventilated lung (703). The lung that is ventilated may become hyperinflated, leading to barotrauma and hypotension. If the tip impinges on the carina, persistent coughing and bucking may occur.

Usually, the tube will enter the right mainstem bronchus, either because of the anatomy of the carina and the tracheal bifurcation or the right-sided bevel of the tracheal tube (704,705,706). Tubes without bevels also tend to enter the right bronchus (707).

Bronchial intubation can occur after correct initial placement. A tracheal tube may descend into a bronchus

as a result of the weight of the attachments, suctioning, movement of the patient's head, and/or neck or patient repositioning. It is important that the correct tube position is confirmed after the patient's position has been altered. The tube will usually move caudally with neck flexion, mouth opening, and change in position from erect to recumbent (148,154,421,708,709,710,711,712,713,714,715,716,717,718). The distance from the cords to the carina is decreased during laparoscopy and with the Trendelenburg position (719,720,721,722,723,724,725,726). Manipulation of an instrument introduced into the mouth such as a transesophageal echocardiography probe, gastroscope, or tongue depressor can result in tracheal tube movement (713,714,727).

A number of techniques and tests have been recommended to avoid or detect bronchial intubation. These should be made after intubation and at intervals during an anesthetic, especially after the patient is repositioned or the head and neck are moved.

Lung Auscultation

Lung auscultation is the most commonly used method to detect bronchial intubation. Auscultation should be performed bilaterally in the midaxillary areas. If surgery has begun and auscultation would disturb the surgical field, the end of the stethoscope can be put in a sterile bag and positioned in each axilla by a member of the surgical team (728). Auscultation may be misleading, as breath sounds can be transmitted to the opposite side of the chest in the presence of bronchial intubation, unless the tube is wedged firmly in a bronchus (700,729,730,731,732,733,734). The presence of a Murphy eye may reduce the reliability of chest auscultation in detecting bronchial intubation.

Symmetrical Chest Expansion

Visualization of symmetrical chest expansion is easily performed but is not reliable. The chest is not always available for inspection.

Chest X-ray

Chest x-rays are reliable but time consuming and expensive. The tracheal tube standard (11) requires a radiopaque marker at the patient end or along the full length of the tube. The tip of the tube should be in the middle third of the trachea, with the head in a neutral position (midway between full extension and full flexion).

In adults, the tube tip should be 3, 5, or 7 cm above the carina with the neck flexed, neutral, or extended, respectively (702). The tip should lie over the second to fourth thoracic vertebrae in the neutral position (612,729) or at the level of the clavicle (724).

In the neonate, infant, and young child, the tip should be 2 cm above the carina with the neck in the neutral position (735). In children approaching 5 to 6 years of age, this distance should be increased to 3 cm.

Tube Position at the Lips/Nostril

Adult Patients

It has been recommended that oral tubes be positioned at the 21-cm mark on the tube at the teeth (or upper anterior edge of the gums in edentulous patients) in normal-size females and 22 to 23 cm in normal-size males and that for nasal intubation, 2 or 3 cm be added to these lengths for positioning at the nostril (415,736,737). Studies show that this is a better method of preventing bronchial intubation than chest auscultation. However, it will result in malpositioning in some patients (419,423,700,701,738).

There is a correlation between airway length and body height (419,423). For patients whose body lengths lie outside the normal range, the tube can be placed alongside the patient's face and neck. The tip of the tube is aligned to the suprasternal notch, and the tube is aligned to conform to the position of a nasal or oral tracheal tube. The place on the tube at which the tube intersects with the teeth or gums (oral intubation) or the nares (nasal intubation) is noted, and the tube is secured at that point.

Pediatric Patients

The margin of safety in children is less than in adults. A number of formulas have been developed, including the following:

Oral Intubation

1. Length in centimeters = age/2 + 12 cm (700).
2. Length in centimeters = weight in kilograms/5 + 12 cm.
3. Length in centimeters = height in centimeters/10 + 5 cm.
4. Rule of 7-8-9: infants weighing 1 kg are intubated to a depth of 7 cm at the lips, 2-kg infants to a depth of 8 cm, and 3-kg infants to a length of 9 cm.
5. Equations based on the crown-rump and crown-heel length have been developed (710).

Nasotracheal Intubation

1. L = (S ÷— 3) + 2, where L is the length in centimeters, and S is the ID of the tube in millimeters (739).
2. Multiplying crown-heel length by 0.21.
3. For total tube length, 0.16 ÷— height in centimeters + 4.5 cm, then leave 2 cm of tube outside the nostril of an infant and 3 cm outside for an older child (740).

While use of special formulas may decrease the incidence of bronchial intubation, they are based on averages and should not be considered totally reliable. Furthermore, tube length markings are not always accurate (741).

Placing the Cuff Just Below the Vocal Cords

Placing the cuff only a few centimeters past the vocal cords should avoid bronchial intubation in adults.

Guide Marks on the Tracheal Tube

Many tubes have lines or rings to help position the tube with respect to the vocal cords (Figs. 19.2, 19.4), and the distal portion of some pediatric tubes are colored (Fig. 19.23) (147,149,153,154,742,743). Guide (depth) marks vary in their position relative to the cuff and tip of the tube (148,150,151,152,153,744,745).

Intentional Bronchial Intubation

The tube can be advanced until unilateral breath sounds and chest movement are observed. The tube is then slowly withdrawn, noting the tube length at nares or gum at which symmetrical breath sounds and chest movement return. The tube is then withdrawn an additional 2 cm in children (735). The tube should be withdrawn further in adults.

Fiberscopic Observation through the Tube

Passing a fiberscope through the tube is equal in accuracy and faster than a chest x-ray for determining tube position in both adults and pediatric patients and is more accurate than auscultation (632,734,746). The ready availability of fiberscopes in most OR suites makes this a practical method of checking tube position. However, head and neck movement during the examination may cause the tube to move (726).

Palpation of the Anterior Neck

Another method to determine tracheal tube location involves inflating and deflating the cuff while palpating the anterior neck (736). The lower border of the cuff should be felt just above the suprasternal notch. This method is not totally reliable (700). With uncuffed tubes, the tip of the tube can be felt during insertion and advancement stopped when the tip has just passed the suprasternal notch.

Monitoring Expired Carbon Dioxide

Monitoring expired CO_2 may lead to the discovery of bronchial intubation, but it is not a reliable means to detect this problem (698,724,747). Either an increase or decrease in end-tidal CO_2 may be seen.

Lighted Intubation Stylet

Inserting a lighted intubation stylet so that the light is at the tip of the tube and positioning the tube so that the maximum transilluminated glow is at the sternal notch and then advancing the tube 2 to 3 cm can be used to place the tube tip at a satisfactory level (748).

Pressure- and Flow-volume Loops

Peak inspiratory pressure will usually increase with bronchial intubation. Pressure-volume and flow-volume loops (Chapter 23) can often be used to detect bronchial intubation. The pressure-volume loop will show low compliance when the tracheal tube enters a mainstem bronchus. As the tube is withdrawn, there will be a marked sudden improvement in compliance as the tube leaves the bronchus. If peak inflation pressure is monitored while delivering a constant minute volume, bronchial intubation will cause an immediate increase in peak inflation pressure (749).

Ultrasound

Ultrasonic imaging of the diaphragm beneath the xiphoid process can detect bronchial intubation (684).

Other

Decreases in saturation of pulse oximetry (SpO_2) and transcutaneous oxygen are often seen with bronchial intubation (618,698,747). However, desaturation will not always be seen, even with massive atelectasis. If the patient is receiving a high oxygen concentration, the oxygen saturation may not fall.

Acoustic reflectrometry has been used to detect bronchial intubation in the presence of equal bilateral breath sounds (730).

When a tracheal tube is believed to be in a bronchus, the cuff should be deflated and the tube gently withdrawn, the cuff re-inflated, and the position rechecked. If reintubation would be difficult because of the patient's position or because the initial intubation was difficult, consideration should be given to advancing a fiberscope or ventilation catheter (see below) into the tube before withdrawing it. If extubation should occur, the tracheal tube can be quickly reinserted.

Swallowed Tracheal Tube

There are a number of case reports of a tracheal tube being lost in the esophagus, usually during newborn resuscitation (750,751,752,753) and in an adult following emergency intubation (754). The use of a connector that fits firmly into the tube can prevent this complication. Bonding between the connector and the tube will be increased if the connector is wiped with alcohol before being inserted into the tube. The tube should be long enough that it protrudes from the mouth when

correctly placed and firmly secured. To secure the tube, tape should be attached to the tube instead of to the connector. If this complication occurs, the tube does not need to be removed immediately.

Foreign Body Aspiration

During intubation, a variety of materials that can cause blockage or check-valve obstruction can be aspirated into the trachea. The tracheal tube may dislodge fragments of tissue, including teeth, from the oral cavity, pharynx, or larynx. A tube inserted nasally may dislodge adenoid or nasal tissue during its passage.

A portion of a cuff or shaft of the tube including the punched-out area from the Murphy eye still in situ may be left in the airway (755,756,757,758,759,760,761). A tracheal tube can separate from its connector and slip below the cords.

Other foreign bodies that have been found in tracheal tubes include cottonoids or pieces of aluminum used to protect the cuff or shaft from a laser beam, the distal portion of a tracheal tube, a cap liner from a tube of anesthetic ointment, and parts of sprays and laryngoscopes (261,628,762,763).

Careful inspection of equipment before use will help to avoid introduction of foreign bodies. The connector should fit firmly in the tracheal tube, and the tape or securing device should be attached to the tube, not the connector. When a cuff leaks, it should be carefully examined for missing portions after it is removed from the patient.

Foreign body aspiration should be suspected whenever obstructive signs or symptoms appear. The patient's airway should be searched immediately and should include bronchoscopy if examination above the level of the larynx proves fruitless. If the foreign body is above the cuff, it might be possible to blow it out of the trachea by deflating the cuff and forcibly compressing the reservoir bag in the breathing system (764).

Leaks

A leak may make it difficult to maintain adequate ventilation, fail to protect against aspiration, and increase the difficulty of surgery involving the oral cavity (765).

During insertion, the cuff, inflation tube, or the tube itself may be torn by a tooth, turbinate, implant, laryngoscope blade, forceps, or stylet (766). A problem with the inflation system (254,316,765,767,768,769,770,771,772,773,774,775,776) or the syringe used to inflate the cuff (777,778) may make it impossible to inflate the cuff. A defect in the tube or eccentric cuff inflation can cause a leak (126,312,779,780,781,782,783). The tracheal tube connector may be the source of a leak (438,618,693,784,785,786,787).

Protrusion of the cuff above the vocal cords can result in a leak despite a large amount of air being injected into the cuff (788,789,790,791,792,793).

The cuff can develop a leak while the tube is in place (794). Application of local anesthetic spray has been associated with

cuff leaks (795,796). The cuff or other parts of the tube may be damaged during cannulation of the internal jugular or subclavian veins, during percutaneous dilatational tracheostomy (Chapter 21), or by other nearby procedures (755,797,798,799,800,801,802,803,804,805,806,807,808,809,810,811,812,813). A laser beam can perforate the cuff. A tube may be damaged by biting (61,66,814,815,816,817). Chewing gum attached to a cuff can cause an unsatisfactory seal (818).

If a leak becomes evident after a gastric tube or other device has been placed, the possibility that that device has passed into the trachea alongside the tracheal tube instead of into the esophagus should be considered (176,177,178,179,180,819,820).

When a leak is present, laryngoscopy should be performed. If the cuff is above the vocal cords, it should be deflated and the tube advanced before the cuff is reinflated. Consideration should be given to using a tube changer or fiberscope during this procedure, especially if intubation was difficult.

If the problem is in the inflation system, it may be possible to repair the damage, or the leak can be bypassed by inserting a stopcock, small catheter, or a needle into the line below the defect (821,822,823,824,825,826,827). It may be possible to seal a cut in the tube itself by using glue (828). Temporary approximation of the cut edges and circumferential packing may be helpful (799).

If the cuff is leaking, several alternatives are available:

1. Use pharyngeal packing to control the leak. It may be necessary to increase the fresh gas flow to compensate for the leak.
2. Fill the cuff with a mixture of lidocaine and saline (829) or use a saline infusion (830).
3. Attach a mechanism for maintaining a continuous gas infusion into the inflation tube. Methods described include tubing connected to an air-filled plastic container to which constant external pressure is applied (831,832), a flowmeter (833,834,835), and a system for maintaining intraocular pressure (836).
4. Place a supraglottic device such as an LMA over the tube, and seal the proximal end (837).
5. Replace the tracheal tube. If this course of action is selected, consideration should be given to using a tube exchanger.

When a damaged tube is removed, it should be carefully examined to make certain that there are no missing portions.

Intubating Device Trapped inside the Tracheal Tube

Whenever any device is placed through a tracheal tube, there is a risk that it could become entrapped in the tube. Anything passed down the tracheal tube such as a suction catheter, tube exchanger, or fiberscope can pass through a Murphy eye and become caught (Fig. 19.34). It may be impossible to remove the

device without also removing the tracheal tube (838). The needle or wire of a percutaneous tracheostomy set (Chapter 21) may traverse the Murphy eye (839,840,841).

A flexible scope or other device inserted into a tracheal tube may become stuck on removal (842). It may be possible to free it by injecting saline into the tracheal tube.

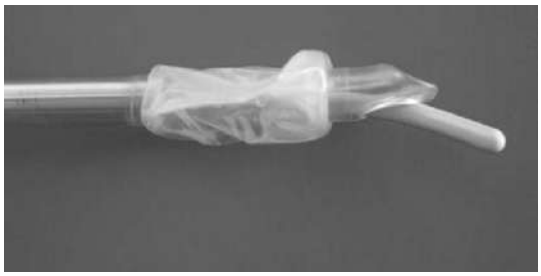


Figure 19.34 The tube changer has become caught in the Murphy eye.

Tracheal Tube Fires

Fires in tracheal tubes have a high likelihood of causing serious harm. Fires are discussed in Chapter 32.

Tracheal Tube Obstruction

One reason for inserting a tracheal tube is to provide a patent airway (618). Unfortunately, the tube itself may become the cause of obstruction. This is especially a problem with infants and children (843,844). Obstruction can be partial or complete. It is possible to have an obstruction such that inspiration is unimpeded but resistance to expiration is increased and vice versa (845,846).

Causes

Biting

Unless protection in the form of a bite block or oral airway is provided, the patient may bite and obstruct the tube (62,64,65,847,848,849,850). Many of the reported cases involve spiral embedded tubes that were permanently deformed after the bite was released (63,67,68,130,848,851,852,853,854,855) (Fig. 19.35). An oral airway may not prevent obstruction, as it can only be placed in the midline (68,856,857).

Kinking

Kinking is a frequent cause of tracheal tube obstruction. Spiral embedded tubes have been used in the OR to overcome this problem, but kinking can still occur at the patient end if the connector is not inserted inside the spirals. Kinking sometimes occurs when the patient's head position is changed, especially

when the neck is flexed (858,859) (Fig. 19.36). It can also occur when a tube is moved from one side of the mouth to other (860). Some tubes may kink in the pharynx after they have been in place for several hours. Kinking can be caused by other equipment in the mouth (69,861,862). Advancing the tube with a ‘€drilling‘€ movement may introduce some torque into the tube (863).

Tubes vary in their resistance to kinking. Smaller tubes kink more readily than larger ones. A structural fault in the tube such as the point where the inflating tube enters the wall of the tube (864,865,866) or the intracuff area (867) can predispose to kinking. At times, tubes are made with thin sidewalls. Kinking sometimes occurs at the distal part of the connector (868). The Endotrol tube may kink at the level of the glottis (88). The tip of a tube may fold, causing obstruction (128). The Lasertubus can kink at the junction of the plastic and outer layers (117).

Material in the Lumen of the Tube

A tracheal tube may be obstructed by dried secretions, blood, pus, tumor, or other tissue (618,869,870,871,872,873,874,875,876,877). Lubricant that is used to help put the connector into the tube may dry and form a film (878). A variety of foreign bodies have been found in tracheal tubes, including a tooth, foam rubber from

a mask, an inflation valve, a cleaning brush, an adaptor from an intravenous set, an intravenous needle, a stop from a stylet, a cork, a glass ampoule, pieces of plastic, part of a nasogastric tube, an oral medication tablet, a smaller tracheal tube, part of a paper towel, part of a sampling tube, caps from syringes, and dead organisms (618,879,880,881,882,883,884). Part of a stylet can be detached and remain in the lumen (885,886,887). A manufacturing defect can cause obstruction (888).

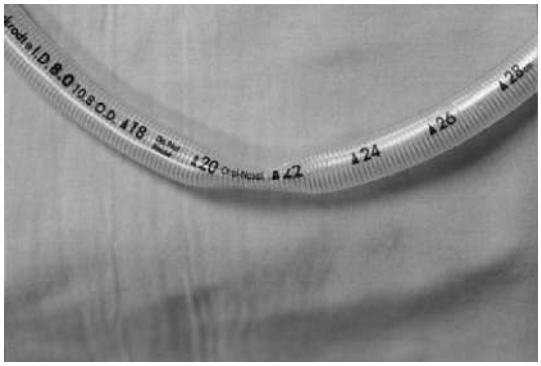


Figure 19.35 Spiral embedded tube permanently deformed by patient biting down on it.

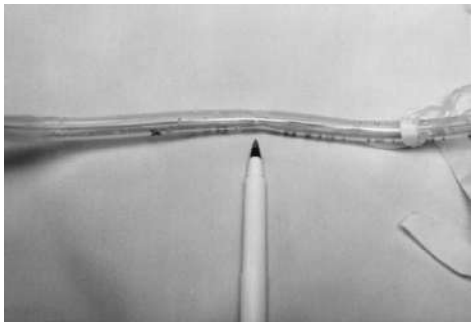


Figure 19.36 This tube kinked in the back of the mouth. The pen points to the site of the kink.

Spiral Embedded Tubes

Most spiral embedded tubes do not have a Murphy eye. Anything that blocks the bevel can cause obstruction (889). In some spiral embedded tubes, the part of the tube distal to the cuff has no spirals. This part may be soft and easily occluded. Pharyngeal obstruction of a spiral embedded tube in a patient with edema of the tongue has been reported (890). Reusing spiral embedded tubes predisposes to problems. Even single use tubes may have air bubbles in the wall that enlarge with nitrous oxide exposure and cause obstruction (60).

Cuff Problems

If the tracheal tube cuff herniates or inflates eccentrically, it may displace the bevel from the center of the trachea (Fig. 19.37). Eccentric cuff expansion from diffused anesthetic gases can cause it to expand in one direction and allow the bevel to impinge against the tracheal wall (Figs. 19.37, 19.38) (618,891,892,893,894,895). An inflated cuff may balloon over the tube tip (618,896) (Fig. 19.37). Inflating the cuff may cause compression of the tube lumen (897,898,899) (Fig. 19.39). Obstruction from these causes may not occur until some time after initial cuff inflation. Deflating the cuff usually relieves the obstruction.

Cases have been reported for which a feeding tube or other device was connected to the cuff inflation system (900,901). This can cause the cuff to overinflate and obstruct the tube.

External Compression or Displacement

The trachea may be displaced by the aorta, or the thyroid gland may cause the bevel to lie against the tracheal wall or compress the tube. A nasogastric tube or suction catheter knotted around the tube or a nearby surgical retractor can cause compression (902,903,904). External tracheal tube compression has been reported associated with Ludwig's Angina, Forestier's disease, or ‶saber-sheath‶ trachea (52,905,906,907,908,909,910). Bony fragments from a LeFort fracture can cause external compression of the tube (911).

Defective Connector

If the connector is defective or damaged during insertion, it can partially or completely obstruct the lumen (912,913,914,915). To avoid problems with reinserting the connector after shortening the tracheal tube, the tube should be cut diagonally, making a short bevel

(916). The connector should be lubricated slightly with alcohol, brought into the longitudinal axis of the tube, and then gently slid into the tube.

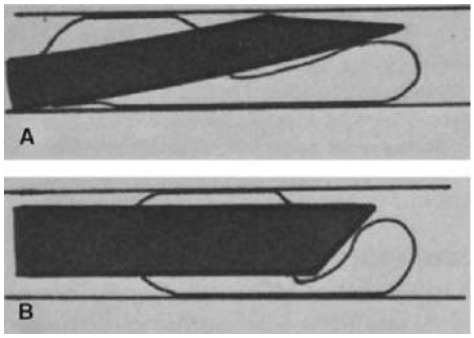


Figure 19.37 Two causes of tracheal tube obstruction. **A:** The bevel is pushed against the wall of the trachea by an eccentrically inflated cuff. **B:** The cuff has ballooned over the end of the tube.

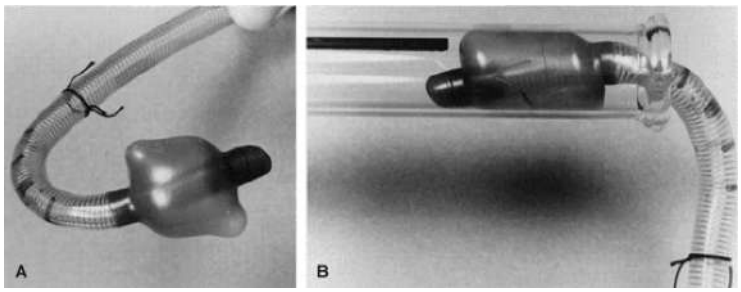


Figure 19.38 Tracheal tube obstruction secondary to eccentric cuff inflation. **A:** The cuff as removed from the patient. **B:** When placed in a glass tube, the inflated cuff pushes the bevel toward the wall of the tube.

Change in Body Position

A shift in body position may cause the tracheal tube to become obstructed (917,918,919). When the tube orifice faces in one direction and the head is turned to the other, the orifice may face the tracheal wall (920).

Prevention

Preventing tracheal tube obstruction starts with the choice of tube. Transparent tubes facilitate identifying material or objects blocking the lumen. The use of a fenestrated (Murphy) tube may avoid some cases of obstruction. A spiral embedded tube may be useful if an operation involves turning the head or other maneuvers that may cause kinking. Spiral embedded tubes should not be reused. Solutions or lubricants that can form a film barrier should be prevented from entering the tube lumen (921).

The tracheal tube should be examined carefully before use and the patency of the lumen verified. Foreign bodies and other problems inside the lumen can be detected by inserting a stylet. The cuff should be examined to make certain that it is securely attached and inflates symmetrically. The lumen should not be reduced when the cuff is inflated. Inserting a metal connector into the tube may prevent external compression (922). If the tube has a soft flexible tip, a stylet should be used during insertion. After insertion, the cuff should be inflated as described earlier in this chapter. Cuff pressure should be readjusted frequently, especially if nitrous oxide is used. When an x-ray is taken, the position of the orifice and the configuration of the cuff should be examined. Once inserted, the tube should not be withdrawn while the cuff is inflated, as this may cause the cuff to balloon over the end of the tube.

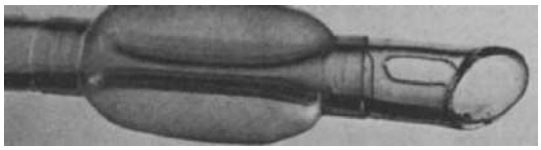


Figure 19.39 Reduction of tube lumen by cuff. Inflation of the cuff caused narrowing of the tube lumen.

Placing a bite block securely between the molar teeth and maintaining an adequate level of anesthesia will prevent biting on the tube. Various methods have been described to avoid kinking of the tube from traction on it (923,924,925,926,927).

After surgery, a spiral embedded tube should be changed to a conventional one if postoperative intubation is required (890,928).

Diagnosis and Treatment

Partial tracheal tube obstruction may present as a decrease in compliance or expiratory flow, high inspiratory pressures and an increase in the difference between peak and plateau airway pressures with volume-controlled ventilation, reduced tidal volume during pressure-controlled ventilation, or wheezing (929,930,931,932). Pressure-volume loops (Chapter 23) are

helpful in diagnosing an obstruction. Paradoxical chest movements may be seen in spontaneously breathing patients. The capnograph (Chapter 22) may show an increased slope in Phase III and a larger ∅ angle (933,934,935). Relying on the anesthesia provider's ‘educated hand’ is not reliable (936). A high negative intrathoracic pressure may result in pulmonary edema (937,938,939). A problem that permits inhalation but prevents exhalation (ball-valve obstruction) may present as circulatory collapse or barotrauma (845,940).

Passing a fiberscope down the tube may facilitate diagnosis. Altering the patient's head position or deflation of the cuff may relieve the obstruction. The tube can be checked for kinking either by examination with a gloved finger or by direct vision using a laryngoscope. Passing a suction catheter or stylet down the tube may be helpful.

Digital pressure at the site of the kink may relieve the obstruction. A kink in a small tube can sometimes be remedied by placing a larger tube over the small tube (927,941). If a large tube kinks, it may be possible to pass a smaller tube through it. A hemostat applied at 90 degrees to the occlusion may relieve obstruction secondary to biting (848,854). If the obstruction is caused by clotted blood or inspissated mucus, it may be possible to remove this by using an embolectomy (Fogarty) catheter (942,943,944,945). In some cases, rotating the tube over a fiberscope or tube exchanger may relieve the obstruction. A new device that is specially designed to remove secretions within a tracheal tube has been devised (946).

Equipment placed between the breathing system and the tracheal tube may be the source of the obstruction. These components should be considered in the differential diagnosis of obstruction, especially if they are added after the initial equipment check or just before the obstruction was detected (947).

Aspirating Fluid from above the Cuff

Although it is generally assumed that a tracheal tube will prevent foreign material from entering the lungs, aspiration can occur around the cuff (948). In one study of long-term intubation, secretions leaking around the tracheal tube cuff were the most important risk for pneumonia in the first 8 days of intubation (949).

The incidence of aspiration is increased by the use of low-pressure cuffs, spontaneous ventilation, and fluid accumulation above the cuff.

Use of Low-pressure Cuffs

Low cuff pressure (below 20 mm Hg) is associated with an increased risk of pneumonia in patients with long-term intubation (165,166,949,950). Many low-pressure cuffs wrinkle despite proper inflation and allow fluid to pass along the folds. Infolding can be decreased by increasing the pressure in the cuff, using a thin-walled cuff, and using a tube in which cuff diameter at residual volume approximates the internal tracheal diameter (157,164). Applying lubricant jelly to the cuff may fill in the folds and prevent aspiration (166,170). When nitrous oxide

administration is discontinued, there will be an outflow of that gas from the cuff. This can cause the cuff to lose volume and decrease the seal (205).

The ultrathin polyurethane cuff may prevent aspiration better than other cuffs (951).

Spontaneous Ventilation

During spontaneous ventilation, there will be negative pressure in the airway during inspiration (952). In addition, the trachea tends to dilate during spontaneous inspiration. With thin-walled cuffs, the negative airway pressure will be transmitted to the cuff. With an uncuffed tube, the negative pressure will be applied around the tube. If the negative pressure exceeds the leak pressure around the tube, blood or secretions may be drawn into the trachea (953). Intermittent positive pressure, PEEP, and pressure-supported ventilation will lower the incidence of aspiration but not totally prevent it (166,952).

Fluid Accumulation above the Cuff

Suctioning to maintain a clear oropharynx will decrease the pressure exerted by fluid above the cuff. It has been suggested that the cuff be placed just below the vocal cords to reduce the volume of fluid that cannot be removed by suctioning. However, if the cuff is just below the cords, head movement may cause the tube to move upward, causing the cuff to exert pressure on the cords and increasing the risk of inadvertent extubation. Furthermore, a cuff placed just below the cords may compress nerve endings against the thyroid cartilage, resulting in vocal cord paralysis. If the patient is in a head-up position, the hydrostatic pressure exerted by the fluid will be higher than if the patient is supine.

Blood from the pharynx can drain below the vocal cords and accumulate above the cuff. If sufficient time elapses for this blood to clot, it can form a sheath between the tube and the tracheal wall. During extubation, this sheath may fall into the trachea, causing complete or partial obstruction.

A tracheal tube that incorporates a dedicated suction lumen and channel can be used to clear secretions above the cuff. Studies show that using this tube may reduce the incidence of ventilator-associated pneumonia during long-term intubation (132,133,134,135,136,137,138).

Aspiration can occur on extubation. Pharyngeal suction may not remove all of the fluid above the tube, and it can find its way into the lungs when the tube is removed. Recommendations to avoid this include withdrawing the inflated cuff until it impinges on the lower surface of the vocal cords, placing the patient in a head down and lateral position before cuff deflation, and deflating the cuff during application of positive airway pressure to blow material collected above the cuff into the pharynx, where it can be removed by suctioning (484).

Misplacement of Other Equipment into the Trachea

A tracheal tube keeps the glottis open, making it easier to pass other equipment into the tracheobronchial tree

(176,177,178,179,180,819,820,954). Misplaced items have included gastric tubes, esophageal stethoscopes, temperature probes, and electrocardiogram (ECG) leads.

Scan Artifacts

Working in the MRI environment is discussed in Chapter 30. Artifacts may be seen on a computed tomography (CT) scan when radiopaque markers are present on a tracheal tube. Tubes without these markers are available and should be used for this application (955,956). The metallic spring in the inflation device of a plastic tube can cause an artifact on an MRI scan (957,958,959). Repositioning it away from the patient will usually solve the problem. Wire-reinforced tracheal tubes will cause image distortion when used in an MRI unit. Nylon-reinforced tubes are recommended for this application (960).

Unintended Extubation

Accidental (spontaneous) dislocation of a tracheal tube from the trachea is at best a nuisance and at worst a life-threatening emergency. It occurs more commonly in smaller patients and in patients with burns (459,843).

Neck extension or lateral head rotation head can cause cephalad tube movement (154,421,711,713,716,717). This movement is increased with nasal intubation (961). The prone position (962) or upper airway swelling can cause the tube to move cephalad (789).

Removing a gastric tube entwined around the tracheal tube can cause extubation (963).

Accidental extubation can occur when the cuff is positioned between or just below the cords. If the cuff is distended as a result of overinflation or nitrous oxide diffusion, it may herniate upward. This may result in a leak. A common response is to inject more air into the cuff. If the cuff is at or just above the vocal cords, this may cause the tube to move farther out of the trachea.

Removing an adhesive surgical drape that is positioned over the tracheal tube may result in unintended removal of the tube (964,965). This can be avoided by placing something over the part of the adhesive strip that is to come into contact with the airway device (966).

Antidisconnect devices may increase the risk of inadvertent extubation. It may be preferable for the connection between the tube and the breathing system to give way under strain than to permit the tube to be pulled out.

To prevent inadvertent extubation, the tube should be positioned with the tip in the middle third of the trachea with the neck in a neutral position. A cuff that requires frequent inflation should suggest that it may be situated between the vocal cords. The tube should be well secured. If the securing tape becomes wet, it should be replaced. Pulling on the tube should be avoided. Care should be taken to avoid extubation whenever the patient is positioned. Using an RAE tube may decrease the incidence of accidental extubation.

If unplanned extubation occurs in the lateral position, using a supraglottic device (Chapter 17) may result in more reliable airway control compared with tracheal intubation in the lateral position (967).

Infection

A high incidence of sinusitis and otitis during and following nasotracheal intubation has been reported (337,338,339,340,341,342,343,968,969). During long-term intubation, the rates of nosocomial sinusitis and pneumonia do not differ significantly between oral and nasal intubation (970).

Difficult Extubation

A difficult extubation is a rare but dangerous problem (971). A common cause is failure of the cuff to deflate. This may be due to obstruction of the inflation tube. If the obstruction is distal to the pilot balloon, the balloon will offer no clue that the cuff has not deflated (972). Heat from a laser or a drill may melt the inflating tube, causing it to occlude (973). The patient may bite the inflating tube, causing it to become occluded. Some users pull the pilot balloon and inflation valve from the inflation tube to deflate the cuff. This can cause the inflation tube to seal (514,515,516). The connector may occlude the inflation tube if it fits below the point where the tube leaves the tracheal tube wall (253). A retaining bandage may kink the pilot tube. The inflating tube may become entangled with a nasogastric tube or turbinate (974). With a sponge cuff, deflation will be difficult if the inflation tube is cut or detached (192,193). A fold or flange in the cuff may impede extubation (975,976,977). Edema of the larynx may make extubation difficult (281).

If the tracheal or inflation tube is transfixed to adjacent tissues, extubation will be difficult (839,978,979,980,981). This problem is commonly associated with surgical procedures near the tube. A suture may catch a portion of the tube wall or be tied around it. Forcibly removing the tube may cause tissue disruption and lead to fatal consequences.

When it is impossible to deflate the cuff, a cut in the inflation tube may relieve the pressure in the cuff (516). It may be possible to insert a syringe and needle into the stump of the pilot tube and deflate the cuff. If the cuff still remains inflated, the tube should be pulled out until the cuff is close to the undersurface of the vocal cords. A needle can then be inserted through the cricothyroid membrane, puncturing the cuff (982). Alternately, the tube can be withdrawn so that the cuff is seen below the cords and punctured from above with a sharp object (983,984). Removal may be aided by relaxing the vocal

cords and/or tube rotation (971,983). If the tube is surgically fixed to adjacent tissues, surgical re-exploration may be required.

Emergence Phenomena

Undesirable phenomena during emergence and extubation include coughing, bucking, restlessness, increases in arterial blood pressure, tachycardia, and increases in intraocular pressure. The incidence of most of these problems can be

decreased by filling the tracheal tube cuff with a lidocaine solution (985,986,987,988,989). Lidocaine will diffuse through the tracheal tube cuff (990). The addition of sodium bicarbonate increases the diffusion rate (991,992). Spraying the trachea with lidocaine before intubation will decrease the incidence of coughing on emergence after cases of less than 2 hours' duration (993).

Postoperative Sore Throat

Sore throat is a common postoperative complaint (228,231,238,994,995,996,997,998,999). It is more common in females, following operations involving the head and neck, with use of larger tubes, and when the patient is in the prone position. Cuff design may be a contributing factor (1000). Limiting intracuff pressure may decrease the incidence (1000,1001,1002). The incidence of sore throat is high with the sponge cuff (114).

Studies associating the incidence of sore throat with the effect of topical lidocaine, steroids, and lubricants on the cuff offer conflicting results (994,1003,1004,1005,1006). Some studies have found that inflating the cuff with a lidocaine or saline solution will decrease the incidence and severity of sore throat (986,987,992,1007,1008,1009,1010,1011). Sodium bicarbonate may enhance the lidocaine effect (1008). Preoperative inhalation of a steroid or gargling with sodium azulene sulfonate may help (1012,1013).

Hoarseness

Hoarseness is commonly seen after intubation. Its incidence may be decreased by using tubes with low-pressure cuffs, smaller tubes, and lubrication with lidocaine jelly (1014,1015). Hoarseness increases with difficult and long intubation but not with increased intracuff pressure (231,998). Hoarseness that is persistent or that develops later in the postoperative period should be investigated.

Neurologic Injuries

Trigeminal, lingual, buccal, and hypoglossal nerve palsies have been reported following short-term intubation (965,1016,1017,1018,1019,1020). Mental nerve neuropraxia has been reported after use of an oral RAE tube (1021).

Upper Airway Edema

Edema may occur anywhere along the path of the tube, including the tongue, lingual follicles, uvula, epiglottis, aryepiglottic folds, ventricular folds, vocal cords, and the retroarytenoid and subglottic spaces (971,1022,1023,1024,1025,1026,1027,1028,1029,1030,1031,1032). The mouth floor can swell due to sialadenitis from a submandibular duct obstructed by a tracheal tube (1032).

Laryngeal edema (postintubation croup or inflammation, acute edematous stenosis, stridor, and subglottic edema) encroaches on the airway lumen, especially in the young child, in whom a mild degree of edema may produce a significant reduction in the internal cross-sectional area. Because the cricoid cartilage

completely surrounds the subglottic region, no external expansion of the swollen tissues may occur at this location.

Laryngeal edema has a peak incidence between 1 and 4 years of age. It is most commonly seen after surgery involving the head and neck and with increased duration of intubation. It is more common in adult females than in adult males (1033). The presence or absence of a leak or the history of a recent respiratory infection does not correlate with the incidence of croup (301). Inflammation, mechanical trauma, a tube that is too large, motion, and allergic reactions to the tube itself or materials used in lubrication or sterilization have been postulated as mechanisms of laryngeal edema.

Edema may manifest itself any time during the first 48 hours after extubation. Usually, the first signs are evident 1 to 2 hours postoperatively. In its mildest form, there is hoarseness or croupy cough. In the most severe cases, respiratory obstruction will occur. Decompensation can be rapid.

Preventing laryngeal edema begins with avoiding irritant stimuli. If there is an upper respiratory infection, the use of a face mask or laryngeal mask should be strongly considered. Tubes, sprays, and lubricants that are used on the tubes should be sterile. Intubation should be atraumatic, and adequate anesthetic depth and/or good muscle relaxation should be maintained to prevent tube movement. Head movement should be kept to a minimum.

Vocal Cord Dysfunction

Vocal cord paralysis and paresis have been reported after tracheal intubation despite the intubation being atraumatic and the site of the surgery remote from the head and neck (550,1034,1035,1036,1037). Most cases resolve spontaneously, usually within days or weeks, but it may be long term (1038). Positioning the tube with the cuff just below the cords and high cuff pressure may increase the incidence of this problem. Because a tube moves cephalad with head or neck extension, the cuff may

become positioned in the subglottic region and should be readjusted when the patient remains in this position for a long time (154).

Ulcerations

Ulcerations (erosions) of the larynx and trachea are common, even when a tube has been in place for only a short time. The incidence and severity increase with the duration of intubation. Ulcers vary from superficial lesions involving only the mucosa to deep lesions in which the underlying cartilage is exposed. The end result will depend on the location and severity as well as other factors, such as infection, that affect the healing process. If the ulcer is superficial, regeneration to normal epithelium occurs relatively quickly. When the damage is deeper, the regeneration follows the same pattern as for the superficial damage but is more protracted. If the ulcer is very deep, scar tissue may form.

Cases of uvular necrosis following intubation have been reported (1039,1040).

Vocal Cord Granuloma

The incidence of vocal cord granuloma following intubation (intubation or postanesthesia granuloma) is reported to be between 1 in 800 and 1 in 20,000 (1041,1042). Most occur in adults, and they are more common in women. A number of possible etiologies have been proposed, including trauma, infection, too large a tracheal tube, excessive cuff pressure, duration of intubation, and the tube position.

Symptoms include persistent hoarseness, intermittent voice loss, pain or discomfort in the throat, a feeling of fullness or tension in the throat, chronic cough, hemoptysis, and pain extending to the ear. Some cases are symptomless. Occasionally, respiratory obstruction is seen. Symptoms may start after extubation or may not develop for as long as several months.

Persistent hoarseness after intubation warrants laryngeal examination. If the examination reveals ulceration over the vocal processes, strict voice rest to allow healing to take place may prevent the development of a granuloma.

Latex Allergy

While most tracheal tubes are made from PVC, some laser tubes are made from latex-containing rubber. A careful history should be taken and proper precautions undertaken if these tubes are used. Latex allergy is discussed in Chapter 15.

Gastric Tube Knotted around the Tracheal Tube

A gastric tube may form a knot around the tracheal tube (902,963,1043,1044,1045). Tandem movement of both the nasogastric tube and the tracheal tube should suggest this problem. Options for dealing with this include cutting the knot under direct vision, leaving the knotted tube in place until tracheal extubation is performed, and reintubation.

Macroglossia

Macroglossia can be a serious problem resulting in airway obstruction after extubation. Patients in the prone position, especially for prolonged periods of time, usually have edema in the dependent facial structures (1046,1047). Macroglossia has also been reported in patients in the sitting position (1048). Hemorrhage into the tongue can occur in an anticoagulated patient (1049). Lingual ischemia can also occur (1050).

Tracheal Stenosis

Tracheal stenosis following brief intubation has been reported (1051,1052). However, this problem is more common with long-term intubation.

Cuff Inflated with Medication

Cases have been reported where a syringe or intravenous line was connected to the cuff inflation system. Medication or fluid was then injected (1053).

Airway Management Adjuncts

Stylets

A stylet (introducer, intubating or malleable stylet) is designed to fit inside a tracheal tube and change the shape of the tracheal tube to facilitate intubation. A stylet is also useful to check the patency of a tracheal tube. A stylet should always be immediately available when intubation is performed. Many anesthesia providers routinely use a stylet, while others reserve its use for difficult intubations.

Description

A variety of stylets are available. Some have special nonstick surfaces. There should be a means to limit the depth that the stylet is inserted into the tracheal tube (Fig. 19.40). If a securing device is not present, the stylet should be bent acutely at the machine end (Fig. 19.41). The machine end of the stylet may have a means to prevent the tube from rotating on the stylet. A stylet

should have enough malleability so that its shape can be changed easily and will yield if pressed against soft tissues, yet enough rigidity to maintain its shape during intubation. It should be resistant to chipping and breaking. It should have a smooth surface devoid of sharp edges. Some stylets allow the user to change their shape in situ (1054,1055) (Fig. 19.42). These may be especially useful in the patient with a cervical spine injury. The stylet may have a light at the end to assist in visualization during and after placement.

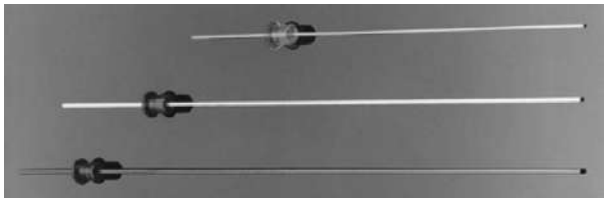


Figure 19.40 Malleable stylets with adjustable stops. The stop fits into the tracheal tube and prevents the stylet from protruding beyond the distal tip of the tube. (Courtesy of Rusch, Inc.)

Techniques of Use

Unless the stylet has a non-stick coating, a thin film of lubricant should be spread over its length before insertion (1056,1057). The stylet should be inserted into the tube until the distal end reaches the bevel and should be fixed so that it cannot advance. Occasionally, the patient's airway may require extending the stylet tip beyond the tracheal tube bevel, but this is best avoided (1057). Removing the connector from the tube before inserting the stylet may make it easier to withdraw the stylet and decrease

the likelihood of damage to the stylet, especially if the tube has a small diameter. If the connector is left in place, the flanges, if present, should be located at the 2 and 8 o'clock positions when viewing the tracheal tube along the central axis (1057).

The tube and stylet should then be bent to the desired shape. For routine intubations, a straight or slightly curved configuration is usually best. When dealing with an anterior larynx, a â€Jâ€ or â€hockey stickâ€ configuration, with the patient end of the tube bent anteriorly at an angle of 70ยฐ to 80ยฐ, is most commonly used. Bending the midpoint of the tube to the right or left may result in a better view of the larynx (1058). Removing the stylet in situ can be difficult and may result in accident extubation (1059,1060,1061). If excessive force is needed, the stylet is kinked or too sharply bent and should be reformed or discarded.

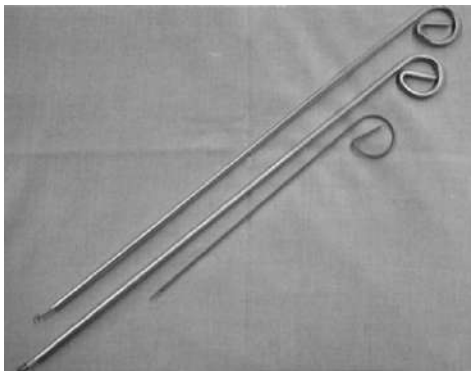


Figure 19.41 Malleable stylets. The proximal end must be bent to prevent it from protruding past the patient end of the tracheal tube.

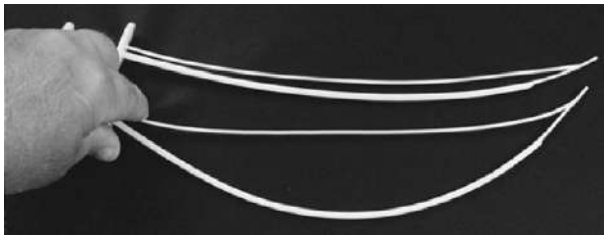


Figure 19.42 Schroeder stylet. By pushing on the proximal part, the angle of the tube is increased.

The tracheal tube is held so that the thumb rests on the connector. The larynx is exposed and the tracheal tube inserted. In most cases, unimpeded passage is achieved by introducing the unit through the right side of the mouth while pointing the

tracheal tube tip toward the larynx and simultaneously supinating the hand 30ยฐ to 40ยฐ from the vertical (1057). Adjustments to the angle of entry are easily made by moving the connector and/or supinating or pronating the hand. The thumb is used to advance the tracheal tube. When the distal part of the tube is believed to have passed the vocal cords, the stylet is carefully withdrawn from the tube. Counterpressure on the tube in the opposite direction from the pull on the stylet may be necessary to prevent the tracheal tube from being removed. As the stylet is withdrawn, the tip of the tube typically moves anteriorly (1056). If this anterior movement is timed with passage under the epiglottis, it may help to direct the tube through an anteriorly positioned glottis.

A slightly different technique involves inserting the stylet into the tube, angling the distal portion anteriorly, and then removing the stylet from the tube (1062). The stylet is placed in a readily accessible location. The tube is advanced to the vicinity of the larynx and the stylet reinserted. This will reduce the pressure on tissues as the tracheal tube is inserted.

Blind styleted tracheal intubation may be performed (1063).

Problems

The use of a stylet may be associated with trauma to the airway or esophagus (574,1064,1065). The risk is increased if the tip of the stylet protrudes from the patient end of the tube. If the tube is advanced into the airway with an acute angle on the stylet, the tube tip may be forced into the anterior larynx. The stylet should be retracted as the tube is advanced beyond the glottis.

Part of the stylet may be sheared off (885,886,887,1066,1067,1068,1069,1070,1071,1072,1073,1074,1075,1076). The stylet may damage the tracheal tube. The inflation tube can become entangled in the stylet (1077). The tracheal tube may not advance over the stylet after intubation (1059,1060,1061).

Bougies

Description

The classic bougie (intubating or intubation catheter or introducer, guide, introducer or stylet; Eschmann tracheal introducer) is shown in Figure 19.43. It is fabricated from a braided polyester base with a resin coating. Its color is golden brown, and it is reusable. It is hollow except at its ends, but the ends may be cut away so that it can be passed over a smaller guide or used to monitor CO_2 (1078,1079,1080,1081). Placing twisted wires in the hollow lumen allows the bougie to be shaped (1082). Some bougies have length markings.

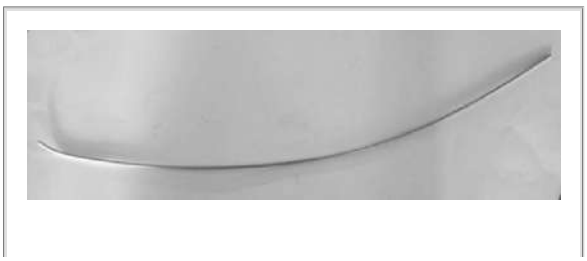


Figure 19.43 Bougie.

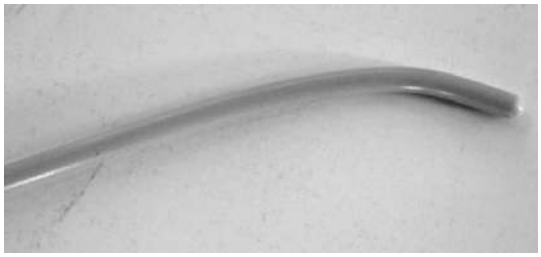


Figure 19.44 Tip of bougie.

The distal end may be angled 30 degrees to 45 degrees (1083,1084) (Fig. 19.44). This makes it easier to pass the device through the laryngeal inlet and prevents the bougie from advancing too far (1085). A bougie with a straight tip may be useful for tracheal tube exchange (510,1086), but is less advantageous than an AEC (1087,1088).

A bougie can be constructed from other materials (1089,1090,1091,1092). The plastic cannula from a Laryngeal Tracheal Anesthesia (LTA) kit may be used as a bougie (1093,1094,1095,1096). Single-use bougies are available but may not work as well as reusable ones and/or may have greater potential for trauma (1097,1098,1099,1100,1101,1102,1103,1104,1105,1106,1107,1108). A hollow bougie allows verification of correct position by inserting a fine fiberoptic endoscope through it or by using capnography (1092) or the esophageal detector device (1109).

A bougie with an angled tip is especially useful when the operator recognizes some anatomical landmarks but cannot direct the tip of the tracheal tube into the laryngeal inlet or when movement of the head and/or neck is undesirable (536,1110,1111,1112,1113,1114,1115,1116,1117,1118,1119,1120,1121,1122,1123,1124,1125,1126,1127,1128,1129,1130,1131,1132). In these situations, it is often possible to intubate the trachea with the thinner and more maneuverable bougie and then guide the tracheal tube into the trachea over it.

Techniques of Use as an Aid to Intubation

It is important to have bougies of various diameters available.

Before use, a bougie should be carefully inspected for fractures and tested for rigidity (1076,1133). It should be well lubricated. It can be placed first in the tracheal tube with the tip protruding, or it can be placed into the glottis and the tracheal tube then advanced over it.

A bougie can be placed in the trachea by internal palpation of posterior pharyngeal and glottic structures or with the aid of a rigid laryngoscope or bronchoscope, a flexible endoscope, or a supraglottic airway device (1121,1134,1135,1136,1137,1138,1139). It is better to pre-position the bougie in the laryngeal mask so that it exits through the middle, rather than pass it blindly (1140).

Because the tip is angled, the tip should be introduced pointing anteriorly. If the tip becomes stuck at the anterior commissure, it should be rotated 180ยฐ and then advanced (367). If the airway curvature is extreme, the tip can be directed even more anteriorly by lifting it with forceps (536). The failure rate from using the straight bougie may be decreased by using a laryngeal (dental) mirror (1141,1142).

The bougie should be advanced gently. The first sign that the tip is traversing the larynx may be a faint upward pressure felt by the person who is applying cricoid pressure (1125). As the bougie advances over the tracheal rings, it will often produce a clicking sensation. The bougie may rotate as it enters a main bronchus and come to a stop when it reaches a smaller bronchus (1111,1118,1121,1143). In the lightly anesthetized, nonparalyzed patient, a cough suggests tracheal rather than esophageal placement (1144). If the bougie is hollow, the proximal end may be attached to a capnograph to confirm intratracheal placement (1144,1145). However, CO_2 may not be detected if the openings are blocked by secretions or the tip is passed too far. Pharyngeal placement of the tip could yield false-positive results. If clicks are not elicited, the bougie should be gently advanced to a maximum distance of 45 cm (1146).

During nasal intubation, the bougie is advanced through the nostril and into the larynx. It is then observed by using a laryngoscope (367). The bougie is directed toward the vocal cords under direct vision. When the tip is inside the laryngeal inlet, the bougie is rotated so that the tip points posteriorly. It will usually then advance into the trachea. In the patient with a limited mouth opening, it may be possible to blindly pass the bougie through a nostril and into the trachea (412).

Once the bougie is believed to be in the trachea, the tracheal tube with its lumen lubricated with a water-soluble gel is gently advanced (railroaded) over the bougie by using a rotary motion. A tracheal tube that is designed to minimize the gap between the leading edge of the tube and the intubation catheter may facilitate insertion (13,89). Intubation may be facilitated by leaving the laryngoscope in the mouth, a jaw thrust, or rotating the tracheal tube counterclockwise 90 degrees (357,535,536,1125,1131,1147,1148,1149). A bronchoscopic adapter (Fig. 19.32) can be used to check for intratracheal placement of the tracheal tube without removing the bougie (1150). The bougie is then withdrawn. If the bougie is inadvertently placed in the esophagus, it may be used as a guide for inserting the LMA ProSeal (1151).

A second technique is to preinsert the bougie into the tracheal tube so that its tip protrudes approximately 5 cm beyond that of the tube (1125). This may save a few seconds but may make steering the tip to the left or right more difficult.

Other Uses

A useful technique for exchanging a tracheal tube is to insert a bougie alongside the existing tube (1152). The existing tube is then removed, and a new tube is inserted over the bougie.

A bougie can be used to improve the utility of the UpsherScope (Chapter 18) by directing the tracheal tube tip anteriorly (1153).

A bougie can be used to direct the ProSeal LMA into the esophagus (1154) or to change a ProSeal LMA (1155).

Evaluation

As an aid to the difficult intubation, the bougie may be superior to a stylet (1110,1114,1146,1156,1157,1158). It may be the first item that should be tried when laryngoscope-assisted tracheal intubation is not successful (1159).

A bougie may be especially useful in the patient with a severely compromised upper airway, anterior larynx, or limited mouth opening (1160). If glottic exposure is impossible, the bougie may be inserted blindly toward the presumed laryngeal inlet and advanced until resistance is encountered. The tracheal tube is then threaded over the bougie.

Using a bougie may result in trauma to the airway (1125,1161,1162,1163,1164). The force exerted by the tip is increased when the bougie is held near the tip (1097). The tip of the bougie may become detached, and the outer layer may become fractured (1133,1165). The bougie can be a source of contamination (1166,1167).

Airway Exchange Catheters

Description

An AEC (guiding catheter, director, stylet catheter, catheter guide, elastic stylet, tracheal tube replacement obturator, tube changer or exchanger, ventilation or exchange bougie, jet-style catheter, jet stylet, intubation catheter, intubating introducer) (Figs. 19.45, 19.46) can be used for a number of purposes (486,505,1168). Numerous ones in differing sizes are on the market. Some have an angular distal tip similar to a bougie. Some have a stiffening cannula. An AEC is more flexible and longer than a bougie.

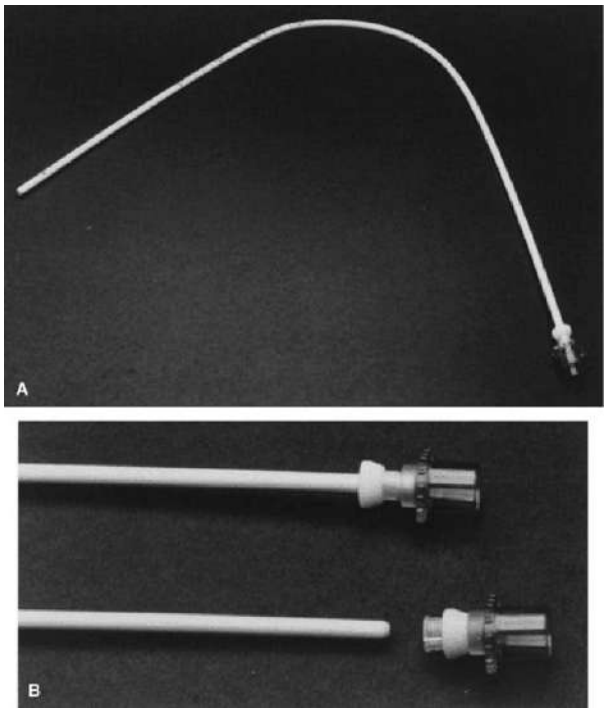


Figure 19.45 A: Airway exchange catheter. Note the marks showing the distance from the tip and the holes near the tip. **B:** The proximal connections allow administration of oxygen, jet ventilation, connection to a CO_2 analyzer, or suctioning. (Courtesy of Cook Critical Care, a division of Cook, Inc.)

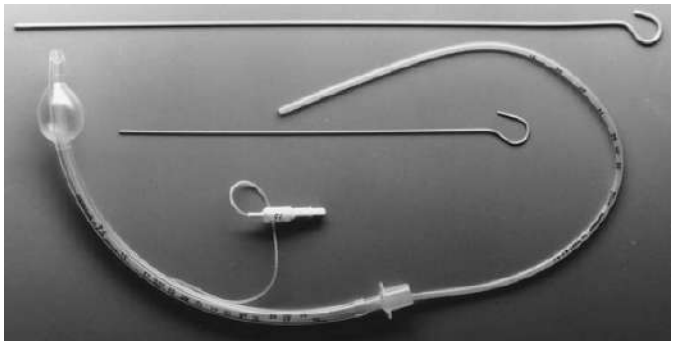


Figure 19.46 Tube changer in place. (Picture courtesy of Kendall Healthcare Products, Inc.)

When used as a tube changer, the catheter must be long enough so that the tube can be completely removed without the catheter being pulled from the trachea. Its length must be greater than double that of the tube being exchanged. It should be stiff

enough that it will not kink as the tube is removed or reinserted. Depth markings that are large, circumferential, and bold are helpful as they allow an estimation of how far the catheter has been inserted into the airway. A catheter with multiple distal side holes may decrease the pressure delivered at the distal end, minimize catheter whipping, and center the catheter within the trachea during jet ventilation (1169).

Various devices have served as AECs, including suction catheters, bougies, urethral catheters, embolectomy catheters, gastric tubes, plastic sheaths, guide wires, and flexible-tipped stylets (1137,1170,1171,1172,1173,1174,1175,1176,1177,1178,1179,1180).

Hollow devices allow oxygen administration by insufflation or jet ventilation and CO_2 measurement. Adaptors for these purposes are often furnished with the AEC. Jet ventilation through an AEC can provide satisfactory gas exchange in most cases (1181). The length and small ID make manual ventilation with a resuscitation bag impractical.

Uses

The choice of an appropriately sized tube changer can be vital. The best chance of a tracheal tube passing easily over a catheter into the trachea occurs when the catheter has a relatively large OD and the tube has a relatively small ID (1182,1183). The AEC may be labeled with the recommended diameter tube to be used with it. Airway exchangers suitable for pediatric tracheal tubes are available.

A silicone spray or water-soluble lubricant should be applied to the outside of the AEC.

The marking on the catheter should be matched with the centimeter markings on the tracheal tube to avoid advancing the AEC too deeply. The user must always be cognizant of the depth that the catheter is inserted, because deep insertion increases the risk of perforation and barotrauma with jet ventilation. The AEC should never be inserted against a resistance.

If the AEC is passed through the self-sealing diaphragm on a bronchoscopy adaptor (Fig. 19.32), ventilation can take place around the catheter. This allows the use of capnography to confirm intratracheal location of the tube without removing the catheter (1184).

A laryngoscope should be used when passing a tracheal tube over an AEC to facilitate passage past the supraglottic tissues (1182,1183). Twisting the tube may aid its advancement. If resistance is encountered, the tube should be turned 90 degrees counterclockwise.

A jet ventilator should be immediately available in case the new tube does not follow the AEC into the trachea, and the jet ventilator should be preset at 25 pounds per square inch (psi) (1183). A short inspiratory time and long expiratory time should be used initially.

Tracheal Tube or Supraglottic Device Exchange

An AEC is especially useful for exchanging a tracheal tube in a

patient who was difficult to intubate. It may also decrease the risk of airway difficulties in patients with an uncompromised laryngeal view during direct laryngoscopy (1185). During tube exchange, ventilation can be maintained by inserting the tube changer via a fiberoptic adaptor (Fig. 19.32). Oxygen insufflation is achieved by connecting the exchange catheter to an oxygen flowmeter.

Replacing an Existing Tube

The lubricated tube changer is inserted into the tracheal tube and advanced until it has reached the end of the tube as indicated by depth markings. Alternately, the tube changer may be placed alongside the tube (1186,1187). While the tube

changer is held steady, the existing tube is withdrawn. A new tracheal tube is then threaded over the tube changer and advanced until it is at the proper depth. Tracheal placement should be confirmed by using CO_2 monitoring, the EDD, or a flexible endoscope. The tube changer is then withdrawn. This technique has been used to exchange a tracheal tube placed submentally (1188), a nasotracheal tube (1086), a double-lumen for a conventional single-lumen tube (1189,1190), a Univent tube for a single-lumen tube (1191), and to replace a tracheostomy tube (1192).

Changing a Tracheal Tube from Oral to Nasal

To change an oral tube to a nasal tube, the tube changer may be passed through the oral tube and a tracheal tube passed through the nose into the pharynx. The oral tube is removed, leaving the tube changer in the trachea. The nasal tube is inserted into the trachea next to the changer.

An alternate method is to advance the tube changer through the nose, then place it alongside the existing tracheal tube. The existing tube is then removed and a tracheal tube advanced over the exchanger into the trachea.

In another technique, the exchange catheter is advanced into one of the nares and then brought out through the mouth (1193). The catheter is then advanced into the oral tracheal tube. The orotracheal tube is then slowly withdrawn, cutting it longitudinally until it is removed from the exchange catheter. A tracheal tube is then advanced over the exchange catheter.

Another technique has been described (1168,1194). A suction catheter or other device is inserted through the nares, and the other end is retrieved through the mouth. The AEC is inserted into the oral tube, and the oral tube is removed. The catheter is attached to the nasal part, and the nasal end is pulled out until the upper end of the catheter appears. This then serves as a guide for a tracheal tube, which is advanced through the nose into the trachea.

Changing a Tracheal Tube from Nasal to Oral

With one technique, a tube changer is placed orally alongside the tracheal tube (by using direct laryngoscopy or a flexible endoscope) (1195,1196). Alternately, a fiberscope loaded with a tracheal tube can be placed alongside the tracheal tube

(478,1197). A tube changer is passed through the nasal tube, which is then withdrawn into the pharynx. A tracheal tube is advanced over the first tube changer (or the fiberscope) until it is in the trachea. The nasal tube and tube exchanger are then removed. If it is not possible to advance the oral tube, the nasal tube can be passed back into the trachea over the tube changer.

With another technique, a tube changer is passed through the nasal tube, then the nasal tube is completely withdrawn (1168,1198,1199). The tube exchanger is located in the pharynx and pulled out through the mouth. A tracheal tube is then advanced over the tube changer into the trachea.

Intubation

The AEC can be used similarly to a bougie to facilitate intubation with a single-lumen or double-lumen tube (1200,1201,1202,1203,1204,1205,1206).

A guide wire may be inserted into the trachea and the tube changer then inserted over the guide wire (1207,1208). Some catheters can be placed over a fiberscope (1209). A supraglottic airway device can be used to place the catheter, although the success rate is not high with blind insertion (1210,1211,1212). It is better to place the AEC by using a flexible endoscope (1206,1213,1214) or preload it so that it passes through the midline slit in the supraglottic device (1140).

Extubation

Despite established extubation criteria, it is difficult to reliably predict subsequent respiratory distress (485,505,797,1215,1216,1217,1218,1219). An extubation trial should be considered, especially for a patient who might be difficult to reintubate. The airway exchange catheter is inserted into the tracheal tube, which is then removed. The catheter forms a bridge that will allow reintubation, administration of supplemental oxygen, ventilation, or measurement of end-tidal CO_2 from the trachea. If the patient is able to ventilate adequately, the catheter is removed. The use of an AEC might produce cost savings by demonstrating that patients will tolerate extubation earlier.

AECs have been left in place for long periods of time and are well tolerated by most patients (1187,1216,1217,1220,1221). Lubricating the distal end of the changer with lidocaine jelly may help the patient tolerate it better (1222). The patient can vocalize while the catheter remains in the trachea (1217). Manipulation of the tube changer may be used to stimulate the cough reflex (1220). Oxygen administration through the exchange catheter may obviate the need for facemask or nasal cannula following extubation. It is possible to enrich the oxygen content of the gas delivered through the catheter by using a facemask.

Other Uses

An AEC may be used to provide ventilation during microlaryngeal surgery (1168). It can provide a useful guide to the trachea during flexible endoscopy.

While a tracheostomy is being performed, it may be useful to re-

establish an airway if a problem occurs and may guide the surgeon to the tracheal lumen (807,1223,1224,1225,1226).

Another use for the AEC is during retrograde intubation (Chapter 21). The exchange catheter is passed over a guide inserted translaryngeally and passed retrograde to the oropharynx or nasopharynx (1078,1227,1228).

Other uses for the AEC include distinguishing esophageal from tracheal intubation (605), ventilating

the patient during management of intraoperative tracheal injury (1229), facilitating passage of a tracheal tube over a fiberscope (1230), facilitating submental intubation (1231), and ventilation of part of the lung during thoracotomy (1232).

Complications

Airway perforation has been reported as a complication of an AEC (505,1215,1233,1234,1235). The risk of perforation is related to the depth of insertion. The exchange catheter should never be inserted against a resistance.

The use of jet ventilation through the AEC may result in barotrauma (1169,1181,1216,1236,1237,1238). The use of standard ventilation through a 15-mm connector is less dangerous, so jet ventilation should be used only if standard ventilation fails to provide adequate gas exchange. The risk of barotrauma with jet ventilation may be decreased by lowering the gas pressure, using a short inspiratory time, providing a long expiratory time, and selecting a properly sized exchange catheter (1215,1233,1239). It is important to keep the distal tip of the airway exchanger above the carina. If incomplete chest deflation occurs, jet ventilation should be discontinued (1240).

There are a number of other complications associated with the AEC. The catheter may not slip off the flexible endoscope if the fit is too tight (1241). The tracheal tube may fail to pass over the AEC. Part of the catheter may break off and be aspirated (1133,1242,1243). The exchange catheter may be inadvertently removed (1217). The replacement tracheal tube may not end up in the trachea (1244). The channel in the exchange catheter tube changer may become occluded by secretions, incorrectly implying esophageal placement (1245). The catheter may dislodge a mucous plug, causing airway obstruction (1246). The catheter may exit through a side hole in the tracheal tube (817). Gastric perforation secondary to oxygen insufflated through a catheter in the esophagus has been reported (1247). The catheter may shear (1248).

Lighted Intubation Stylets

A lighted intubation stylet (lightwand, [flexible] lighted stylet, Trachlight™, illuminating or lighted intubating or intubation stylet) uses transillumination of the soft tissues in the anterior neck to guide the tip of the tracheal tube into the trachea or to determine the position of the tracheal tube or other airway device (1249,1250,1251,1252,1253,1254,1255,1256,1257,1258,1259,1260,1261). During direct laryngoscopy, the lighted stylet can be used to improve the view in the hypopharynx.

The lighted stylet is especially useful in situations where a fiberscope is unavailable or endoscopy is difficult to perform (e.g., when an airway is obscured by blood or secretions or when a patient's head cannot be flexed or extended).

Description

Several different lighted stylets are available commercially. Each has a reusable handle containing the power source and a malleable wand with a light at the end. The wand section may be detachable from the handle and may be disposable. Depth markings should be present. Lighted stylets differ from stylet laryngoscopes in that they do not have a means to see through the stylet. There is only a light transmission bundle. Stylet laryngoscopes are discussed in Chapter 18.

Some have a means to secure the lighted stylet to the tracheal tube. It may have a tip that can be manipulated during insertion. On some devices, it is possible to vary the length of the wand section to accommodate tracheal tubes of various lengths. Some have a retractable inner stylet that allows the distal portion to be made semirigid.

Some of the devices use fiberoptic light. The light blinks after being continuously ON for 30 seconds (1260). Pediatric lighted stylets that can accommodate tubes as small as 2.5 mm are available (1257,1260).

Techniques of Use

A lighted intubation stylet that is lubricated with a silicone spray or a water-based lubricant is passed through a tracheal tube so that the light is just short of the end of the tube (1262). If the bulb protrudes past the tube, trauma may result. Adult-sized tubes must be trimmed when used with shorter stylets. The stylet should be firmly attached to the tube.

The stylet is bent to the desired shape. For oral intubation, a 75- to 120-degree bend just proximal to the cuff is recommended (1255,1260,1263). Care should be taken not to bend the stylet at the point at which the bulb meets the shaft (1254). It may be useful to measure the mandibular-hyoid distance (1251). Another study found good success with a bent length of 6.5 cm (1264). If the patient has protruding upper teeth, another bend to coincide with the teeth should be made (1265). If desired, a catheter may be threaded under the housing and used to administer topical anesthesia (1266).

Softening the tracheal tube (by immersion in warm saline solution or by placing it inside the hose from a forced-air warming device) and reversing loading the tube (upside down from the usual position) may facilitate passing the tube into the trachea (531).

A relatively extended position will make it easier to observe the neck. In obese or pediatric patients or in patients with extremely short necks, placing a pillow under the shoulders and neck may be useful. It helps if an assistant retracts the breast or chest wall tissues

and indents the tissues around the trachea. These maneuvers

enhance transillumination in the anterior neck. The room lights should be dimmed or the anterior neck shaded in obese patients or in those with thick necks (1267,1268).

The operator may stand at the head or to the side of the patient's head. Lowering the bed may aid in observing the neck. The mouth is opened, and the tongue and mandible are pulled forward. A bite block may be needed to prevent the patient from biting the tube-stylet. The tube should be inserted from the side, then brought into the midline of the oropharynx. It is then rotated toward the tip of the chin and rocked (1267). The lighted stylet may be inserted through the intubating port of a mask (1269).

As the tube and stylet are advanced, the light trans-illuminates the tissues and can be seen through the anterior neck. A properly advancing lighted stylet produces a well-defined bright glow in the midline. A faint glow above the laryngeal prominence indicates that the tip is in the vallecula. A widespread glow to either side of the midline signals entry into a pyriform fossa. A very diffuse, fuzzy, or absent light means that the esophagus has been entered. This can be corrected by retracting and lifting the stylet to bring the tip more anterior (1251).

Applying cricoid pressure may increase the intensity of the illumination but may prolong the intubation attempt and increase the failure rate (1270). If resistance is felt, the lighted stylet-tube should be rocked backward and the tip redirected by using the glow from the light as a guide.

A loss of resistance and/or click may be felt when the lightwand is advanced under the epiglottis and through the cords (1261,1267). When the larynx is sharply trans-illuminated, the tracheal tube should be advanced into the trachea. The locking device is then released and the lightwand withdrawn from the tracheal tube.

A modification to this technique has been described (1271). Rather than retracting the stylet on the Trachlight, the thumb is used to push the handle vertically down while the finger holding the stylet maintains its position. This retracts the stylet distally while converting some of the vertical height of the stylet into horizontal distance.

Another technique for oral intubation has been described. This technique utilizes the Bullard Laryngoscope (Chapter 18) to visually assist intubation with the lighted intubation stylet. The Bullard stylet is removed. The cords are identified, and the Bullard scope is moved to the left. A tracheal tube over a lighted stylet is used to intubate the larynx. This is guided into position under direct vision from the Bullard scope (1272).

If ventilation is needed during intubation, the tracheal tube over the lighted stylet can be inserted through the diaphragm of a ventilating mask (1273) or through a supraglottic airway device (1274,1275,1276,1277,1278,1279,1280,1281,1282).

The patient with a clenched jaw can be intubated by retracting the cheek and inserting the lightwand from the side lateral to the teeth.

Nasal intubation can be performed by using a lighted intubation stylet (372,402,1252,1255,1256,1257,1258,1283,1284,1285,1286,1287).

The shape of the stylet should be prepared against the patient profile. The lighted stylet with tracheal tube is inserted through the nostril and gently advanced. When the light is seen in the oropharynx, the handle is rotated and the tip directed toward the thyroid prominence, using the glow of the light as a guide. Flexing the patient's neck, applying pressure to the larynx, or inflating the tracheal tube cuff may help to align the tracheal tube tip with the glottis. The Endotrol tube (discussed earlier) may be useful for nasal intubation with a lighted stylet.

The lighted intubation stylet can be used to aid direct laryngoscopy (1288). Placing the lighted stylet in the tracheal tube will improve the view in the hypopharynx, and transillumination can assist in guiding the tracheal tube into the trachea. In another technique, the lighted intubation stylet is placed through the Murphy eye of the tracheal tube and advanced beyond the end of the tube (1289). Once the tip of the lighted stylet is in the trachea, the tracheal tube is threaded over it. Rotating the tracheal tube may aid in advancing it.

Useful Situations

Studies suggest that the lighted intubation stylet can play a major role in tracheal intubation, especially in patients whose larynx cannot be visualized with conventional direct laryngoscopy (1256,1260,1290,1291,1292,1293,1294,1295,1296,1297,1298,1299,1300,1301,1302,1303). These include patients with a limited mouth opening, micro-gnathia, prominent upper incisors, restricted cervical spine movement or spinal immobilization, glossoptosis or glossomegaly, or restricted access to the airway (halo traction, stereotaxic frame). It may be especially useful in situations in which a flexible endoscope is unavailable (e.g., ambulances or emergency departments) or endoscopy is difficult to perform (e.g., when the airway is obscured by blood or secretions or when a patient's head cannot be flexed or extended) (1303,1304). It may also be advantageous with extensive dental work or poor teeth (1256). The lighted intubation stylet is useful when the anesthesia provider has limited use of the left arm (1305). It has been included on the ASA Practice Guidelines for Management of the Difficult Airway on the ‾€nonemergency pathway‾€ (506).

Other situations where the lighted intubation stylet may be useful include patients in head frames and where head extension is not possible. In this situation, the success rate was not as high and took longer than direct laryngoscopy (1306).

The lighted intubation stylet may be especially useful in emergency settings (1254). It is possible to use the device from the front or side of the patient, so the technique can be used in cramped quarters such as hallways and helicopters (1291,1257). It is especially suited to low-light settings.

The lighted stylet can be used to check that the tracheal tube has entered the trachea and not the esophagus (1280,1307,1308) as well as to check for proper depth of the tracheal tube (748,1309). It has been used to identify the trachea during tracheostomy (1310).

A lighted stylet can be used to aid retrograde intubation

(1311,1312) and to place a double-lumen bronchial tube (1313,1314). It may be useful in the patient with a clenched jaw in whom nasal intubation is contraindicated (1315), the patient with cervical instability (1316,1317), and tracheostomy (1318).

A lighted stylet may be used to aid intubation through a laryngeal mask (1279,1280,1282,1319,1320,1321,1322,1323,1324,1325,1326,1327,1328,1329,1330,1331,1332). It can be used in pediatric patients (1291,1294,1297,1333,1334). It can be used with the patient in the lateral position (1335).

Contraindications

Contraindications to use of the lighted intubation stylet include patients with tumors, infection, trauma, or foreign bodies in the upper airway; anything that interferes with transmission of the light from the neck (anterior neck scarring, flexion contractions, a beard, excessive adipose tissue, midline neck tumors or swellings, covering of the bulb with blood and/or secretions); and potential cervical spine instability.

This is not an emergency airway technique. The procedure can take a significant amount of time and may need to be performed in the dark (1336). For ‘€can't intubate‘€“can't ventilate‘€ situations, a supraglottic airway device (Chapter 17) may be more appropriate.

It is more difficult to use the lighted intubation stylet in children and infants than in adults and should not be undertaken in small patients without experience in older ones (1302).

Advantages

The lighted intubation stylet is simple, inexpensive, lightweight, reusable, reliable, compact, easily cleaned, portable, and reasonably durable. Intubation can be accomplished rapidly after facility with the technique has been attained (1259,1260,1331,1337,1338). It can be performed with cricoid pressure and in uncooperative patients (1303). The presence of blood or secretions is not a strong impediment to success. It can be used when access to the head and airway are limited. Head and neck manipulation can be kept to a minimum. A wide mouth opening is not required.

Intubation by using the lighted stylet is associated with a low incidence of mucosal injury, dysphagia, sore throat, and dental trauma compared with direct laryngoscopy (1259,1261,1339,1340), but one study found a greater incidence of hoarseness with the lighted stylet (1341).

The circulatory responses and effects on intraocular pressures are similar to direct laryngoscopy (1339,1341,1342,1343,1344,1345,1346,1347,1348,1349). In awake patients, the magnitude of stress is less than with a laryngoscope (1350).

The intubation technique with the lighted stylet is easily learned, although there is a learning curve (1340).

Compared with blind nasal intubation, nasal intubation with a lighted stylet has been shown to require less time and fewer attempts (1252). In patients with cervical spine disorders, intubation with a lighted stylet is faster and associated with a

higher success rate than intubation through an intubating laryngeal mask (1298). It causes less cervical spine movement than intubation with a Macintosh laryngoscope and is faster than using a Bullard laryngoscope or fiberscope (1317).

Disadvantages

This is a blind approach and proficiency in use requires practice. The time to intubation and number of attempts are greater than with the patients intubated with a rigid laryngoscope (1250,1251,1256,1341,1351).

Complications

The bulb or lens may become detached (1250,1254,1290,1352,1353). The device may fracture near the handle (1354).

There is the potential for trauma in the upper airway associated with its use. Cases of arytenoid dislocation and epiglottis malposition have been reported (1355,1356,1357). A case has been reported where the epiglottis was partially pushed into the laryngeal inlet (1355).

It is not uncommon to cause some bleeding with this technique. If this technique fails, the presence of blood makes fiberoptic techniques more difficult.

With repeated use and sterilization, the stylet may become irregular and difficult to retract (1358). A small amount of lubricant may help the problem. The electrical contact between the stylet and the handle may fail, causing intermittent light.

While there is concern that the bulb could cause a burn in the trachea, this has not been reported. The absence of injury may be a result of continuous movement of the light bulb (1359).

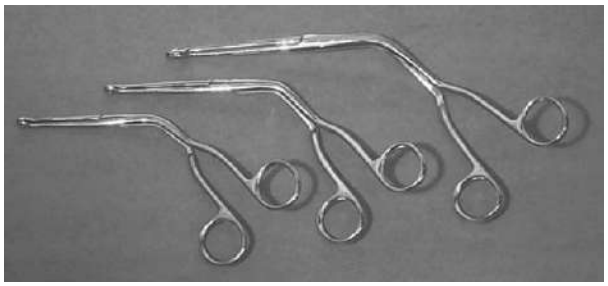


Figure 19.47 Magill's forceps. (Picture courtesy of Sun Med.)

Forceps

Forceps can be used to direct a tracheal tube into the larynx or a gastric tube or other device into the esophagus. It may also be used to insert or remove pharyngeal packing and to remove foreign bodies from the upper airway or esophagus (1360,1361). Forceps should be immediately available whenever an intubation

is performed.

Description

A popular type is Magill's forceps (Fig. 19.47). These are designed so that when the grasping ends are in the axis of the tracheal tube, the handle is to the right. When the larynx is exposed, most of the forceps is out of the line of sight. Modifications of Magill's forceps and use of other devices have been described (1362,1363,1364,1365,1366,1367,1368).

Problems

The tracheal tube cuff may become damaged, especially when forceps are used with high-volume, low-pressure cuffs. The tube should not be grasped at the cuff. Another way to avoid cuff damage is to smooth the ridges on the forceps (1362). The forceps may cause damage to the airway mucosa. Another problem is that one arm of the forceps may become lodged in a Murphy eye (28). A forceps may break (1369,1370).

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Questions

For the following question, select the correct answer

1. The best way to detect an esophageal intubation is

A. Seeing the tube pass through the vocal cords

B. Observing chest wall movement during inspiration and exhalation

C. Hearing breath sounds during controlled ventilation

D. Monitoring CO_2 in exhaled gases

E. Seeing a drop in oxygen saturation as measured by pulse oximeter

View Answer

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

2. Factors that help to determine the resistance to breathing

that result from the use of a tracheal tube include

A. Tube length

B. ID of the tube

C. Tube configuration

D. Gas viscosity

View Answer

3. Which statements about dead space are accurate?

A. Pediatric tubes and connectors can increase dead space above normal

B. The use of a shorter tracheal tube will decrease dead space

C. Mechanical ventilation can overcome the effects of increased dead space

D. The dead space of the tube plus connector is greater than natural dead space in adults

View Answer

4. Materials commonly used in tracheal tubes today include

A. PVC

B. Rubber

C. Silicone

D. Polyethylene

View Answer

5. Concerning the Murphy eye,

A. It may reduce trauma during nasal intubation

B. A fiberoptic scope may become trapped in it

C. It may mask a right mainstem bronchial intubation

D. Secretions may tend to accumulate there

View Answer

6. Advantages of a spiral embedded tracheal tube include

A. Ease of insertion over a fiberscope

B. Resistance to kinking

C. Flexible enough to be placed in tracheostomies

D. Unlikely to be the cause of obstruction

View Answer

7. With respect to tracheal tube size,

A. Pediatric tubes are sized by the OD

B. Tubes larger than size 6.0 must have the OD marked on them

C. The French scale is required to be marked on the tube

D. Size is often displayed on the pilot balloon

View Answer

8. With tracheal tubes,

A. Cuff pressure should be kept between 25 and 34 cm H_2O

B. Measuring the intracuff pressure in high-pressure cuffs gives an indication of the pressure applied to the tracheal wall

C. Nitrous oxide can cause the cuff pressure to increase

D. Intracuff pressure in low-pressure cuffs does not vary during controlled ventilation

View Answer

9. Advantages of the foam cuff tube include

A. Measuring intracuff pressure is not necessary

B. Even large cuffs do not present excessive pressure to the tracheal wall

C. Diffusion of anesthetic agents will not affect cuff pressure

D. A seal sufficient to prevent aspiration will be achieved regardless of the relative size of the tube and trachea

View Answer

10. Features of the Lanz pressure-regulating valve include

A. It gives an indication of cuff inflation

B. It has an external reservoir for cuff air

C. It limits the pressure in the cuff

D. Intracuff pressure is maintained at 26 to 33 torr

View Answer

11. Products approved for use as a laser-resistant wrap for tracheal tubes include

A. Copper foil

B. Aluminum tape

C. Aluminum foil

D. Sponge and adhesive-backed corrugated silver foil

View Answer

12. Disadvantages of wrapping tracheal tubes include

A. The OD of the tube is increased

B. A rough surface may be created

C. A reflected beam could damage other tissues

D. The airway could become obstructed

View Answer

13. Problems associated with a tracheal tube cuff that is too large include

A. Pressure on the tracheal wall will be increased

B. Trauma to the vocal cords is more likely

C. Intracuff pressure will be increased

D. Aspiration is more likely to occur

View Answer

14. In determining proper inflation of a low-pressure, high-volume cuff,

A. The volume of air just needed to abolish air leak may not be enough to prevent aspiration

B. The feel of the inflation balloon is a good indication of the cuff pressure

C. Measurement of cuff pressure is needed to determine proper inflation

D. Cuff pressure needs to be checked during the inspiratory phase of ventilation

View Answer

15. Possible complications of nasotracheal intubation include

A. Removal of segments of turbinates

B. Esophageal perforation

C. Perforation of the nasal septum

D. Perforation into the retropharyngeal space

View Answer

16. Ways to minimize trauma when a nasal intubation is performed include

A. Avoiding lubricants

B. Warming the tracheal tube

C. Vasodilating the nasal mucosa

D. Using smaller tubes than those that would be used for oral intubation

View Answer

17. If there is a leak around the tracheal tube that recurs despite added air,

A. The tube may be sliding in and out of a bronchus

B. The cuff may be above the cords

C. Gas may be diffusing out of the cuff

D. There may be a leak in the cuff

View Answer

18. Factors that tend to promote inadvertent bronchial intubation include

A. Trendelenburg position

B. Neck flexion

C. Laparoscopy

D. Use of RAE tubes for children

View Answer

19. Reliable methods for determining the presence of an inadvertent bronchial intubation include

A. Auscultation of the lungs

B. Pulse oximetry

C. End-tidal CO_2 monitoring

D. Fiberscopic visualization through the tube

View Answer

20. Ways to handle a cuff leak include

A. Reintubation

B. Packing the pharynx

C. Attaching a mechanism for continuous air infusion to the cuff inflation system

D. Fill the cuff with lidocane and saline

View Answer

21. Ways of preventing tracheal tube obstruction include

A. Checking the cuff for even inflation

B. Not withdrawing the tube with the cuff inflated

C. Using an oral airway or bite block

D. Putting traction on the tracheal tube

View Answer

22. Factors increasing the incidence of aspiration of gastric contents include

A. Head-up position

B. Controlled ventilation

C. Accumulation of fluid above the cuff

D. High-pressure cuffs

View Answer

23. Factors that increase the likelihood of accidental extubation include

A. Removing an adhesive plastic drape

B. Using antidisconnect devices

C. Removing a nasogastric tube before extubation

D. Placing the tube at the carina

View Answer

24. Possible causes of difficult extubation include

A. Obstruction of the inflating mechanism

B. Pulling the pilot balloon and inflation device from the inflating mechanism

C. Surgical transfixion

D. Swelling in the airway

View Answer

25. Postoperative sore throat

A. Is more common in males than females

B. Is increased if the patient is in the prone position

C. Is related to both duration of anesthesia and age of the patient

D. Is associated with use of larger tubes

View Answer

26. Concerning hoarseness following intubation,

A. The incidence is decreased with the use of low-pressure cuffs

B. Lubrication of the tube with lidocaine jelly does not decrease the incidence

C. Smaller tubes are associated with a decreased incidence

D. The incidence is not increased if the intubation was traumatic

View Answer

27. Laryngeal edema

A. May be caused by pre-existing inflammation, bacterial contamination, or chemicals

B. May be caused by inadequate muscle relaxation or too large a tube

C. May be caused by an allergic reaction to the tube or lubricants

D. Can occur anytime during the first 48 hours after extubation

View Answer

28. Granulomas of the vocal cords

A. Are found most commonly in males

B. May not become symptomatic for several months

C. Are most common in children

D. May be symptomless

View Answer

29. Disadvantages of preformed RAE tubes include

A. The tube may not be cut

B. Increased resistance

C. Height and weight are not useful to determine the proper size tube

D. Age in years is not useful to determine the proper size tube

View Answer

30. Advantages of the microlaryngeal tracheal surgery tube include

A. Small diameter providing better visibility for the surgeon

B. Lower resistance to both inhalation and exhalation

C. Can be used for patients with a narrowed airway

D. Can be used with lasers

View Answer

31. Which tube(s) have a high-pressure cuff?

A. Norton tracheal tube

B. Sheridan Laser tracheal tube

C. Lasertubus

D. Intubating laryngeal mask tracheal tube

View Answer

32. Disadvantage(s) of using a tracheal tube with a low-pressure cuff include

A. Aspiration of fluid from the upper airway into the trachea

B. It may be torn easily

C. A greater incidence of sore throat compared with the high-pressure cuff

D. More difficulty during insertion

View Answer

33. Situation(s) that will cause tracheal tube cuff pressure to vary include

A. Heated humidification

B. Oxygen diffusion into the cuff

C. Changes in head position away from the neutral position

D. Increases in altitude

View Answer

34. What are some ways to limit changes in the intracuff pressure in the low-pressure cuffs?

A. Monitoring cuff pressure

B. Filling the cuff with a mixture of oxygen and nitrous oxide

C. Filling the cuff with water or saline

D. Leaving a syringe attached to the inflation tube

View Answer

35. Advantages of cuffed tracheal tubes include

A. Less operating room pollution with anesthetic gases

B. Decreased aspiration risk

C. Improved monitoring of respiratory gases

D. Greater margin of safety

View Answer

36. Drawbacks of using cuffed tubes in children include

A. Possible obstruction by the cuff

B. Higher gas flows must be used

C. Suctioning through the tube is more difficult

D. Lower inflation pressure must be used

View Answer

37. Advantages of oral intubation include

A. Can be performed quickly

B. Minimal cervical spine motion

C. Can use a tracheal tube with a larger diameter

D. Well tolerated in the conscious patient

View Answer

38. Indications for nasotracheal intubation include

A. Temporomandibular joint movement limitation

B. Intraoral pathology

C. Cervical spine injury

D. Fractured maxilla

View Answer

39. Advantages of nasotracheal intubation include

A. A larger tube can be used

B. Tube will not be occluded by biting

C. Lower incidence of bacteremia

D. Less cervical spine movement than oral intubation

View Answer

40. Relative contraindications to nasotracheal intubation include

A. Coagulopathies

B. Previous repair of the cribiform plate

C. Abscesses

D. Trans-sphenoidal surgery

View Answer

41. Which technique(s) will facilitate passing a tracheal tube

through the vocal cords over a flexible endoscope, bougie, or exchange catheter?

A. Warming the tracheal tube

B. Rotating the tube counterclockwise 180 degrees

C. Applying a jaw thrust

D. Using a smaller endoscope, bougie, or exchange catheter

View Answer

42. Way(s) to avoid trauma associated with tracheal intubation include

A. Thermosoftening the tube

B. Use only gentle pressure

C. Do not let a device in the tracheal tube protrude from the tip

D. Applying a vasoconstrictor to the nose

View Answer

43. While observing chest wall motion as a test of tracheal intubation, which conditions may simulate tracheal intubation during an esophageal intubation?

A. Patients with a low lung volume

B. Obese patients

C. Low chest wall compliance

D. Abdominal respiration

View Answer

44. Which auscultatory technique(s) give the most reliable indication that the tracheal tube is in the trachea?

A. Auscultation of the upper abdomen and lungs

B. Gurgling sounds with ventilation

C. Airway auscultation

D. Auscultation of high mid-axillary area

View Answer

45. Situations where end-tidal CO_2 detection may not indicate that the trachea has been intubated include

A. Cardiac arrest

B. Exhaled gases in the stomach

C. Pulmonary embolism

D. Bronchospasm

View Answer

46. Situations where the esophageal detector device will be more accurate in detecting tracheal intubation than CO_2 monitoring include

A. Severe bronchospasm

B. Cardiac arrest

C. Pulmonary embolism

D. One-way tracheal tube obstruction

View Answer

47. Situations where CO_2 monitoring may cause a false-positive reading about tracheal tube placement include

A. Exhaled gases forced into the stomach during previous mask ventilation

B. Intravenous lactated Ringer's solution

C. Antacids that have reacted with gastric acid to form CO_2

D. Bronchospasm

View Answer

48. Complications that can occur with the lighted stylet include

A. Burns from the hot light bulb

B. Arytenoid dislocation

C. Takes more time and more attempts than blind nasal intubation

D. Epiglottis malposition

View Answer

49. Ways to avoid tracheal tube obstruction include

A. Using transparent tracheal tubes

B. Deflating the cuff before withdrawing the tube

C. Cutting the machine end of the tube at a bevel before the connector is inserted

D. Placing a bite block between the incisor teeth

View Answer

50. Indications that a partial tracheal tube obstruction is present may include which of the following?

A. Wheezing

B. An alteration in the pressure-volume loop

C. Paradoxical chest movements during spontaneous breathing

D. A decreased slope in Phase III and a smaller ∅ angle on the capnogram

View Answer

51. A partial tracheal tube obstruction can be diagnosed by which of the following maneuvers?

A. Deflating the tracheal tube cuff

B. Digital examination

C. Fiberscopic examination

D. Inserting a stylet or suction catheter

View Answer

52. Ways to relieve a partially obstructed tracheal tube include

A. Using a hemostat or clamp to relieve the kink

B. Passing a smaller tube through the tracheal tube

C. Using an embolectomy catheter

D. Placing a larger tracheal tube over the kinked tracheal tube

View Answer

53. Which of these techniques may avoid pulmonary aspiration when the tracheal tube is removed?

A. Withdrawing the tube with the cuff inflated until the cuff is just above the vocal cords

B. Placing the patient in the head down lateral position

C. Withdrawing the tracheal tube during suctioning

D. Withdrawing the tube under positive pressure in the trachea

View Answer

54. Situations that can contribute to macroglossia include

A. Sitting position

B. Anticoagulation

C. Prone position

D. Hemorrhage in the pharynx

View Answer

55. Indication(s) that a bougie has entered the trachea include

A. Rotation, if the bougie enters a mainstem bronchus

B. A clicking sensation as it passes over tracheal rings

C. Resistance as it enters smaller bronchi

D. A decrease in force needed to advance the bougie

View Answer

56. Situations where the lighted intubation stylet is particularly useful include

A. Limited mouth opening

B. Micrognathia

C. When a flexible endoscope is not available

D. When the anesthesia provider has limited use of the left arm

View Answer

57. Contraindications to the lighted stylet technique of intubation include

A. Foreign bodies in the upper airway

B. Placing double-lumen or bronchial tubes

C. Infection

D. Cervical instability

View Answer

Chapter 20
Lung Isolation Devices

Indications for Lung Isolation

Thoracic Procedures

A deflated lung provides better operating conditions and reduced trauma during thoracic procedures.

Control of Contamination or Hemorrhage

A lung isolation device can prevent infected material from one lung from contaminating the other lung (1). When hemorrhage occurs in one lung, an isolation device allows the unaffected lung to be ventilated (2,3,4,5,6,7,8,9,10,11).

Unilateral Pathology

A bronchopleural or bronchocutaneous fistula may have such a low resistance to gas flow that most of the tidal volume passes through it, making it impossible to adequately ventilate the other lung (12,13,14). Large cysts or bullae may rupture under positive pressure, making it mandatory that they be excluded from ventilation. Another indication for lung separation is when lungs have markedly different compliance or airway resistance such as that which occurs following single-lung transplantation or unilateral injury (15).

The best method of producing lung isolation in a given situation will depend on several factors, including the indication for lung isolation, patient variables, available equipment, and the skill and training of the anesthesia provider.

Anatomical Considerations

The right mainstem bronchus is shorter, straighter, and has a larger diameter than the left. It takes off from the trachea at an angle of 25 degrees in adults. The left mainstem bronchus diverges from the median plane at a 45-degree angle. These angles are slightly larger in children (16). The right upper lobe bronchus takeoff is very close to the origin of the right mainstem bronchus. These anatomical features mean that it is usually easier to intubate the right mainstem bronchus than the left, but it is more difficult to place a tube in the right mainstem bronchus without obstructing the upper lobe orifice.

Double-lumen Tubes

The double-lumen tube (DLT, DLET) is the device most commonly used to provide lung isolation.

Description

A DLT is essentially two single-lumen tubes bonded together and designated either as right- or left-sided, depending on which mainstem bronchus the tube is designed to fit. The tracheal lumen is designed to terminate above the carina. The distal portion of the bronchial lumen is angled to fit into the appropriate mainstem bronchus.

The internal lumen of each tube is D-shaped with the straight side of the D in the middle of the tube. The resistance of each lumen of a 35 to 41 French (Fr) DLT has been found to be comparable to the resistance of a size 6 to 7 mm internal diameter single-lumen tracheal tube (17).

The bronchial cuff for right-sided tubes varies in shape, depending on the manufacturer. On some tubes, the cuff has a slot to allow ventilation of the right upper lobe. Some right-sided DLTs have two bronchial cuffs with an opening for the right upper lobe between them. The resting volume and compliance of bronchial cuffs varies between different sizes and brands of DLTs (18,19). Most manufacturers color the bronchial cuff blue. They also use blue markings on the pilot balloon and/or the inflation device for the bronchial cuff.

A few DLTs have a carinal hook to aid in proper placement and minimize tube movement after placement. Potential problems with carinal hooks include increased difficulty during intubation, trauma to the airway, malposition of the tube because of the hook, and interference with bronchial closure during pneumonectomy. The hook can break off and become lost in the bronchial tree.

Most manufacturers place a radiopaque marker at the bottom of the tracheal cuff or at the end of the tracheal lumen. Other marks may be placed above and/or below the bronchial cuff. Some have a radiopaque line running the length of the tube.

Disposable DLTs are supplied in sterile packages, which include a stylet, connectors, and suction catheter(s). A means to supply continuous positive airway pressure (CPAP) may be included with the tube or can be purchased separately.

The connector (20) allows both lumens to attach to a breathing system at the same time.

Sizing

Adult DLTs commonly come in sizes 35, 37, 39, and 41 Fr. The French scale is the external diameter of the tracheal segment times three. Some manufacturers also provide 26, 28, and 32 Fr tubes for younger patients. Unfortunately, the French gauge markings are of limited value in determining the most important measurement—the diameter of the bronchial segment.

There are major variations between manufacturers in the dimensions of the bronchial segment of DLTs of the same nominal size and even among tubes of the

same size from the same manufacturer (21,22,23,24). An International Technical Specification has recommended that outside circumference of the bronchial segment be designated in millimeters (25). The diameter of the bronchial segment with the cuff inflated may not increase with tube size (26).

Margin of Safety

The margin of safety for a DLT is the length of the tracheobronchial tree between the most distal and proximal acceptable positions (27,28). The margin of safety will depend on the length of the lumen into which the cuff is placed and the length of the cuff. If the cuff is short or the mainstem bronchus long, the margin of safety will be greater.

Left-sided Tubes

The outermost acceptable position for a left-sided DLT is when the bronchial cuff is just below the carina. If the tube were more proximal, the bronchial cuff could obstruct the trachea and/or the contralateral (right) mainstem bronchus. In this case, the seal between the two lungs would be lost. The most acceptable distal position is when the the bronchial segment tip is at the proximal edge of the upper lobe bronchial orifice. More distal insertion would result in obstruction of the upper lobe bronchus.

The average length of the left bronchus from the carina to the takeoff of the upper lobe bronchus is 5.6 cm. This leaves a relatively small margin for placement, as there could be up to 3.5 cm of movement with neck flexion and extension (29). There is great variability in the length of the bronchial segment of left-sided DLTs currently available (30).

Right-sided Tubes

The margin of safety is defined differently for right-sided tubes. A right-sided DLT is acceptably positioned if the right upper lobe ventilation opening or the space between the two cuffs is aligned with the right upper lobe orifice. Thus, the margin of safety is the length of the ventilation opening minus the diameter of the

orifice. The margin of safety for right-sided tubes is considerably less than for left-sided tubes.

Specific Tubes

Carlens Double-lumen Tube

The Carlens DLT (Figs. 20.1, 20.2) is intended to be inserted into the left mainstem bronchus. It has a carinal hook (spur). This tube may be especially useful with massive hemoptysis when verification of tube placement is especially difficult (31).

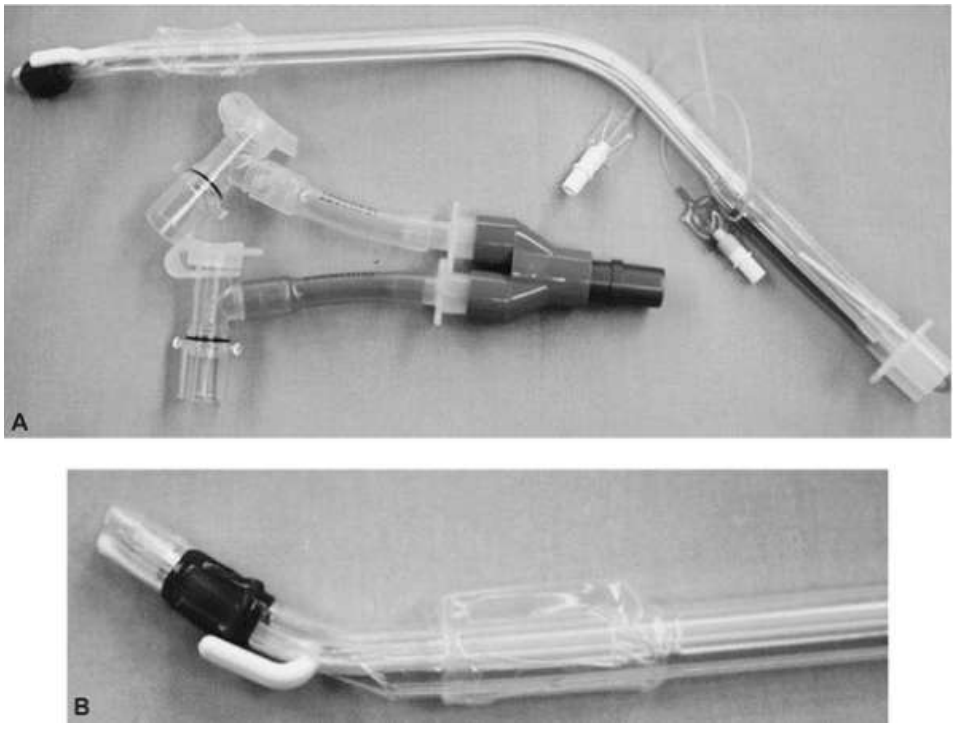

Figure 20.1 Carlens double-lumen tube. **A:** The connector has ports for fiberscope insertion or suctioning and areas where a clamp can be applied to occlude gas flow. **B:** Note the carinal hook and the blue bronchial cuff.

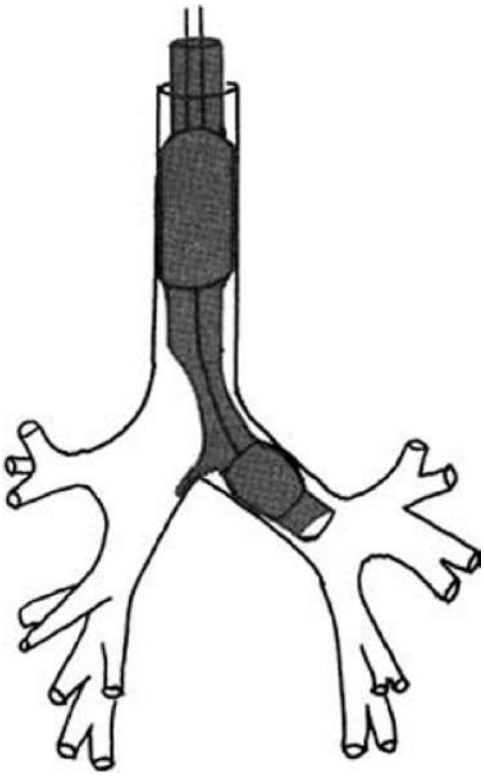

Figure 20.2 Carlens tube in place.

White Double-lumen Tube

The White DLT (Fig. 20.3) is designed to fit the right mainstem bronchus. It has a carinal hook. The cuff for the right mainstem bronchus is circumferential superior to the opening to the upper lobe bronchus and continues distally behind the opening.

Robertshaw Right Double-lumen Tube

The bronchial portion of the Robertshaw right DLT (Fig. 20.4) is angled at 20 degrees (32). The bronchial cuff has a slotted opening in its lateral aspect (Fig. 20.5). The bronchial cuff is proximal to the slot on the lateral surface and extends tangentially toward the medial surface.

Robertshaw Left Double-lumen Tube

The Robertshaw left DLT is shown in Figures 20.6 and 20.7. The angle of the bronchial portion is 40 degrees (32). The average length of the bronchial segment is 23 mm for sizes 35/37 and 25 mm for sizes 39/41 (30).

Broncho-Cath Right-sided Tube

The Broncho-Cath right-sided tube has a bronchial cuff that is roughly the shape of an S, or slanted doughnut. The cuff edge nearest the right upper lobe bronchus is closer to the trachea than the part of the cuff touching the medial bronchial wall (Figs. 20.8, 20.9). A slot in the tube just beyond the cuff corresponds to the opening of the upper lobe bronchus (27). The end of the bronchial segment has no bevel (33).

The shape of the right bronchial cuff allows the ventilation slot to ride off the right upper lobe orifice, increasing the margin of safety. One study found that when this tube was inserted blindly, right upper lobe obstruction occurred in 89% of cases (34). Placement using fiberoptic endoscopy resulted in much better positioning (35).

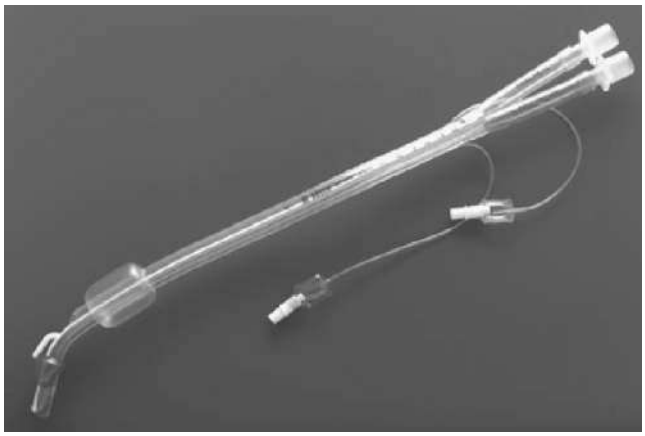

Figure 20.3 White double-lumen tube. (Picture courtesy of Teleflex Medical.)

Broncho-Cath Left-sided Tube

On the Broncho-Cath left-sided DLT (Fig. 20.10), the bronchial portion of the tube is at an angle of approximately 45 degrees (33,36,37). The bronchial portion has a curved tip. The bevel was removed in 1994 but reintroduced in 2001 (33,38). The average length of the bronchial segment is 30 to 31 mm (30). The tube is available with or without a carinal hook.

Sher-I-Bronch Right-sided Double-lumen Tube

The Sher-I-Bronch right-sided DLT has two cuffs on the bronchial segment, one proximal and one distal to the upper lobe

ventilation slot. The slot is 13 to 14 mm long (Figs. 20.11, 20.12). One study found that poor lung isolation was more common when this tube was used (39). A case has been reported in which the tube tip became trapped in the right upper lobe bronchus (40).

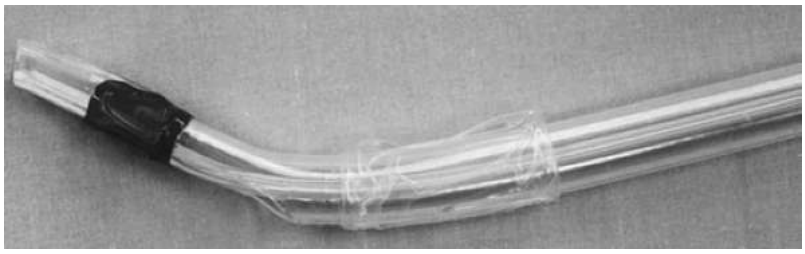

Figure 20.4 Robertshaw right double-lumen tube in place.

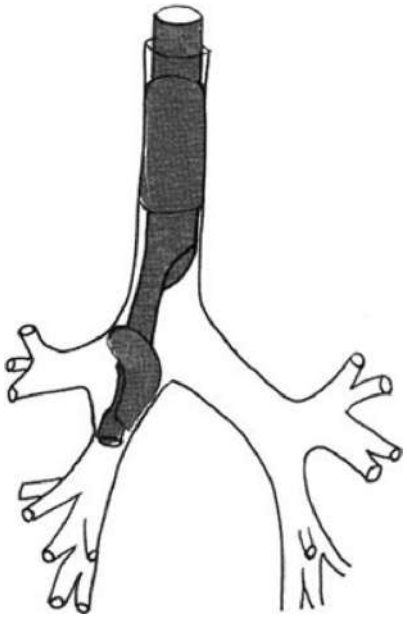

Figure 20.5 Robertshaw right double-lumen tube in place.

Sher-I-Bronch Left-sided Double-lumen Tube

The bronchial segment of the Sher-I-Bronch left-sided DLT diverges from the main tube at an angle of 34 degrees. The average length of the bronchial segment is 35 mm (30). The bronchial segment has a bevel (30). One study found that the bronchial cuff on this tube required significantly higher pressures to achieve one-lung isolation than cuffs on other DLTs (41).

Silbroncho Double-lumen Tube

The Silbroncho DLT (Fig. 20.13) is made of silicone, which is softer than polyvinylchloride (PVC). The tube does not contain latex. The bronchial segment is wire-reinforced distal to the tracheal cuff. This allows it to be flexible and prevents kinking. The wire reinforcement also makes tube position easy to determine on x-ray. The bronchial cuff is small and near the end of the tube. It is available in sizes 33, 35, 37, and 39 Fr.

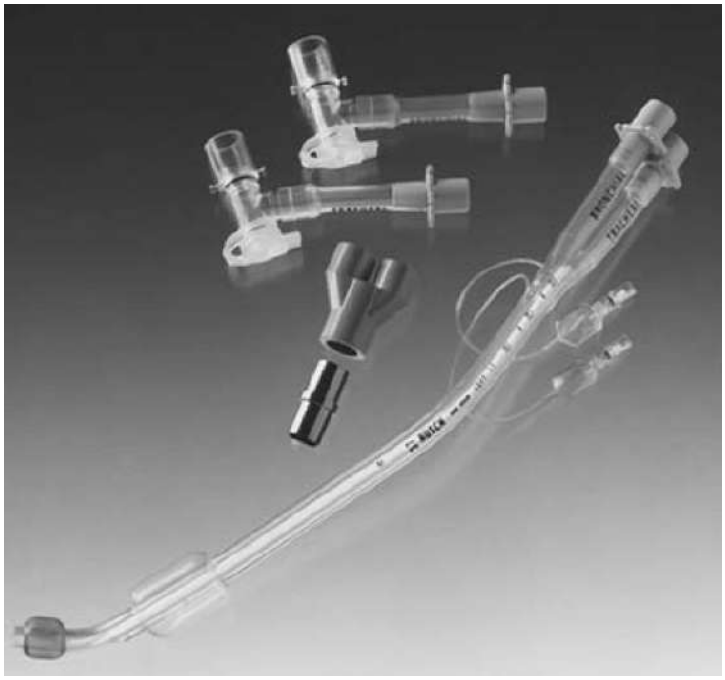

Figure 20.6 Robertshaw left double-lumen tube. (Courtesy of Rusch, Inc.)

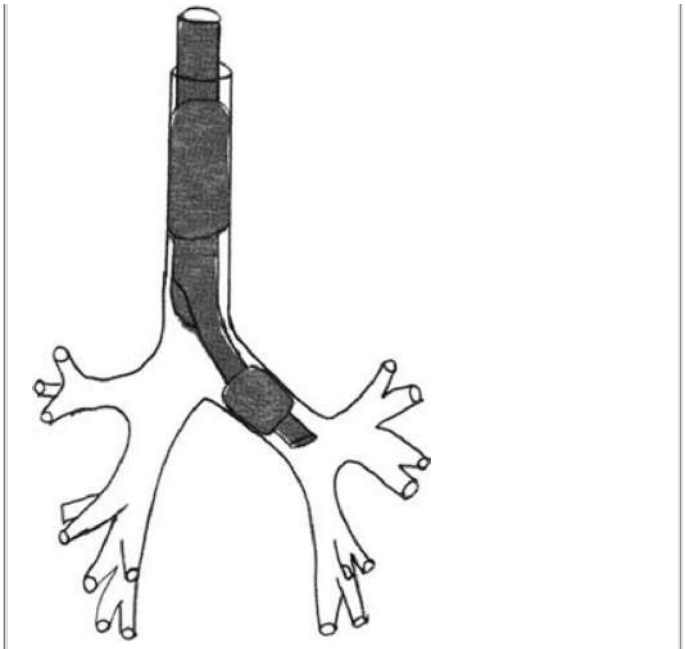

Figure 20.7 Robertshaw left double-lumen tube.

Techniques

Tube Choice

Right versus Left

When surgery is performed on the right lung, a left-sided DLT should be used (42,43,44). Because the margin of safety in positioning a right-sided DLT is so small, some prefer to use a left-sided DLT whenever possible for left lung surgery (28,45). During left pneumonectomy, immediately before the left mainstem bronchus is clamped, the DLT can be pulled from the bronchus and used for ventilating the right lung. A disadvantage of this technique is the risk of blood and secretions moving from the operative (left) bronchus to the nonoperative bronchus. Other possible problems include the tube becoming dislodged or sutured in place during surgery. A ball-valve obstruction may occur as a result of secretions or mediastinal pressure pushing the tracheal lumen against the tracheal wall (46). A left DLT may not provide optimum conditions for ventilating the residual lung after left upper lobectomy (47).

A right-sided DLT should be used when it is important to avoid manipulation/intubation of the left main bronchus (e.g., an exophytic lesion), when the left main bronchus is narrowed or

the left mainstem bronchus is so cephalad that the bronchial lumen will not enter the

left mainstem bronchus, left pneumonectomy, left lung transplantation, left mainstem bronchus stent in place or when there is tracheobronchial disruption on the left (43,48,49,50,51).

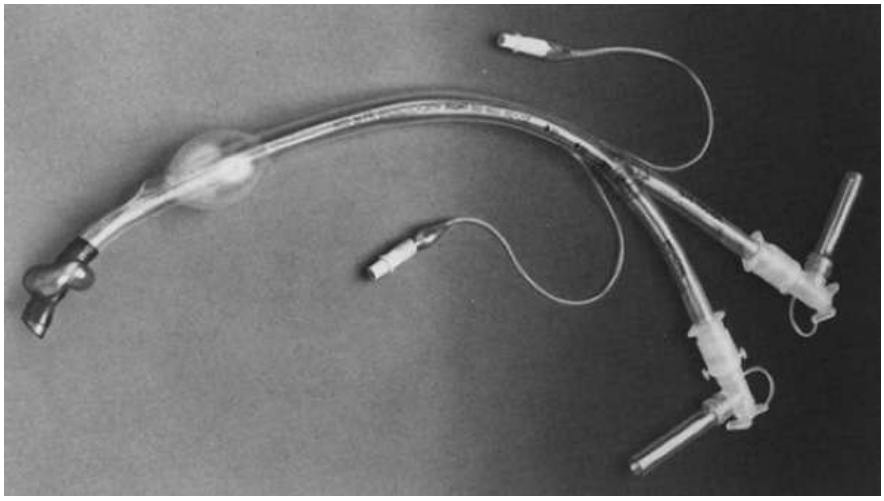

Figure 20.8 Broncho-Cath right double-lumen tube. Newer versions have no bevel at the end of the bronchial segment. (Courtesy of Mallinckrodt Medical, Inc.)

Before placing a right DLT, the patient's chest x-ray or computed tomography scan can be closely examined to identify a right upper lobe bronchus takeoff, which would make it difficult to use a right DLT. A left DLT should be placed in the right mainstem bronchus in Kartagener's syndrome, which includes complete situs inversus and a longer-than-normal right mainstem bronchus (52).

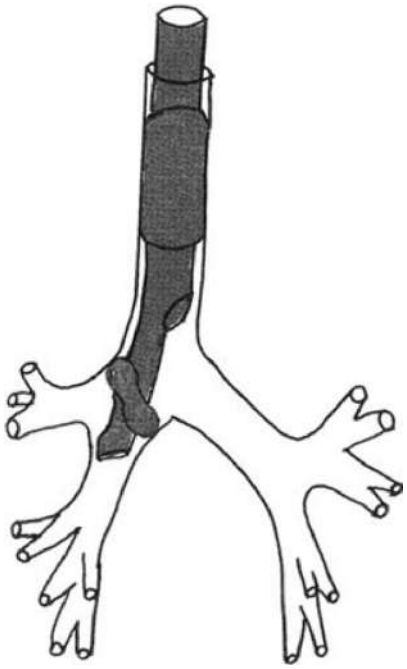

Figure 20.9 Broncho-Cath right double-lumen tube. The bronchial cuff has the shape of an S or a slanted doughnut, with the edge of the cuff nearest the right upper lobe bronchus closer to the trachea than the part of the cuff touching the medial bronchial wall. A slot in the tube beyond the cuff corresponds to the opening of the right upper lobe bronchus. Newer versions have no bevel on the bronchial segment.

Size

Selecting an appropriately sized DLT for a given patient is critical to minimize the frequency of complications (53).

A DLT that is too small may fail to provide lung isolation or may require bronchial cuff volumes and pressures that could produce mucosal ischemia or bronchial rupture. Using too small a DLT can result in the tube advancing too far into the bronchus, a higher level of autoPEEP (positive end-expiratory pressure), or barotrauma (54,55). An undersized tube may be more likely to be displaced. Ventilation and suctioning are more difficult with a small tube.

Using a large DLT will result in less resistance to gas flow, facilitate suctioning and passage of a fiberscope, and reduce the risk of advancing the DLT too far into the bronchus but may result in trauma (56). Inability to insert a larger tube through the larynx or past the carina or intrinsic or extrinsic obstruction in

the mainstem bronchus to be intubated may necessitate use of a smaller tube.

A tube is oversized if the bronchial lumen will not fit into the bronchus or there is no air leak with the bronchial cuff deflated (22,38,57,58,59,60). It is too small if the bronchial cuff inflation volume is greater than the resting cuff volume. Not more than 3 cc of air in the bronchial cuff should be required to create a seal. When there is a high risk that fluids will seep past the bronchial cuff, a smaller DLT should be used (61).

In adults, the dimensions of the cricoid ring best define those of the main bronchi (23). In children, age but

not weight is a predictor of bronchial diameter, and the right main bronchial diameter is significantly larger than the left (62). Suggested sizes for DLTs in children are shown in Table 20.1. Tubes from different manufacturers vary in size and may not fit this table.

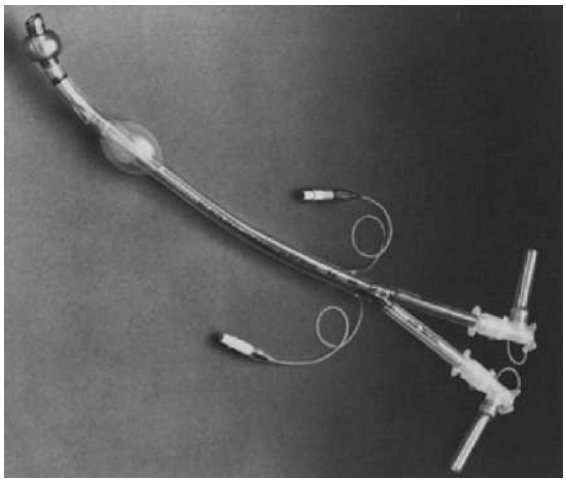

Figure 20.10 Broncho-Cath left double-lumen tube. (Courtesy of Mallinckrodt Medical, Inc.)

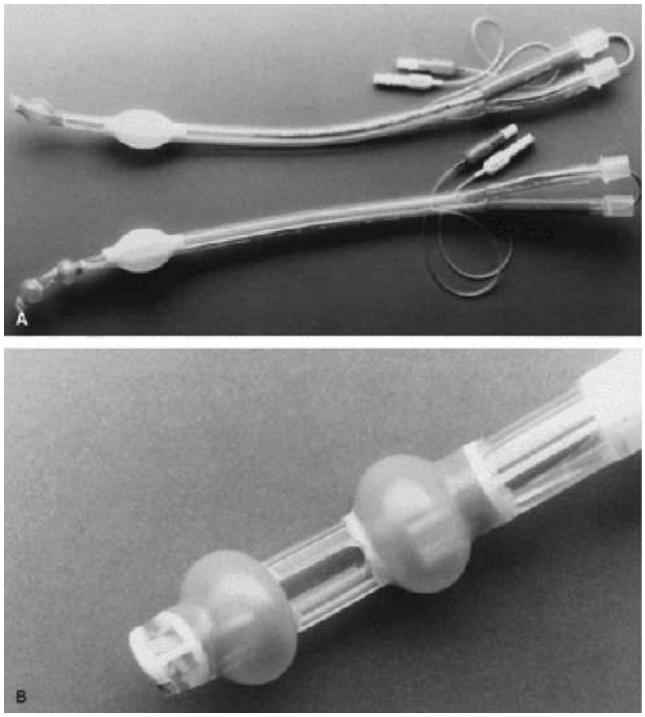

Figure 20.11 Sher-I-Bronch double-lumen tubes. **A:** Left-sided tube **(top)**. Right-sided tube **(bottom)**. **B:** Close-up of right bronchial segment, showing opening to the right upper lobe. (Courtesy of Sheridan, Inc.)

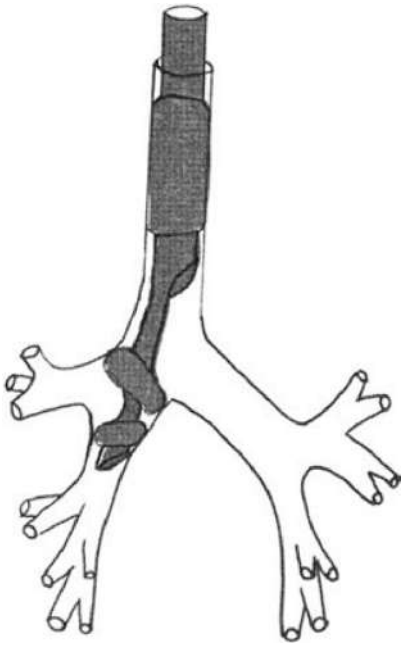

Figure 20.12 Sher-I-Bronch right double-lumen tube. Note the two cuffs proximal and distal to the opening to the right upper lobe.

The optimal size of DLT is easily selected if the diameters of the patient's main bronchus and the DLT tip are known. The diameter of the DLT bronchial lumen should be 1 to 2 mm smaller than the intubated bronchus (22). The diameter of the mainstem bronchus in any given patient can be difficult to determine. There are considerable variations in mainstem bronchial diameters. Age, sex, gender, weight, and height have relatively weak predictive value when selecting the proper DLT (22,60).

TABLE 20.1 Sizes of Double-lumen Tubes for Children

Age (years)	*Double-lumen Tube (French)*
8 to 10	26
10 to 12	26 to 28
12 to 14	32
14 to 16	35

From Hammer GB, Fitzmaurice BG, Brodsky JB. Methods for single-lung ventilation in pediatric patients. Anesth Analg 1999;89:1426â€“1429.

The size of the mainstem bronchus may be determined by measuring the width of the patient's bronchus from a chest x-ray or computed tomographic scan (22,54,60,63,64,65,66,67,68). Unfortunately, it is not possible to accurately measure bronchial width on many chest x-rays, and the correlation between the tracheal and bronchial size may not be reliable enough to determine the proper size DLT from the size of the trachea (56,59,63,69,70,71,72). Reliability may be increased by measuring the tracheal diameter both anteropostally and mediolaterally (73). The lung transplant patient may have a significantly different sized bronchus than would have been predicted from the size of the trachea (56).

Preparing the Double-lumen Tube

The tracheal and bronchial cuffs should be inflated and checked for leaks and symmetrical cuff inflation, making certain that each inflation tube is associated with the proper cuff. The cuffs and stylet should be lubricated with a water-soluble lubricant and the stylet placed

inside the bronchial lumen, making certain that it does not extend beyond the tip. The connector should be assembled so that it can be quickly fitted to the tube and breathing system after intubation.

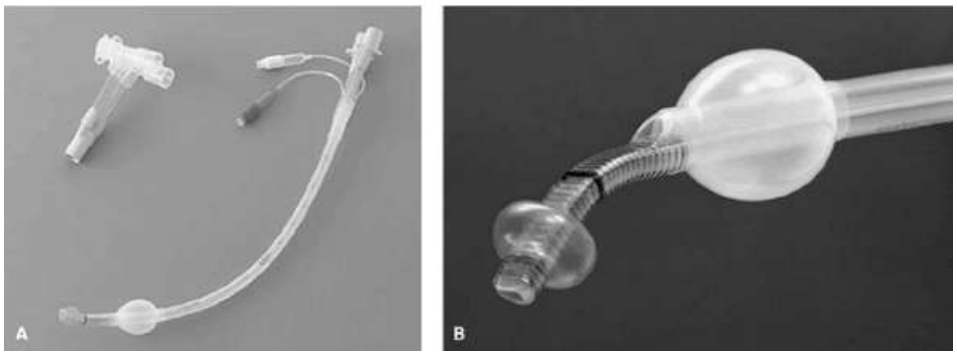

Figure 20.13 A: The Silbroncho double-lumen tube. **B:** The bronchial segment is wire-reinforced distal to the tracheal cuff.

Insertion

The DLT is advanced through the larynx with the angled tip directed anteriorly. After the bronchial cuff has passed the cords, the tube is turned 90 degrees so that the bronchial portion points toward the appropriate bronchus. If the tube is to be placed in the left mainstem bronchus, the head and neck should be rotated to the right before rotating and advancing the tube (74). Leaving the stylet in place for the entire intubation procedure rather than removing it once the bronchial cuff has passed the vocal cords may result in more rapid and accurate placement (75). However, some recommend that the stylet be removed just after the tube passes the vocal cords to prevent trauma (76).

A DLT is most accurately placed by inserting a fiberscope into the bronchial lumen and directing it into the appropriate bronchus under direct vision (77,78,79,80,81,82). Concurrent direct laryngoscopy may be required to elevate the supraglottic tissues to facilitate passing the DLT through the glottic opening after the fiberscope is in the trachea (83). This ensures that the correct bronchus is intubated on the first attempt and avoids inserting the tube too deeply or the tube becoming kinked in the upper lobe bronchus (40).

A DLT with a carinal hook should be inserted with the bronchial segment concave anteriorly until the bronchial cuff passes the cords. It should then be rotated 180 degrees so that the hook is anterior and advanced until the hook passes the vocal cords. The tube is then advanced until the hook engages the carina. The hook can be tied closely to the tube with a slip knot to facilitate passage through the larynx and then untied.

Inserting the bronchial portion into the bronchus can be performed blindly after insertion through the vocal cords. In some cases (e.g., bronchorrhea, bleeding), blind placement may succeed where the fiberoptic technique does not (79).

With blind insertion, the correct depth of insertion may be difficult to determine. However, this method may be useful where rapid lung isolation or collapse is necessary. In adults, there is a correlation between the ideal depth of insertion of left DLTs and patient height but not weight or age (24,84,85,86,87). The ideal depth of insertion can be estimated from the chest x-ray (84,85,86). Advancing the tube with the bronchial cuff partially inflated until an increase in resistance is felt (or only one side of the chest moves and compliance is reduced) may prevent inserting the tube too deeply (88,89,90,91). The bronchial cuff is then deflated and the tube advanced a distance equal to the length of the bronchial cuff plus 1 to 1.5 cm to place it just beyond the carina (92,93). Depth of insertion may be estimated by monitoring bronchial cuff pressure (94).

Since the tube usually moves upward with positioning, some clinicians recommend that the tube should initially be inserted more deeply than would be the ideal position (36,38,95,96). Others believe that the danger of trauma is increased if the tube is intentionally placed too deeply (97).

If the patient is anatomically difficult to intubate, a single-lumen tracheal tube may be placed by any of the means that facilitate difficult intubations (98). An exchange catheter can then be inserted into the single-lumen tube and the DLT inserted over the catheter after the single-lumen tube has been withdrawn (99). The WuScope (Chapter 18) has been successfully employed to place a DLT in a patient who was difficult to intubate (100). A DLT can be placed by using a lighted stylet (Chapter 19) in the bronchial lumen (101) or a retrograde intubation technique (102). Awake fiberoptic bronchial intubation with a DLT has been reported (103). A DLT may be introduced over a gum elastic bougie (45,104,105,106). It may be helpful to pass the bougie through the opening for the right upper lobe orifice on right DLTs (105).

A DLT may be inserted through a tracheostomy (107,108).

Cuff Inflation

Once the tip is thought to be in a mainstem bronchus, the tracheal cuff should be inflated in a manner similar to that of a tracheal tube (109,110). It is more difficult to inflate the bronchial cuff correctly. An overinflated bronchial cuff is more likely to herniate into the trachea, cause the carina to be pushed toward the opposite side, or result in narrowing of the bronchial segment lumen. Inflating the bronchial cuff beyond its resting volume may result in dangerously high pressure (18,111).

The bronchial cuff should be inflated with small incremental volumes until an airtight seal is just attained (109,112). The total volume should be less than 3 mL (41). One technique is to immerse the proximal tracheal lumen in water during ventilation via the bronchial lumen. The bronchial cuff is inflated until no bubbles are seen escaping during positive-pressure inspiration (110,111) (Fig. 20.14). Variations of this are to connect a balloon (113) or a capnograph (111) to the tracheal lumen. Another method is to apply suction to the tracheal lumen (110). Absence of bronchial seal will cause the reservoir bag in a breathing system that is connected to the bronchial lumen to collapse.

Inflating the bronchial cuff to an airtight seal may not prevent the spread of blood or secretions (61). The bronchial cuff may also be inflated with water (114).

Confirming Position

Confirming proper tube position is essential because the tube may not perform properly if incorrectly

positioned. Position should be checked after insertion, after repositioning the patient, and before beginning one-lung ventilation, as these tubes often move during patient positioning or surgical manipulations (97,115,116,117,118,119,120,121,122,123). The most frequent DLT movement is during lateral decubitus positioning. While movement is usually outward, distal migration may also occur. DLT position should be confirmed whenever there is evidence of malfunction.

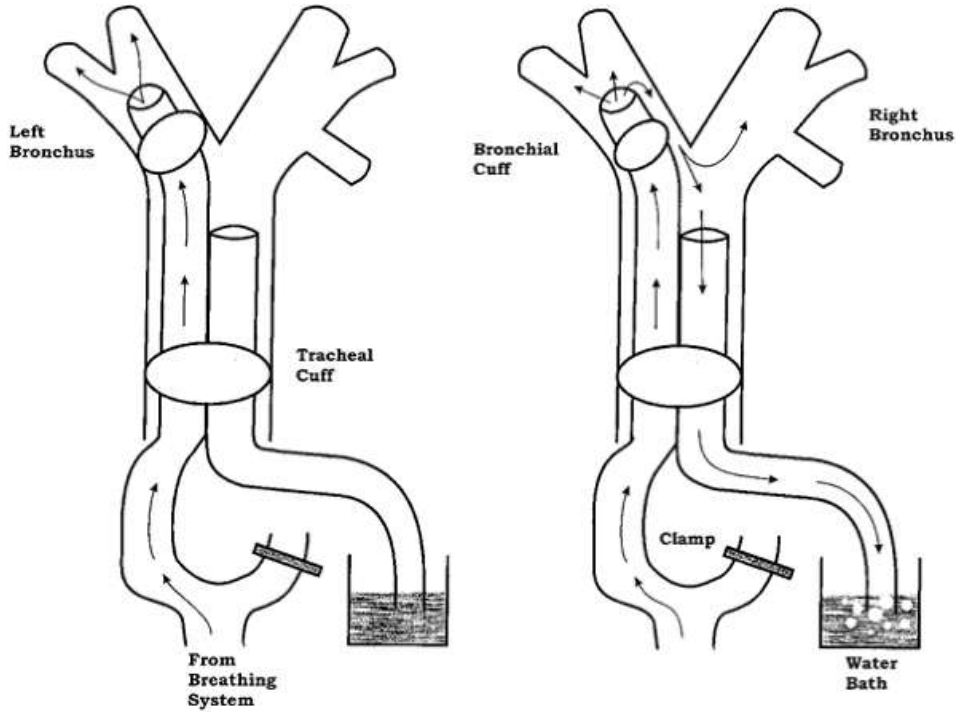

Figure 20.14 Inflating the bronchial cuff. With the tracheal cuff inflated, the bronchial cuff is slowly inflated. **Right:** A bronchial cuff leak is indicated by bubbles when the end of the tracheal lumen is placed under water. **Left:** With a seal, no bubbles appear.

Auscultatory Techniques

Unfortunately, auscultation detects DLT malposition only part of the time because breath sounds can be transmitted from one region of the lung to adjacent areas (124,125,126,127). Studies

have shown that a significant percentage of DLTs thought to be positioned satisfactorily by auscultation were found to be inappropriately positioned on subsequent fiberoptic examination (116,120,128). A DLT may function satisfactorily although not in an ideal position. Another problem with auscultation is that once the patient is prepped and draped, the chest is no longer available for auscultation. One study found that auscultatory placement was not associated with an increased incidence of complications during one-lung ventilation (39).

Clamping Method

Left-sided Tubes

With only the tracheal cuff inflated and the tracheal lumen connected to the breathing system, both lungs should be auscultated in the axillary regions and upper lung fields to detect differences. The bronchial cuff should then be inflated and both lumens connected to the breathing system. Auscultation should then be repeated.

Next, the attachment between the breathing system and the tracheal lumen should be occluded and the tracheal lumen opened to atmosphere. Breath sounds should be heard only over the left lung. If breath sounds are heard bilaterally, the tube is too high in the trachea. Both cuffs should be deflated and the tube advanced. If breath sounds are heard only over the right lung, the bronchial lumen is on the right side. If this is the case, both cuffs should deflated, the tube withdrawn until its distal end is above the carina, rotated, then reinserted. The steps outlined should be repeated.

The attachment between the breathing system and the bronchial lumen should then be clamped and the patient ventilated through the tracheal lumen. The bronchial lumen should be opened to atmosphere. Breath sounds should be heard only over the right lung. If there is marked resistance to ventilation, the tube is either too far into the left bronchus or is not deep enough. The position can be determined by deflating the bronchial cuff while continuing to ventilate through the tracheal lumen with the bronchial lumen clamped. If the tip is too deep in the left bronchus, breath sounds will be heard only on the left side. If the tube is not deep enough in the bronchus, breath sounds will be present bilaterally. The tracheal cuff also should be deflated and, depending on where breath sounds were heard, the tube pulled back or advanced. Both cuffs should be reinflated and the auscultatory sequence repeated.

Right-sided Tubes

Auscultation of a right-sided DLT is similar to that of a left-sided

tube. It is especially important to confirm ventilation of the right upper lobe.

Single Connector Method

An alternative technique is the single connector technique in which a single connector is used to ventilate each lung in turn by simply transferring the distal end of the DLT from one lumen to the other, eliminating the need for repeated clamping and unclamping (126). This has the advantage of being simpler and requiring fewer steps and may result in reduced risk of creating a potentially harmful ball-valve effect in a partially obstructed lobe or lung by detecting it earlier.

After the DLT is advanced to the desired depth, a single connector from the breathing system is attached to the bronchial lumen. While performing manual ventilation, the bronchial cuff is inflated to create an airtight seal. Auscultation is used to confirm that the intended lung is being ventilated. The connector is then transferred from the bronchial lumen to the tracheal lumen. The tracheal cuff is inflated to create an airtight seal, and it is confirmed that the proper lung is ventilated. The connector is then transferred to the bronchial lumen and short ventilations performed while listening over the apex of the lung for vesicular breath sounds. If these are not heard, the single connector is detached from the bronchial lumen and a double connector is connected to the two lumens.

Flexible Endoscopic Techniques

Flexible endoscopy is the most accurate method for determining DLT position (120,129,130,131,132). Many recommend that this should be the standard of care (81,131,133,134,135,136). Others believe that the fiberoptic scope is helpful but not essential (95,124,137,138,139). There is general agreement that fiberoptic endoscopy is always needed for right-sided DLTs. Fiberoptic methods to confirm the position of the DLT may not work in the presence of blood or secretions (140). Whenever there is any doubt, this method should be used to check the position. A further advantage is that it can be used to remove blood or secretions. It can also be used after the patient is prepped and draped if a question arises with regard to proper tube placement.

Left-sided Tubes

A fiberscope is placed in the tracheal lumen through the open end of the tube or through a port in the connector that is specially designed for this purpose. As the fiberscope is advanced, the carina should come into view. The top surface of

the blue bronchial cuff should be seen below the carina in the left mainstem bronchus. The bronchial cuff should not herniate over the carina, neither should the carina be pushed to the right. An unobstructed view of the nonintubated right mainstem bronchus should be obtained.

The fiberscope should then be advanced through the bronchial lumen to check for narrowing of the lumen at the level of the cuff and an unobstructed view of the distal bronchial tree.

Right-sided Tubes

Looking down the tracheal lumen, the bronchial cuff's upper surface should be seen below the carina in the right mainstem bronchus. The fiberscope is then placed in the bronchial lumen. The right middle lower lobe bronchial carina should be seen below the end of the tube. The endoscopist should be able to look into the right upper lobe orifice by flexing the tip of the fiberscope superiorly.

Bronchospirometry

Pressure-volume and flow-volume loops are discussed in Chapter 23. Changes in compliance or resistance may mean that the DLT is not correctly placed (141,142,143,144,145,146,147,148,149,150). If a DLT is advanced into the trachea with the bronchial cuff partially inflated, compliance is reduced when the tube impacts the bronchus (92).

Chest X-ray

Chest x-ray may be useful to confirm tube position when a fiberscope is not available or cannot be used. However, it is less precise than the fiberoptic bronchoscopy and is costly, time consuming, and awkward to perform.

Stabilizing the Tube

Once correct tube position is confirmed, the tube should be secured in place. Special fixation methods have been recommended (151). During positioning, the tube should be held at the level of the incisors and the head immobilized in a neutral or slightly flexed position to prevent the tube from migrating into an incorrect position.

Intraoperative Care

The bronchial cuff should be kept deflated (unless the lung needs to be isolated to prevent spread of blood or infection) until the lung needs to be collapsed to minimize damage to the bronchial mucosa (38). Lung collapse will be most rapid if lung

separation is initiated at end-expiration. Suction is of limited utility because the gas trapped in the lung is distal to collapsible airways. If despite best efforts complete lung separation cannot be accomplished and gas is introduced into the ipsilateral lung with each breath, then continuous suction may be helpful to evacuate the gas as it enters the lung (38). Bronchial cuff pressure should be monitored and adjusted to the minimum necessary to achieve an airtight seal.

A useful technique when the bronchial lumen is in the surgically operated lung is to pass a suction catheter through the bronchial lumen when the lung is deflated and to leave it until ready for reinflation (152). This may prevent the bronchial lumen from becoming obstructed by blood or mucus.

Replacing a Double-lumen Tube with a Single-lumen Tube

If mechanical ventilation needs to be continued at the conclusion of a case in which a DLT was used, it is usually desirable to replace the DLT with a standard tracheal tube. Personnel who are caring for the patient in the postoperative period are not usually familiar with a DLT. After pneumonectomy, when all of the patient's ventilation is conducted through one lumen of the DLT, the small diameter of the lumen may make if difficult for the patient to breathe spontaneously. With high minute ventilation, this can lead to auto-PEEP (17). Pressure-support ventilation (Chapter 12) can be used to decrease the imposed work of breathing during spontaneous ventilation if replacing the DLT cannot be performed. Suctioning through a DLT is difficult.

In most cases, the procedure is simply to remove the DLT and insert a single-lumen tube in its place. If the patient was difficult to intubate or circumstances make visualizing the larynx difficult, other techniques should be considered. One technique would be to insert an airway exchange catheter into the tracheal lumen before the DLT is removed. Special extra-long exchange catheters are needed for the exchange. After the DLT has been removed, the single-lumen tube is then advanced over the catheter (153,154). Oxygen insufflation via the catheter will reduce the incidence of hypoxemia.

Another technique has been described (155). At the conclusion of the case, both cuffs are deflated and the DLT withdrawn until the bronchial lumen is above the carina. The bronchial cuff is then inflated and the lungs ventilated through the bronchial lumen. The tracheal lumen is clamped, and an opening is created in the wall of the tracheal lumen. A single-lumen tube is then slipped over a fiberscope, and the fiberscope is advanced through the hole in the tracheal lumen and into the trachea. The

opening in the DLT is extended, and the DLT is slowly removed. The fiberscope is then removed.

Hazards Associated with Double-lumen Tubes

Many of the hazards associated with single-lumen tracheal tubes (Chapter 19) can also occur with DLTs.

Difficulty with Insertion and Positioning

Inserting a DLT may be time consuming. When there is severe hemorrhage, this can be a major problem. Multiple insertions and repositionings increase the risk of trauma. While they are very useful in adults and older children, they are often too large for small children. They are often difficult to position and usually must be replaced with a single-lumen tube at the end of surgery.

The rigidity and width of the DLT can make intubation complicated. The tube does not allow preshaping before intubation, and the large width makes it difficult to pass the DLT through a tracheostomy stoma, small airway, or nasal passage.

Tube Malposition

Certain physical conditions may make it difficult or impossible for a DLT to be correctly placed (156,157). Preoperative fiberoptic endoscopy may detect many of these problems. Even if a correct position is achieved initially, head movement, a change in body positioning, or surgical manipulation may result in tube malposition. Displacement during positioning can be decreased by using a neck brace (123,158). Malpositioning is increased when anesthesia providers have limited experience in lung isolation (159).

If DLT malposition is suspected, fiberoptic techniques are clearly advantageous in defining the problem and afford a means of visual correction. While some have reported that monitoring carbon dioxide waveforms helps to detect DLT displacement (160,161), capnography does not reliably indicate DLT misplacement (142,148,149,162).

Consequences

Functional indications of misplacement include the following:

Unsatisfactory Lung Collapse

An obstruction in the unventilated lumen can prevent the unventilated lung from deflating. If the lung cannot be collapsed, operating time will be increased, and the surgical result may be compromised. Another cause may be a tumor fragment in the

airway (163).

Obstruction to Lung Inflation

If the bronchial cuff is not below the carina, it may obstruct the trachea and right mainstem bronchus. With right-sided tubes, misalignment of the port for the right upper lobe can result in obstruction. If the bronchial cuff on a left-sided DLT is too deep, it may obstruct the upper lobe bronchus.

Gas Trapping

Gas trapping or expiratory obstruction may be the result of a one-way valve effect that allows inflation but not deflation. If unrecognized, it can result in cardiorespiratory embarrassment and/or lung parenchymal damage.

Failure of Lung Separation

If the airway to a bronchopleural fistula cannot be isolated from that to the normal lung, barotrauma may develop with positive-pressure ventilation, or the air leak through the fistula may be so large that ventilation of the normal lung is compromised. An incompletely protected dependent lung may be flooded with blood or secretions.

Possible Malpositions

Bronchial Lumen in the Wrong Mainstem Bronchus

In some cases, the bronchial portion will enter the opposite

lung. This is usually easy to detect and correct by using fiberoptic endoscopy (115). In some cases, it may be best to leave the bronchial lumen in the operative bronchus and isolate the operative lung by clamping the bronchial limb and using the tracheal lumen for ventilation (118,122). This may be appropriate for right lung surgery but not for surgery on the left lung, since the right upper lobe bronchus would almost certainly be occluded. An alternative option is to withdraw the tube until it is intratracheal and to use a bronchial blocker (see below) to block the operative lung.

It may be possible for the surgeon to assist in correctly placing the tube once the chest is open (164). If it is determined that the tube is in the wrong bronchus, both cuffs are deflated, and the tube is withdrawn into the trachea. The surgeon then compresses the bronchus, and the anesthesia provider advances the tube into the correct side with surgical guidance. The cuffs are then reinflated.

Bronchial Portion Inserted too Far into the Appropriate Bronchus

If a left-sided DLT is inserted too deeply, the problem may be that the tube is too small (156,165,166,167). It will result in obstruction of the upper lobe. In some patients, a left-sided DLT placed so that the bronchial cuff is just distal to the carina still may cause left upper lobe obstruction. A high peak airway pressure during one-lung ventilation should suggest this malposition (135).

Tube too Proximal in the Airway

If the tube is not sufficiently advanced into the bronchus, the bronchial cuff may protrude into the trachea. The need to inject more than 3 mL of air into the bronchial cuff to achieve a seal should alert the user that the tube may be malpositioned. The bronchial segment may slip out of its bronchus, especially during changes in the patient's position. In many cases, no untoward sequelae will occur. However, there may be obstruction of gas flow to the other lung and inability to isolate the surgical lung.

Tip of Bronchial Lumen above the Carina

The tip of the bronchial lumen may be above the carina because of a tracheal lesion that prevents the tube from being advanced farther. With this malposition, there will be unsatisfactory lung deflation and failure of lung separation.

Incorrect Placement with Respect to the Upper Lobe Bronchus

Malposition with respect to the upper lobe bronchus is particularly a problem with right-sided tubes (34). Even with a left-sided tube, it is possible to obstruct the upper lobe bronchus (129,168). The result of such a malposition is usually hypoxemia and failure of the upper lobe to deflate satisfactorily. A case has been reported where the bronchial lumen entered the right upper lobe bronchus (40).

Asymmetric Bronchial Cuff Inflation

The inflated bronchial cuff can cause the tip of the bronchial lumen to face into the bronchial wall, producing one-way valvular obstruction that allows lung inflation but not deflation (169,170).

Hypoxemia

In many instances, hypoxemia during one-lung ventilation is at least partly the result of a malpositioned DLT (171). For this reason, whenever hypoxemia occurs, tube position should be

reassessed and adjusted if necessary. Even with correct positioning, hypoxemia can result from blood continuing to flow through the unventilated lung (shunting) after one-lung ventilation has begun.

Another cause of hypoxemia is the presence of a tracheal bronchus arising from the lateral tracheal wall (166,172,173,174). If a DLT is used, the tracheal bronchial opening must be checked after the tube is placed. In some of these cases, a bronchial blocker may be a better choice for one-lung ventilation.

Another mechanism that can produce hypoxemia is ambient pressure ventilation of the nonventilated lung. Attaching an oxygen source at ambient pressure to the opening to the nonventilated lung may help to prevent hypoxia (175,176,177,178). This may also enhance collapse of the nonventilated lung.

If hypoxemia is a problem despite proper tube position, CPAP can be applied to the nondependent lung (179). Some DLT manufacturers include a CPAP device with each DLT, or they may be purchased separately (Fig. 20.15). Other measures to improve oxygenation include dependent lung PEEP, occasional ventilation of the nondependent lung (one breath every 5 to 10 minutes), insufflation of 2 to 3 L/minute of oxygen to the nonventilated lung, and clamping of the pulmonary artery before clamping the bronchus. Jet ventilation of the nondependent lobes that are not being removed by using an airway exchange catheter may be used to improve oxygenation (180).

Obstructed Ventilation

Many cases of obstruction are the result of a malpositioned tube. In addition, inflating the bronchial cuff can cause narrowing of the bronchial lumen (129,156) or may cause the carina to be displaced laterally, producing obstruction of the other mainstem bronchus (181). A defective tube or connector may cause obstruction (182,183).

Other causes of bronchial obstruction have been reported. In one case, the bronchial cuff was left deflated until one-lung ventilation was to begin, and necrotic tumor migrated into the bronchus of the dependent lung, causing obstruction when one-lung ventilation was begun (184). The bronchial lumen can become twisted (185). A carinal hook may obstruct the opening of the tracheal lumen (186).

Figure 20.15 Device for applying continuous positive airway pressure to a nonventilated lung. The adjustable valve supplies pressures from 1 to 10 cm H_2O.

A relative contraindication to using a DLT is a lesion (airway narrowing or endoluminal tumor) somewhere along the pathway where the tube will reside. An aberrant tracheal bronchus may be a contraindication for using a DLT (172,173).

Trauma

Trauma to the respiratory tract can occur whenever intubation with a DLT is performed (187,188). Tears in the trachea and mainstem bronchus have been reported (76,187,188,189,190,191,192,193,194,195,196,197,198,199,200,201,202,203).

Tube size is a factor. Large tubes have been involved more often in injury than smaller ones (188). A tube that is too small and requires excessive cuff inflation may cause ischemic injury. In

one reported case, an endobronchial polyp that developed at the bronchial cuff site ended in a fatal hemorrhage (204).

Measures to reduce airway trauma include removing the stylet after the tip of the tube has passed the vocal cords, avoiding cuff overinflation, deflating the tracheal and bronchial cuffs when repositioning the patient or the tube, and not advancing the tube when resistance is encountered. Some bronchial cuffs can provide one-lung isolation with significantly lower pressures than others (41). It has been recommended that the bronchial cuff be kept deflated until needed to minimize pressure on the bronchial mucosa. This may not be prudent if there is a bronchial tumor, as necrotic tumor may migrate into the other lung (184).

Tube Problems

Reported problems with DLTs include mislabeling, tracheal lumen distortion that prevented a suction catheter from passing, a slit in the septum, a defect that made the bronchial lumen kink on itself, a split in the tubing to the bronchial cuff, a kink in the inflating tube to the tracheal cuff, a protuberance in the wall of the tube with resultant tracheal lumen obstruction, and foreign bodies in the DLT (205,206,207,208,209,210,211,212). The carinal hook may bend backward, obstructing the opening of the tracheal lumen (213).

Tracheal or bronchial cuff rupture can occur. This most commonly results from contact between the tube and the teeth or laryngoscope during insertion. Proposed methods to avoid this problem include the use of a retractable protective sheath (214), a lubricated Penrose drain (215), and lubricated teeth guards (216) and increasing the curve of the bronchial portion of the DLT with the stylet (217). Another possible cause of cuff rupture is movement during repositioning (218).

Surgical Complications

The bronchial cuff may be punctured by the surgeon (219,220). A suture or staple may be placed through the DLT, or the surgical procedure may result in a tight stenosis, which could entrap the bronchial segment (221).

Failure to Seal

One of the reasons to use a DLT is to prevent material from passing from one lung to the other during the surgical procedure. Failure to prevent fluids from traversing the bronchial cuff could result from malposition or from improper cuff inflation. Neither an airtight bronchial seal nor a cuff pressure of 25 cm H_2O guarantees protection against aspiration (61). Lubricating the cuff with a gel will reduce the risk that fluid will leak past the cuff

(222,223).

Difficult Extubation

Difficulty in removing a DLT may be due to anatomical abnormalities, surgical fixation, or entanglement by other surgical or anesthetic hardware (220,224).

Single-lumen Bronchial Tubes

Another option for achieving lung separation is to use a single-lumen tube to intubate a mainstem bronchus. Two bronchial tubes may be used in situations where dual lung ventilation is needed but circumstances bode against having one tube in the trachea (225,226,227).

Single-lumen bronchial tubes are sometimes used in pediatric patients whose airways are too small for DLTs or in whom a bronchial blocker cannot be used (1,165,226,228,229,230,231,232,233,234,235,236,237). In the patient with massive hemoptysis, bronchial intubation with a single-lumen tube is often the easiest and quickest method of separating the lungs (5,10).

Equipment

Bronchial intubation is most often carried out with a conventional tracheal tube. A cuffed tube will prevent re-expansion of the collapsed lung. The distance from the tip of the tube to the cephalad edge of the cuff must be shorter than the length of the mainstem bronchus to ensure that the cuff can lie entirely inside the bronchus and the upper lobe bronchus is not obstructed (238).

Special tubes with a single lumen, an angulated distal (bronchial) tip, and cuffs at both the tracheal and bronchial positions are available (239,240). They are longer than conventional single-lumen tracheal tubes.

Techniques

Before insertion, the correct length and size of the tube should be estimated from a chest x-ray or computed tomography (CT) scan (238). If the nasotracheal route is used, most conventional single-lumen tubes will not be long enough to provide a reliable mainstem intubation. It is recommended that the tube should be one half to one size smaller than the usual size selected for tracheal intubation (237). For bronchial intubation in children, a tracheal tube 0.5 to 2.0 mm smaller than recommended for the particular patient should be used (229,231).

Right-sided intubation can usually be performed blindly, but the tube is more reliably placed by using a bronchoscope. It may be possible to align the Murphy eye with the right upper lobe bronchus. It may be possible to rotate the tube so that the bevel faces the upper lobe bronchial orifice.

Left mainstem intubation may be achieved blindly by using a stylet to curve the distal end of the tracheal tube to the left (231) but often requires bronchoscopic guidance. If blood or secretions preclude fiberoptic visualization, fluoroscopy is another option. The chance of intubating the left bronchus will be increased if the tube is rotated 180 degrees from its usual position before advancing it beyond the vocal cords and the patient's head is turned to the right (228,229,241,242,243).

A gum elastic bougie can be inserted into the chosen bronchus by using a bronchoscope. The bronchial tube can then be railroaded over the bougie into position (244).

Correct positioning can be confirmed by auscultation, x-rays, and/or flexible bronchoscopy.

The tube should be withdrawn into the trachea when one-lung ventilation is no longer needed.

Evaluation

Advantages of using a single-lumen tube for lung separation include simplicity and the rapidity with which lung separation can often be achieved, particularly when the right lung must be ventilated.

Disadvantages include frequent lack of ventilation of the right upper lobe with right mainstem intubation (38,236). Left upper lobe ventilation may also be excluded when the left mainstem bronchus is relatively short (238). Neither suctioning nor application of CPAP to the nonventilated lung is possible.

There may be failure to achieve an adequate seal, especially if an uncuffed tracheal tube is used or if the cuff is not inside the bronchus (226,236,238,245). Lung collapse will be incomplete, and the healthy ventilated lung will not be protected from contamination. Both lungs cannot be ventilated at the beginning of anesthesia, and the collapsed lung cannot be re-expanded and ventilated until the tube is withdrawn into the trachea (236).

Bronchial-blocking Devices

Indications and Use

Indications for bronchial blockers are similar to those for a DLT, with the exception of independent lung ventilation (44,226,246). They are often used in patients in whom using a DLT is not

possible or advisable (nasal intubation, small patient, difficult intubation, patient with a tracheostomy, subglottic stenosis, thick and excessive secretions, need for continued postoperative intubation) (240,247,248,249,250,251,252,253,254,255,256,257,258,259,260,261). A blocker may be especially useful for providing lung separation in a critically ill patient with a single-lumen tracheal tube already in place. Another indication may be the patient on anticoagulants, since placing a blocker is usually less traumatic than inserting a DLT (8). A blocker may allow a larger fiberoptic endoscope to be used and provide better suctioning than a DLT (262). A modified bronchial blocker can be used for tracheal gas insufflation to reduce carbon dioxide within the dead space by delivering fresh gas near the end of the tracheal tube (263).

Another indication for a blocker is the need to block a segment of a lung rather than the entire lung (9,14,258,259,264,265,266,267,268,269,270). This cannot be done with a DLT. A blocker may be used to sequentially block different parts of the lung (270).

A blocker may be used to achieve lung isolation in the patient with an improperly positioned double-lumen or bronchial tube (53,122,238,271,272,273). A blocker may be useful if both lungs require sequential blockage (274). The blocker can be shifted to the opposite lung when needed. If one blocker does not provide complete one-lung isolation, a second blocker may be used (173,275,276,277).

Finally, there is no need to change the tube at the end of the operation if postoperative mechanical ventilation is needed if a bronchial blocker is used.

Devices

Univent Bronchial-blocking Tube

Description

The Univent tube is a cuffed silicone tracheal tube with a small additional internal lumen along its concave side (7,11,226,236,278,279,280,281,282,283,284) (Figs. 20.16, 20.17). The small channel contains a movable tubular blocker that has a blue high-pressure, low-volume cuff. The blocker can be advanced sufficiently beyond the tip of the tube to block airways smaller than a mainstem bronchus (246,260,264,265).

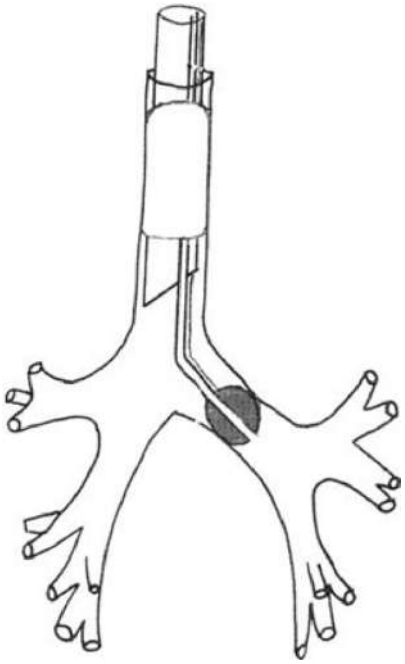

Figure 20.16 Univent bronchial blocker. The cuffed tracheal tube has a small lumen along its concave side, which contains a tubular cuffed bronchial blocker. The blocker can be advanced into a mainstem bronchus or smaller airway.

The blocker has external depth markings to help determine the blocker position in relation to the tube. There is a slight bend in the blocker above the cuff. The blocker tip is radiopaque. A grip allows the user to rotate the blocker. A locking clamp fixes its depth below the tip of the tube.

As shown in Table 20.2, the Univent tube is available in several sizes. It has a slightly larger-than-usual external diameter for its internal diameter because of the space required by the blocker. Univent tubes that are 5 mm and larger have a lumen that can be used for suctioning, CPAP, or oxygen insufflation (285). Adult versions of the Univent blocker are hollow.

The Univent blocker (Uniblocker) can be purchased separate from the tracheal tube and used with other tracheal tubes coaxially or in parallel (265,286) (Fig. 20.18). It is supplied with a swivel adaptor that fits onto the tracheal tube connector. This adaptor allows connection to the breathing system and has a port for a fiberoptic scope in addition to a port for the blocker.

Use

Before use, the bronchial blocker and tube cuffs should be inflated and checked for leaks. Both the tube and the blocker should be well lubricated. After the cuffs have been deflated, the blocker should be pushed back and forth in the tube to ensure free movement. The blocker should then be fully retracted into the tube lumen and fixed in place by using the clamp.

If there is an unobstructed view of the larynx, the Univent tube is inserted in the same way as a conventional tracheal tube. If the patient has a difficult airway, it can be inserted over an airway exchange catheter or other device (287). The blocker can be extended and used as an introducer (288,289). After the blocker has passed the vocal cords, the tube is threaded over it and into place.

After the Univent tube is inserted, the tracheal tube cuff is inflated, and the patient is ventilated. The blocker is visualized by using a flexible fiberoptic endoscope through an airway adaptor with a port for the scope and is maneuvered into the appropriate bronchus. The blocker tip direction can be changed by twisting the shaft (290). It may be useful to deflate the tracheal tube cuff and rotate the tube so that the blocker is directed toward the side to be occluded.

A guide wire can be inserted through the blocker's lumen and be used to direct the blocker into place, especially when it is necessary to block an airway smaller than a mainstem bronchus (258).

Another method of placing the blocker in the right or left main bronchus is to insert a fiberscope through the trachea tube into the bronchus to be blocked and then to advance the tube into that bronchus. The blocker is then advanced into the bronchus and the tube withdrawn into the trachea, leaving the blocker in the bronchus. This technique may result in trauma to the airway (291).

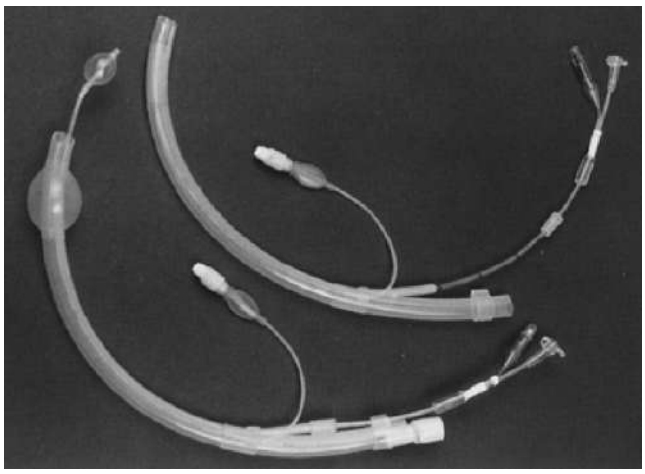

Figure 20.17 Univent bronchial-blocking tubes. **Top:** The bronchial blocker is retracted. **Bottom:** The bronchial blocker is advanced, and the cuff is inflated. (Courtesy of Vitaid.)

TABLE 20.2 Univent Tubes

Internal Diameter (millimeters)	*Outer Diameter (millimeters)a*	*Age (years)*
3.5 (uncuffed)	7.5/8.0	6 to 10
4.5	8.5/9.0	10 to 14
6.0	9.7/11.0	14 to 16
6.5	10.2/12.0	16 to 18
7.0	11.6/12.5	Adult
7.5	11.2/13.0	Adult
8.0	11.7/13.5	Adult
8.0	12.2/14.0	Adult

9.0	12.7/14.5	Adult

[a]Values are sagittal/transverse.
From Hammer GB, Fitzmaurice BG, Brodsky JB. Methods for single-lung ventilation in pediatric patients. Anesth Analg 1999;89:1426â€“1429; Frolich MA. Postoperative atelectasis after one-lung ventilation with a Univent tube in a child. J Clin Anesth 2003;15:159â€“163; Hammer GB, Brodsky JB, Redpath JH, et al. The Univent tube for single-lung ventilation in paediatric patients. Paed Anaesth 1998;8:55â€“57; Tobias JD. Variations of one-lung ventilation. J Clin Anesth 2001;13:35â€“39.

The bronchial blocker can be inserted blindly. The whole tube is turned so that its concavity faces the side to be blocked. The blocker is advanced into the mainstem bronchus and the cuff inflated. This method has not proved very successful and may be associated with airway trauma (282,292).

The blocker position should be checked by using a fiberscope. The cephalad tip of the bronchial cuff should be below the carina. The blocker should then be fixed to the tracheal tube by using the cap stopper and blocker grip.

When the bronchus needs to be blocked, the lung is deflated with the blocker open to atmosphere. The bronchial blocker cuff should be inflated by using the least amount of air that will provide a seal. This can be achieved by attaching the sample line from a carbon dioxide analyzer to the proximal end of the blocker and noting when the waveform disappears (293). Another method is the bubble test, in which the end of the bronchial lumen is placed into water in a beaker (294). When the bronchus is sealed, no bubbles will be observed passing through the water. The typical cuff inflation volume is 5 to 6 cc (112).

The blocker from a Univent tube can be removed from the tube and inserted alongside a tracheal or tracheostomy tube (265,295,296). The blocker is then

guided into place with a fiberscope inserted through the tube.

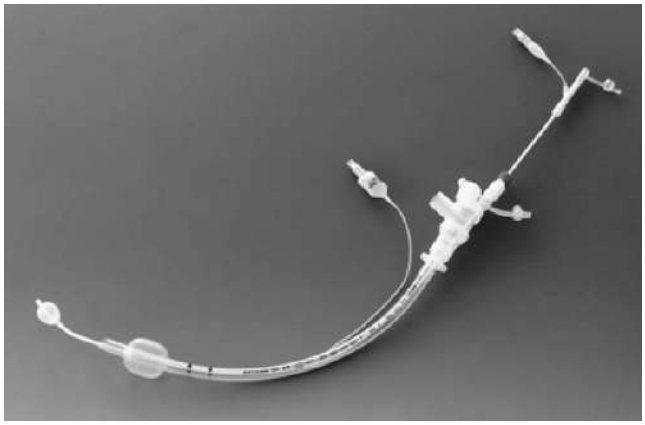

Figure 20.18 The Univent bronchial blocker can be purchased separately from the tube. The connector has ports for attachment to the tracheal tube and breathing system, for introducing the blocker, and for a fiberscope. Note the cap that fits over the end of the blocker.

When the blocker is no longer needed, the cuff is deflated and withdrawn into the main tube. If the Univent is to be used for postoperative ventilation, the blocker should be fully retracted and disabled to avoid inappropriate use by caregivers who are unfamiliar with the device (297).

Evaluation

Most studies show that the Univent provides lung isolation equivalent to that of a DLT (11,280,298,299,300,301).

The Univent may be easier to insert and position correctly than a DLT and may be especially useful for the difficult-to-intubate patient (287,288,289,302,303,304,305). It can be used in the patient with a tracheostomy (254,253,296) and for nasal intubation (247). It can be used for postoperative ventilation without having to reintubate the patient.

It is possible to use suction, apply CPAP, or insufflate oxygen through the blocker lumen (278,306). The blocker with the cuff deflated has been used for jet ventilation during carinal resection (307,308).

Reports of problems with the Univent include the cap becoming dislodged from the tip of the blocker (309,310) and fragmentation of the tube inner wall and connector (311,312).

The Univent's curved shape is fixed, and this may be a disadvantage when sliding it over a bronchoscope. It will not soften in a warm water bath (38). It may distort the neck

anatomy sufficiently to make internal jugular vein cannulation difficult (313). Bronchial perforation by the blocker during blind insertion has been reported (292). A case has been reported of prolonged postoperative atelectasis after using a Univent tube (262). It is not recommended for use in children below the age of six years.

When comparing the Univent with a left DLT, there was a greater incidence of malposition with the Univent (119), but comparison of the Univent and a right DLT failed to demonstrate a clear advantage (35). The Univent is more expensive than a DLT or other blockers (79,119,310).

A disadvantage of the Univent tube is the large amount of cross-sectional area occupied by the blocker channel, especially in the smaller tubes (236). It is not available in a size that would fit an infant or small child.

Another problem is that the small lumen is relatively easily blocked by blood or pus (285). As a result, blood or pus may accumulate and contaminate the dependent lung when the blocker is deflated.

The blocker's low-volume, high pressure cuff may cause in mucosal injury (314,315).

The larger external diameter may make it difficult to pass the Univent between the vocal cords.

Arndt Bronchial Blocker

Description

The Arndt bronchial blocker assembly (wire-guided bronchial blocker, WEB, FWEB) is designed to be used for a patient with a single-lumen tracheal tube already in place (44,111,246,253,316,317,318,319,320,321,322,323). It consists of two parts: A blocking catheter and a special airway adaptor. Either may be purchased and used separately.

Blocking Catheter

The Arndt blocking catheter (Fig. 20.19) has a low-pressure, high-volume balloon that has either an elliptical or spherical shape. The spherical balloon is relatively compliant unless overinflated and takes an elliptical form when inflated in a small bronchus. The 9 Fr catheter is available with an elliptical balloon that provides a longer sealing profile. It is recommended that the elliptical cuff be limited to left mainstem intubation (236,246).

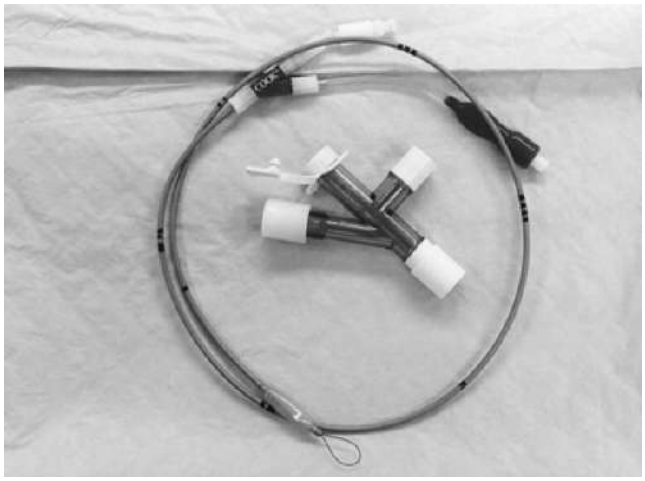

Figure 20.19 Arndt bronchial blocker with multiport adaptor. The wire loop can be cinched around the tip of the fiberscope, or the fiberscope is passed through the loop. The adaptor has ports for attachment to the tracheal tube and breathing system, for introducing the blocker, and for a fiberscope.

A flexible nylon wire passes through the proximal end of the catheter and extends to the distal end, then exits as a small loop (Fig. 20.19). The size of the loop may be increased or decreased by advancing or retracting the wire assembly.

There are three sizes: 9, 7, and 5 Fr. Characteristics of the blockers are shown in Table 20.3. Near the distal end of the 9 Fr catheter are side holes to facilitate lung deflation.

Airway Adaptor

The multiport adaptor (Fig. 20.19) allows simultaneous introduction of a bronchoscope and the blocker while maintaining mechanical ventilation. It has four ports:

1. A 15-mm female connector that attaches to the tracheal tube;
2. A side port with a 15-mm male connector that attaches to the anesthesia breathing system;
3. A port angled approximately 30 degrees for the bronchial blocker; and
4. A port for the flexible endoscope.

The blocker port has a Tuohy-Borst type connector to maintain an airtight seal and lock the blocker in place (by tightening the

connector around the blocker) or to allow free movement of the blocker (by loosening the connector). The bronchoscopy port has a plastic sealing cap.

Use

Before use, the inside of the tracheal tube and the outside of the blocker and the bronchoscope should be well lubricated with a silicone spray. The loop should be adjusted so that it loosely approximates the outside diameter of the bronchoscope. The blocker balloon should be inflated to test for leaks and then fully deflated.

For each size Web, there is a tracheal tube size for which coaxial placement is limited by the diameters of the blocker and fiberscope used during placement. When these limits are exceeded, parallel placement may be required. Either the web is passed outside the tracheal tube with guide loop inoperable, or a fiberscope is also placed in parallel with the tracheal tube before or after intubation.

TABLE 20.3 Arndt Endobronchial Blockers

Size (French)	*Smallest Single-lumen Tube Internal Diameter for Coaxial Use (millimeters)*	*Length (centimeters)*	*Cuff Shape*	*Average Cuff Inflation Volume (cubic centimeters)*
9	7.5	78 and 65	Elliptical	6 to 12
			Spherical	4 to 8
7	6.0	65	Spherical	2 to 6
5	4.5	65 and 50	Spherical	0.5 to 2.0

From Klafta JM. One-lung anesthesia; making it work (ASA Refresher Course #509). Park Ridge, IL: ASA, 2004.

The wire in the blocker lumen is used in either of two ways: (i) when cinched tightly around the tip of the fiberscope, the fiberscope carries the blocker into its desired location, and (ii) when the fiberscope is passed through the loop, it provides a track for blocker to pass through after the fiberscope is placed

into the bronchus.

After the patient is intubated and ventilation has begun, the multiport adaptor is connected between the breathing system and the tracheal tube. The bronchoscope is advanced through the guide loop. This allows the blocker to follow the bronchoscope. Alternately, the wire loop may be placed over the end of the blocker prior to attaching the airway adaptor to the tracheal tube (324).

The bronchoscope is advanced into the airway to be blocked and then the guide loop is slid over the end of the bronchoscope. The bronchoscope is withdrawn slightly to visualize the blocker. The blocker is then advanced or withdrawn into position (324,325). It may be advisable to advance the blocker approximately 1 cm beyond the optimal position when the patient is in the supine position to avoid dislodging the blocker toward the trachea while the patient's position is changed to the lateral decubitus position (246). The balloon is then inflated under direct vision. The balloon should fill the entire bronchial lumen and not herniate into the trachea. Following placement, the balloon may be deflated until one-lung ventilation is required.

Removing the wire loop will result in an open channel, which allows CPAP application, oxygen insufflation, suctioning, or intermittent inflation. Leaving the wire loop during the operation might damage the airway and entails the risk that the loop may accidentally be stapled into the bronchial closure (326). However, leaving the loop in place allows the blocker to be repositioned (327). It may be possible to reposition the blocker by using fiberoptic endoscopy (326). Excessive force should not be used when removing the wire guide, because this may displace the blocker.

Lung collapse can be expedited by attaching a syringe or applying suction to the blocker channel (44,328). However, some clinicians do not recommend using suction through this channel because of the risk of developing negative pressure pulmonary edema (326). When no longer needed, the blocker cuff should be fully deflated and the blocker removed.

Evaluation

The Arndt blocker system can be used in the patient who is already intubated (316,317,329), in the patient with a tracheostomy (318,324,325), or with a nasal intubation (253,318). It has been used to provide single-lung ventilation in children as young as 17 months (245). It may be especially useful for the patient in whom a DLT would be difficult to use (260,316,318,319,320,321,330). It has been used in a newborn (322). It allows a larger internal cross-sectional area than a DLT

or Univent tube of similar outside diameter (331). It may require fewer insertion attempts than a DLT (332). If the wire is removed, the lumen can be used for suctioning or administering oxygen or CPAP.

Problems

A disadvantage is that once the wire loop is removed, it cannot be reinserted through the channel to allow repositioning of the blocker. Placement requires the availability of fiberoptic equipment and someone able to use it. It takes longer to position and to achieve complete lung collapse compared with the Univent tube or a DLT (328,332). The balloon may be sheared when it is removed from the blocker port (333).

Cohen Tip-deflecting Bronchial Blocker

The Cohen tip-deflecting bronchial blocker (Fig. 20.20) has a 9 Fr external diameter and a central lumen with a 1.6 mm diameter (334). The high-volume, low-pressure blue balloon at the tip is spherical in shape. The average inflation volume is 5 to 8 mL. There are side holes between the tip and the balloon to evacuate gas from the distal lung or to insufflate oxygen. A proximal control wheel that can be operated with the thumb and forefinger is used to adjust tip deflection (Fig. 20.21). The catheter has depth markings and an indicator arrow that shows the direction in which the tip deflects.

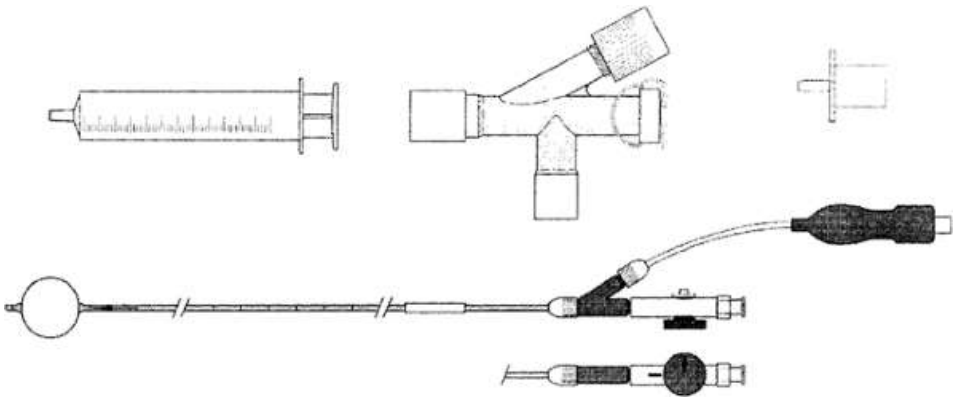

Figure 20.20 Cohen tip-deflecting bronchial blocker. The proximal control wheel is used to adjust tip deflection. An arrow on the wheel indicates the direction to which the tip deflects. (Courtesy of Cook Critical Care.)

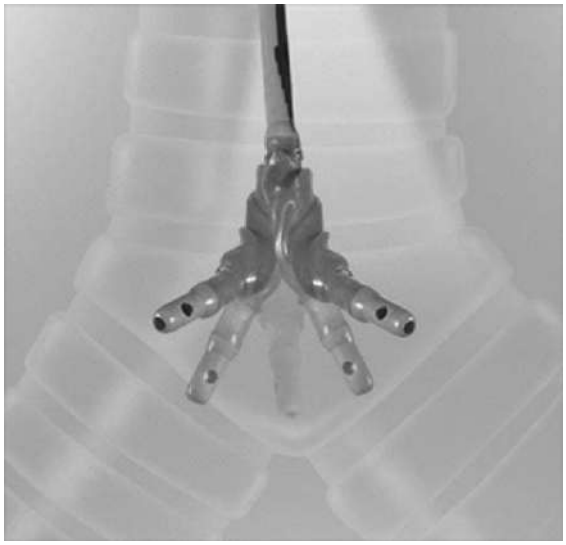

Figure 20.21 The tip of the Cohen bronchial blocker can be manipulated to fit into either bronchus.

In most cases, the blocker and a fiberscope are inserted through an appropriately sized tracheal tube. The blocker can also be placed outside the tracheal tube and guided into place with a bronchoscope placed through the tracheal tube.

A multiport airway adaptor like the Arndt is attached to the breathing system end of the tracheal tube. Alternatively, a standard swivel adaptor can be used for insertion.

An assistant with or without video flexible fiberoptic scope may be necessary because it may require two hands to manipulate the blocker into position, one to deflect the tip and the other to rotate and advance the catheter.

Embolectomy Catheter

Description

An embolectomy (Fogarty) catheter can be used as a bronchial or segmental blocker (1,14,53,62,226,248,251,256,257,267,268,269,275,324,335,336,337,338,339,340,341,342,343,344). This catheter is readily available in most operating suites where vascular surgery is performed or can be purchased for this purpose. It comes with a stylet in place so that it is possible to place a curvature in the distal tip to facilitate guidance to the target bronchus. The occlusion balloon has a high-pressure, low-volume cuff (246). It comes in a variety of sizes. Adult bronchi can be blocked with 7 Fr catheters, whereas 2 Fr to 5 Fr catheters are suitable for segmental or pediatric blockade.

Use

Prior to use, the blocker should be lubricated with jelly or silicone spray to facilitate passage. The balloon should be tested for leaks and then fully deflated. A catheter with a faulty or eccentric balloon should be discarded.

The embolectomy catheter may be placed before or after intubation with a single-lumen tracheal or tracheostomy tube and can be passed either through or alongside the tube. Placing the catheter alongside the tube allows the tube to splint the blocker in position. An alternative method is to insert the catheter through a hole made in the side of the tracheal tube (345).

If the patient is already intubated, the catheter containing a stylet may be passed through a fiberoptic endoscope adaptor (335,341,342). This allows uninterrupted ventilation. The Arndt multiport airway adaptor (previously mentioned) or similar device (346) may also be used to prevent an air leak. An annular space around the fiberoptic endoscope and embolectomy catheter equivalent to a single-lumen tube with an inner diameter of 4 to 5 mm will be necessary to allow exhalation in a reasonable period of time (347).

A fiberoptic endoscope is passed down the tracheal tube, and the embolectomy catheter is guided into the appropriate bronchus under direct vision. Twirling the catheter between the fingers at the proximal end or rotating the tracheal tube will impart lateral direction to the tip (98). Additional lateral direction may be gained by rotating the tracheal tube to one side or the other. After the tip is advanced into the proper position, the stylet is removed, the catheter balloon is inflated under direct vision, and then the fiberscope withdrawn.

A modification of this technique is to deliberately intubate a mainstem bronchus with a tracheal tube one size smaller than would be appropriate for the trachea, advance the blocker through the tracheal tube, then withdraw the tracheal tube into the trachea (348,349,350,351). It may be helpful to preshape the tracheal tube by using a stylet (351). Once the catheter is in the targeted bronchus, the stylet is removed. Removing the tracheal tube followed by insertion of a larger tracheal tube beside the Fogarty catheter will securely fix the catheter in place. The catheter balloon is inflated slowly until no air enters the blocked lung, as detected by using auscultation. The Fogarty catheter should be securely taped to the tracheal tube to prevent it from being dislodged. A fiberoptic endoscope should be used to check the position of the blocker. The catheter ballooon should be deflated and the lung collapsed by using pressure on the chest and/or suction through the tracheal tube (351). The catheter

balloon should then be reinflated to the same volume as previously used.

Evaluation

The use of an embolectomy catheter has many advantages. It can be passed through a single-lumen tracheal tube in an already intubated patient, and there is no need for reintubation if postoperative mechanical ventilation is needed. It may be useful in

pediatric patients (62,236,267,268,324,337,338,340,345,352), the patient with a tracheostomy (252,336,351,353), or for a nasal intubation. The embolectomy catheter is less expensive than a DLT, Univent tube, or Arndt blocker (326,339). Fogarty catheters are relatively thinner for a given balloon volume when compared with other bronchial blockers and thus will allow the use of larger tracheal tubes, especially in pediatric patients when they are placed side by side in the trachea (351).

Problems

A significant disadvantage is the lack of a hollow center. Suctioning, oxygen insufflation, or applying CPAP to the blocked lung is not possible, and lung collapse takes longer and may not be as complete as with a DLT or a blocker with a hollow lumen (62). The obstructed lung segment cannot be re-expanded until the blocker is removed. Another disadvantage is that it is made of latex, so it cannot be used in the patient with potential latex allergy (Chapter 15). Most of these devices have low-volume, high-pressure cuffs and can damage the airway, although the pressure may be less than that exerted by the cuff on a DLT (109,236).

There are no reported complications with the embolectomy catheter in adults (246). Bronchial rupture has been reported with an overinflated balloon in a child (337).

Other

Balloon atrioseptostomy, Foley urinary, and Swan Ganz pulmonary artery catheters have been used as bronchial blockers. They have a central lumen for suction or administration of oxygen to the blocked lung.

Problems with Bronchial Blockers

A blocker may not be suitable for the patient with a high right upper lobe bronchus takeoff or a tracheal bronchus (173,354). It may be necessary to either use a second blocker or a DLT under these conditions. If the distance between the carina and the

tracheal bronchus is small, it may be possible to herniate the balloon on the bronchial blocker so that it blocks the upper lobe bronchus (355). It may be possible to use the tracheal cuff of the Univent tube to block a tracheal bronchus (356).

A blocker may be dislodged into the trachea (357). The inflated balloon may then block ventilation to both lungs, prevent collapse of the operated lung, and/or cause air trapping. Other complications reported include fixation by surgical staples (358); perforation of the blocker balloon by a surgical needle (359); and accidental inflation of the blocker cuff when it was just below the tip of the tube, resulting in obstruction to gas flow (360).

The narrow blocker lumen may result in ineffective removal of secretions and pulmonary soiling after the cuff is deflated (361). Lung deflation may not be as satisfactory or achieved as rapidly with a bronchial blocker as with a DLT (332).

Development of severe hypoxemia has been reported after continuous suctioning of the nondependent lung through a bronchial blocker (362). If suction is used to facilitate lung collapse, it should be applied for only a few seconds, intermittently and with low pressure (246).

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Questions

Each question below contains four suggested answers of which one or more is correct. Choose the answer:

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. if D is correct

E. if A, B, C, and D are correct.

1. Indications for a double-lumen tube include

A. Patient with hemorrhage

B. Patient having one-lung surgery

C. Control of infection from one lung

D. Patient with a lesion in the trachea

View Answer

2. When placing a left-sided double-lumen tube,

A. The outermost acceptable position for the bronchial cuff is just below the carina

B. The average length from the left upper bronchus to the carina is 3 cm

C. The tip of the bronchial lumen should be at the proximal edge of the left upper lobe bronchus

D. The margin of safety is less than for right-sided tubes

View Answer

3. Which of the following statements are correct?

A. A left double-lumen tube can usually be used for right

lung surgery

B. A left double-lumen tube can be used for left pneumonectomy

C. A right double-lumen tube must be used for left lung surgery if there is rupture of the left mainstem bronchus

D. Manipulation during surgery is likely to alter the position of a tube in the contralateral bronchus.

View Answer

4. Which of the following apply to inserting a double-lumen tube?

A. A stylet needs to be used for all intubations

B. The tube should be inserted at a 90-degree angle from where it will eventually rest

C. If the tube is to be placed in the left mainstem bronchus, the head and neck should be rotated to the right before rotating and advancing the tube

D. Removing the stylet after passing the cords may prevent trauma

View Answer

5. Techniques useful in confirming the position of a double-lumen tube include

A. Auscultation of the chest

B. Fiberoptic examination

C. Chest x-ray

D. Capnography

View Answer

6. Possible consequences of bronchial tube malposition include

A. Unsatisfactory lung deflation

B. Air trapping

C. Airway obstruction

D. Trauma

View Answer

7. Possible double-lumen tube malpositions include

A. Obstruction of the upper lobe bronchus

B. Bronchial tip above the carina

C. Bronchial tip inadequately advanced into the bronchus

D. Insertion into the wrong mainstem bronchus

View Answer

8. Possible causes of obstruction to ventilation when a double-lumen tube is in use include

A. Tube malposition

B. Foreign body migration into the dependent lung

C. Overinflation of the bronchial cuff

D. Twisting of the bronchial lumen

View Answer

9. Possible consequences of trauma resulting from double-lumen tubes include

A. Vocal cord paralysis

B. Rupture of a mainstem bronchus or the trachea

C. Mediastinal emphysema

D. Hemorrhage

View Answer

10. Uses of bronchial-blocking devices include

A. Patient on anticoagulants

B. Bronchopleural fistula

C. Pulmonary hemorrhage

D. Differential lung ventilation

View Answer

11. Problems associated with a carinal hook on a double-lumen tube include

A. Hook fracture

B. Trauma to the airway

C. Interference with bronchial closure during pneumonectomy

D. Malposition of the tube

View Answer

12. Which problems can be attributed to using too small a double-lumen tube?

A. High cuff volume with high pressure on the mucosa

B. Displacement may be more likely

C. The tube may advance too far into a bronchus

D. Hemorrhage

View Answer

13. Indications that the bronchial lumen is not the correct size include

A. No air leak with the bronchial cuff deflated

B. The tube will not fit into the bronchus

C. More than 3 mL of air in the bronchial cuff is needed to make a seal

D. There is obstruction of the bronchus

View Answer

14. In determing the proper size double-lumen tube for a patient,

A. The left bronchus is larger than the right

B. The size of a mainstem bronchus may be reliably determined by measuring the width from a chest x-ray

C. Weight is the best predictor of bronchial diameter in children

D. In adults, the dimension of the cricoid ring best defines those of the main bronchi

View Answer

15. How is the proper depth of insertion for blind insertion of a left double-lumen tube determined?

A. Patient sex

B. Patient weight

C. Patient age

D. Patient height

View Answer

16. Insertion techniques that can be used to attain the proper insertion depth include

A. Monitoring the bronchial cuff pressure

B. Looking for one side of the chest to inflate

C. Advancing the tube with the bronchial cuff inflated until it wedges into the bronchus and then deflating the cuff and inserting the tube an additional 1 to 1-1/2 cm

D. Inserting the bronchial portion under direct vision with a flexible endoscope

View Answer

17. What are the possible consequences of overinflating the bronchial cuff on a DLT?

A. Shifting the carina toward the opposite side

B. Herniation into the trachea

C. Narrowing the bronchial segment lumen

D. Obstructing the opposite mainstem bronchus

View Answer

18. When should the position of a DLT be checked?

A. After it is initially placed

B. At the beginning of one-lung ventilation

C. After the patient is positioned for surgery

D. Before the chest is closed

View Answer

19. Possible causes of hypoxia associated with using a double-lumen tube include

A. Bronchial tube in the wrong bronchus

B. Presence of a tracheal bronchus

C. DLT blockage

D. Shunting, even with a properly placed tube

View Answer

20. Possible measures to combat hypoxemia during double-lumen tube use include

A. CPAP to the nonventilated lung

B. Occasional ventilation of the operative lung

C. PEEP applied to the dependent lung

D. Clamping the pulmonary artery before clamping the bronchus

View Answer

21. Problems associated with a single-lumen bronchial tube include

A. Inability to ventilate the right upper lobe bronchus

B. Inability to administer CPAP to the nonventilated side

C. Inability to ventilate the left upper lobe bronchus

D. Incomplete lung collapse

View Answer

Chapter 21

Devices for Managing the Difficult Airway

Ensuring a patent airway with adequate ventilation and oxygenation is a primary goal in anesthesia and resuscitation. Although death and brain damage from the difficult airway have declined, its management remains a significant problem (1).

The American Society of Anesthesiologists (ASA) has developed an algorithm to help the anesthesia provider recognize and deal with patients who have, or are likely to have, a difficult airway (2,3). If a difficult airway is recognized beforehand, the course is likely to be different from that which occurs if that problem goes unrecognized.

Various aspects of airway preservation are dealt with in other chapters, including masks and airways (Chapter 16), tracheal intubation (Chapter 19), and use of the supraglottic airway devices (Chapter 17). When these techniques are unsuccessful, other measures need to be considered.

Combitube

Description

The Combitube (ETC, esophageal-tracheal double lumen airway, ETLDA, esophageal tracheal Combitube) (Fig. 21.1) has two separate lumens that are fused

longitudinally and two inflatable cuffs (4,5,6). Each lumen is linked by a short tube to a standard 15-mm connector at the breathing system end. The pharyngeal lumen has an occluded distal end and eight oval-shaped perforations (ventilating eyes) between the cuffs. The tube and connector associated with the pharyngeal lumen may be colored blue. The other (tracheoesophageal, tracheal) lumen has a patent distal end and a clear tube. The smaller distal cuff serves to seal either the esophagus or trachea, depending on its placement. The larger (pharyngeal) cuff (balloon) is above the perforations. It serves to seal the pharynx by filling the space between the base of the tongue and soft palate so that gas cannot escape through the mouth or nose. The pilot balloon for the pharyngeal cuff is colored blue. If the tip is inserted into the trachea, the distal cuff is inflated and the tube is used as a conventional tracheal tube. If the tip is inserted into the esophagus, both cuffs are inflated and ventilation occurs through the holes above the distal cuff.

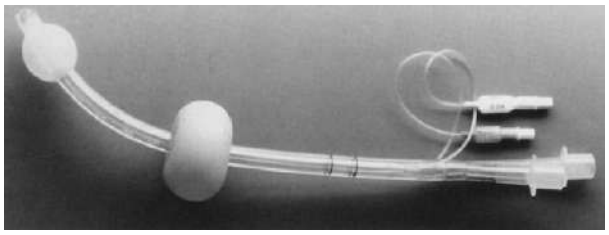

Figure 21.1 Combitube. Note the ventilating eyes between the two cuffs. (Courtesy of Sherican Cather Corp.)

The Combitube has a pronounced anterior curve toward the patient end. It is marked with two black rings at the machine end that help to indicate the insertion depth.

The Combitube is available in two sizes: the regular (41 French [Fr]) for adult males and the small adult (SA, 37 Fr) for females and small adults. The Combitube is recommended for patients with a height greater than 5 feet (152 cm). The Combitube SA is recommended for use in patients 4 to 6 feet tall (120 to 180 cm) but has been used in patients up to 6-1/2 feet tall (198 cm) (7,8,9). The Combitube is not recommended for patients younger than 12 years of age.

Use

It is important to practice inserting the Combitube under controlled conditions before attempting to use it on a difficult airway. If a cervical collar is in place, it should be removed and the cervical spine immobilized manually while the Combitube is inserted (10,11,12). Once the ETC has been inserted successfully, the anterior portion of the collar should be reapplied before releasing the manual stabilization (6).

The Combitube can be inserted from any position. For blind insertion, the head should be in a neutral position with the occiput on the flat surface on which the patient is positioned, not the sniffing position that is usually used for tracheal intubation. Bending the Combitube in the portion between the balloons for a few seconds may facilitate insertion (6,13,14,15,16). Suctioning is not necessary, even in the presence of blood or vomitus (4).

The Combitube is inserted with one hand, while the other hand pulls the tongue forward and lifts the jaw (4,17,18). It should be passed along the surface of the tongue, not the palate. It is important to keep the Combitube midline during insertion to avoid blind pockets such as the vallecula. The Combitube is advanced until the space between the two black rings lies between the patient's teeth or gums or until resistance is felt. Temporary release of cricoid pressure (if used) may be required (19). If there is difficulty advancing the ETC, rotating the tube may be helpful in some patients (16). The use of a laryngoscope may facilitate successful placement and lower the number of complications (7,20,21,22).

The pharyngeal balloon is inflated with 100 mL (85 cc for the Combitube SA) of air. The Combitube often moves outward about 1 cm during inflation (5). The distal cuff should be inflated with 5 to 12 mL of air (Combitube 37 Fr) or 5 to 15 cc of air (Combitube 41 Fr). It may be preferable to inflate the distal cuff first if the patient is at risk for aspiration (23). The blue balloon should not be visible when looking into the patient's oral cavity (16).

After insertion and balloon inflation, ventilation is begun in order to determine whether the distal lumen is in the esophagus or trachea. Since most insertions result in esophageal placement, ventilation should be attempted first via the blue lumen. Gas travels down the tube, through the lateral wall perforations, into the pharynx, and on into the trachea. It is prevented from entering the stomach by the distal cuff in the esophagus and from escaping through the mouth and nose by the pharyngeal cuff. If no evidence of ventilation is detected, a switch should be made to the clear lumen without altering the Combitube's position. If ventilation is satisfactory, the device is then used as a tracheal tube. If ventilation continues to be inadequate, the Combitube should be

withdrawn 1 to 3 cm after deflating the cuffs and ventilation attempted again with the blue lumen (24). If this third attempt at ventilation is unsatisfactory, the Combitube should be removed and ventilation established by using another technique.

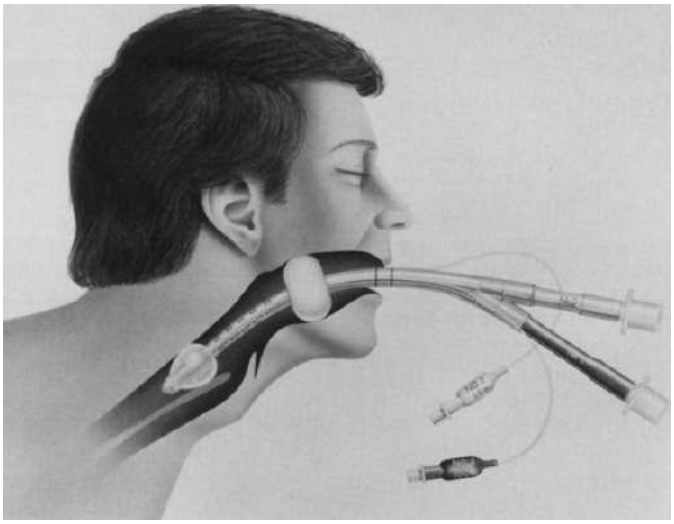

Figure 21.2 Combitube in place in the esophagus. (Courtesy of Sherican Cather Corp.)

The esophageal detector device and the colorimetric carbon dioxide detector (Chapter 22) have been used to verify correct position (24,25,26,27,28,29,30,31). In anesthesia settings, capnography can be used.

After stabilizing the tube, the amount of air in the cuffs should be reduced. If the Combitube is inserted into the trachea, inflation

should be to just sealing volume (32). The volume in the pharyngeal balloon should be reduced to the minimum required to form an effective seal (7,22,33,34,35,36). If ventilation is controlled, a slight positive end-expiratory pressure may be present (21,37,38,39).

In the esophageal position (Fig. 21.2), the unused tracheal lumen can be connected to suction to aspirate fluids or a gastric tube can be inserted (22). Epinephrine can be instilled through the esophageal lumen (40). The dose should be ten times that administered through a tracheal tube.

The Combitube in the esophageal position may be exchanged for a standard tracheal tube by using a flexible fiberscope, rigid laryngoscope, or retrograde intubation around the Combitube (5,7,9,41,42,43,44).

Indications

The Combitube is useful for airway management in the difficult-to-intubate patient (6,25,45,46,47,48,49,50,51,52,53,54,55,56,57). Because it can be placed without having to visualize the larynx, it may be especially useful for patients with massive airway bleeding or regurgitation. It can be used in patients with limited access to the airway and limited mouth opening and for patients in whom neck movement is contraindicated. It has been used successfully in patients in a halo head frame (58,59), a patient with excessive pharyngeal bleeding (60), a hematoma causing upper airway obstruction (61), a patient who had a wooden splinter through the mouth partially blocking the pharynx (62), respiratory arrest secondary to an acute asthmatic exacerbation (63), a patient with facial burns (64), and a patient trapped in a car (65). It may be useful in entertainers in whom it is important to avoid vocal cord damage (18). It has been used for Cesarean section (66). The ETC has been used successfully after failure with a laryngeal mask airway (LMA) (54,59).

The ETC has an established role in cardiopulmonary resuscitation in both prehospital and in-hospital settings (56,67,68,69,70,71,72,73). It is included in the Guidelines for Advanced Cardiac Life Support of the American Heart Association, Practice Guidelines for Management of the Difficult Airway of the ASA, the Canadian Airway Focus Group, and guidelines for resuscitation of the European Resuscitation Council as a suitable alternative airway to tracheal intubation, especially in the ‘€cannot ventilate, cannot intubate‘€ situation (2,45,74).

The Combitube has been used successfully for anesthesia lasting up to 6 hours, including gynecologic laparoscopic surgery (5,21,22,38,41,75). Relatively high airway pressures can be used (4,21,22). While it is not recommended for routine anesthesia, it may be a viable option for patients in whom it has been placed to secure a difficult airway (76,77). Using it in elective cases may

increase the anesthesia provider's comfort with the device. It has been used in the esophageal position with mechanical ventilation for up to 8 hours (38).

The Combitube has been used during percutaneous dilatational tracheostomy (see below) (78) but may not be the best choice for airway management during this procedure (79). The trachea is free of any appliance, but it does not allow a fiberscope to be used during the procedure (80). It has also been used for ventilation during tracheotomy (81).

Contraindications

Contraindications to using the Combitube include active pharyngeal or laryngeal reflexes; known esophageal trauma or pathology; ingestion of corrosive agents; and oropharyngeal, pharyngeal, or hypopharyngeal mass. It should not be used in patients younger than 12 years of age or in those under 4 feet tall.

Advantages

Compared with a tracheal tube, the time needed for insertion is significantly shorter, and less skill is required (82). Because successful use does not require direct visualization, the presence of blood and/or vomitus does not prevent successful placement. Once in place, the Combitube provides comparable ventilation and improved oxygenation compared with tracheal intubation (37,38,41,48,67,68,71,83). It can be used by an anesthesia provider who has limited use of the left arm (84).

Minimal training is needed before use. The skills required to insert a Combitube do not need to be reinforced as often as they do for tracheal intubation. The Combitube can be used successfully by non-anesthesia personnel both as a first-line treatment and after failed tracheal intubation (71,72,73,83,85,86,87,88). It is often used by paramedics.

The Combitube in the esophageal position is well tolerated by the patient during emergence from anesthesia (4). Its use is not associated with high levels of trace gases (89). There is no danger of bronchial intubation in the esophageal position. The pharyngeal balloon anchors the device in place, lessening the risk of accidental extubation.

The Combitube provides good but not complete protection from aspiration (7,9,22,48,58,63,72,90,91,92). Gastric distention can occur with its use (36).

Disadvantages

Tracheal suctioning or fiberoptic bronchoscopy is not possible through the Combitube in the esophageal position unless the Combitube is modified (93).

If inserted into the trachea, the result is a tube with a relatively large outer diameter but small internal lumen. The airflow resistance with a small adult Combitube is greater than that of a 7-mm tracheal tube but lower than that of a 6-mm tube (94,95).

A case has been reported where the patient could not be ventilated after the Combitube was placed (96). The tube was found to be so deep that the upper cuff obstructed the tracheal lumen. Pulling the tube backward remedied the problem. In another case where ventilation was difficult, flexible fiberoscopy showed a valvelike mechanism by the aryepiglottic folds over the

perforations in the tube (97).

Insertion and removal of the Combitube may be associated with a higher stress response than that with a tracheal tube or supraglottic airway device (22,39). Insertion takes longer than with the LMA (72). The Combitube may be inserted without moving the head or neck, but there may be more cervical spine motion during airway management with a Combitube than with other devices (98,99).

Trauma to the airway and esophagus may occur with the Combitube (12,21,36,71,100,101,102,103,104,105). It exerts relatively high pressure on the tracheal mucosa (106). Sore throat and dysphagia are common after its use (33,100). Trauma may be reduced by using the small adult Combitube when appropriate, gentle insertion, halting further advancement in the presence of resistance, using a laryngoscope to aid insertion, adequate anesthetic depth, slow cuff inflation, and regular assessment of both cuff pressures.

The proximal cuff of the Combitube is made of latex, making it unsuitable for use in a patient with latex allergy (Chapter 15).

The Combitube is expensive compared to other single use devices. This makes it uneconomical to use for routine anesthetics.

Retrograde Intubation

Retrograde (translaryngeal-guided, guided blind) intubation is an elective or emergency technique for securing a difficult airway, either alone or in conjunction with other techniques (107,108,109). It should be considered part of the armamentarium of every anesthesia provider (2). Retrograde intubation is a useful option in patients who cannot be intubated by using traditional techniques (110,111,112,113,114,115,116,117,118,119). It may not be suitable for patients who require immediate intubation and ventilation, as the procedure can be expected to take 5 minutes or more for completion.

A retrograde intubation set is shown in Figure 21.3. After skin preparation, a catheter-over-needle device with an attached syringe is inserted through the

cricothyroid membrane in a cephalad direction (Fig. 21.4). Entering the airway lower in the airway (between the cricoid cartilage and the first tracheal ring or between the first and second tracheal rings) allows more room for advancing the tube (107,117,120,121,122,123). Free air aspiration confirms the location. Local anesthesia should be injected through the syringe. The needle and syringe are removed, and a guide wire is inserted through the catheter (124) (Fig. 21.5). Another device such as an epidural or central venous catheter may be used as a guide.

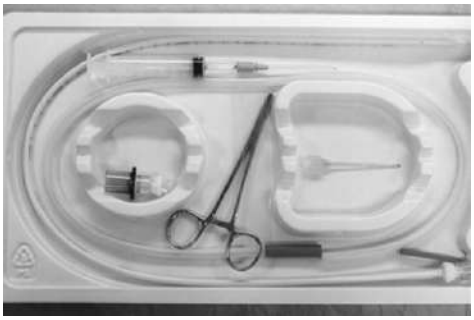

Figure 21.3 Retrograde intubation set.

The guide is advanced cephalad until it emerges at the oral cavity or nares (Fig. 21.5). It may be necessary to use a special device to retrieve the guide wire (123,125,126). If nasotracheal intubation is desired, a catheter can be inserted nasally, brought out through the mouth, and secured to the guide wire (127). The catheter is then pulled out through the nose, bringing the guide wire with it. The catheter at the cricothyroid membrane is removed and the guide clamped at the skin.

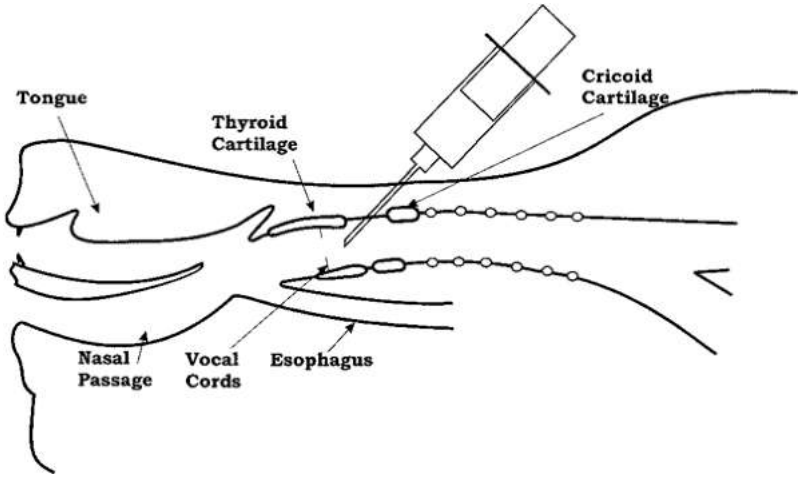

Figure 21.4 The catheter-over-needle with syringe attached is inserted through the cricothyroid membrane in a cephalad direction. Aspiration of air confirms placement within the airway.

A larger device such as an epidural catheter or airway exchange catheter can be slid over the guide wire and the tracheal tube advanced over the catheter (108,123,128,129,130,131,132) (Figs. 21.6,21.7,21.8). Alternately, the tracheal tube can be threaded over the guide wire, with the guide wire going either through the Murphy eye or main lumen.

The guide should then be put under slight tension. The tracheal tube is advanced until it reaches the point where the guide wire enters the airway. The guide wire is removed from above and the

tracheal tube inserted to the proper depth. If the tracheal tube cannot be advanced, it may be helpful to rotate it 90 degrees counterclockwise, exchange it for a smaller tube, relax the tension on the guide, or insert a fiberscope through the tracheal tube (112,123,133). The tracheal tube may also be pulled into the trachea by tying the retrograde guide to the tracheal tube (108,117,122,131,134).

Alternately, after the guide wire is retrieved through the mouth or nose, it may be placed through the channel of a flexible fiberscope with a tracheal tube threaded over it (108,109,111,114,123,135,136,137,138). The fiberscope is advanced over the guide and down to the point of exit of the guide wire from the trachea. At this point, the guide wire can be loosened and the fiberscope advanced further (139). After confirmation that the fiberscope is in the trachea, the guide is removed via the proximal port of the fiberscope. The tracheal tube is then advanced into the trachea.

Retrograde intubation is a safe, easy, and dependable method of intubation (117). It may be especially useful in patients with airway trauma or limited neck mobility and in the presence of oropharyngeal bleeding, which

may obscure the field of the fiberscope (108,113,140). It has been used in infants and children (112,123,135). It has been used to place a double-lumen tube (141). This method may be a useful means for reintubation when a tracheal tube is removed (142). It has been used to intubate a patient with a Combitube in place (143). It is included in the ASA Algorithm for Management of the Difficult Airway (3).

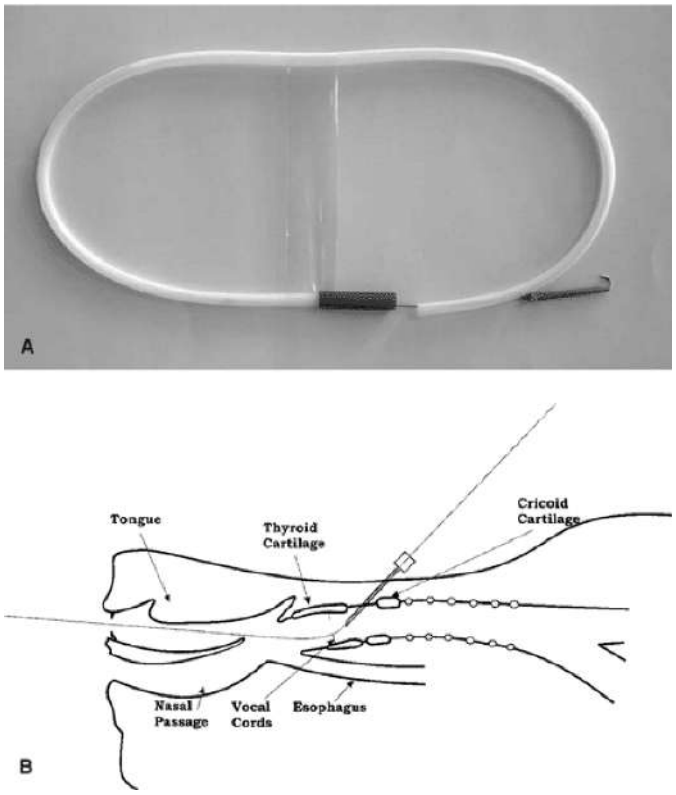

Figure 21.5 **A:** Guide for retrograde intubation. **B:** The guide is inserted through the catheter and advanced cephalad until it emerges from the mouth.

Complications of retrograde intubation include sore throat, trauma, barotrauma, and pretracheal abscess (117,119,138,144,145). The tracheal tube may inadvertently slip out as it is advanced (146).

Cricothyrotomy

Placing a device through the cricothyroid membrane to gain control of the airway is not a new procedure (147,148,149,150). In recent years, the technique has been refined and is now commonly used by emergency medical services (151,152). It is part of the ASA and Difficult Airway Society difficult airway algorithms (2,3). Cricothyrotomy equipment should be on every difficult airway cart.

General Considerations

The thyroid cartilage is prominent and easily palpable in most individuals, especially in males. It may be difficult to palpate in obese patients and infants. The relatively avascular cricothyroid membrane is located approximately 2 to 3 cm below the thyroid notch in adults. This area is usually the most accessible part of the respiratory tree below the glottis. Occasionally, it may be necessary to choose a site lower in the airway between the second and third tracheal rings (153,154).

Cricothyrotomy can be performed by placing a small needle or catheter (needle cricothyrotomy), a large cannula specially designed for this purpose, or surgically inserting a cuffed tube (147,155). If time allows, fiberoptic guidance may decrease the incidence of malposition (156).

Techniques

Needle Cricothyrotomy

Technique

The patient's head is extended and the cricothyroid membrane identified. A needle or catheter-over-needle unit with a syringe attached is inserted in

the midline pointing between 30 degrees and 45 degrees in a caudal direction. If air can be aspirated freely into the syringe, the needle is inside the airway. A three-way stopcock can be placed between the syringe and needle with one limb of the stopcock connected to a capnograph (154,157). Aspirating carbon dioxide confirms airway placement. The cannula is then slipped off the needle into the trachea and the needle removed.

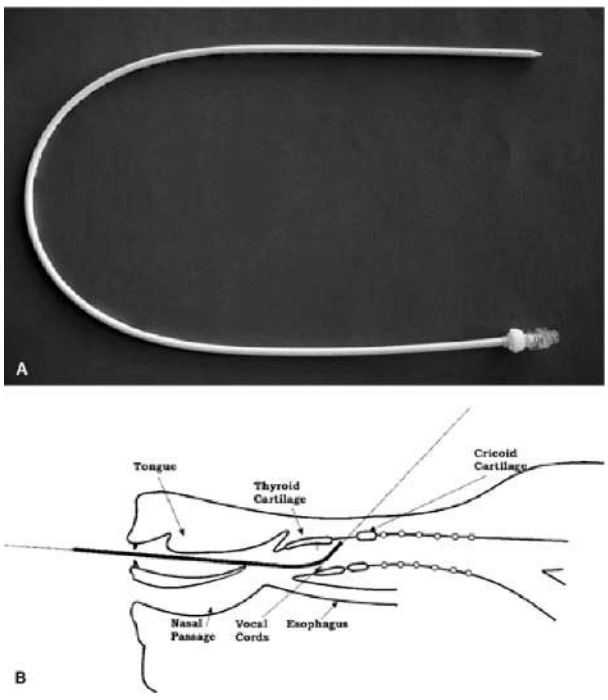

Figure 21.6 A: Airway exchange catheter. **B:** Airway exchange catheter has been advanced over the guide wire (after removal of the connection).

Small intravenous cannulae are usually readily available but are easily compressed and prone to kinking (158,159,160). Placing a

small bend in the end of the catheter may decrease the incidence of kinking (159). Some

intravenous catheters are not suitable, because a syringe cannot be attached and many are too short (161).

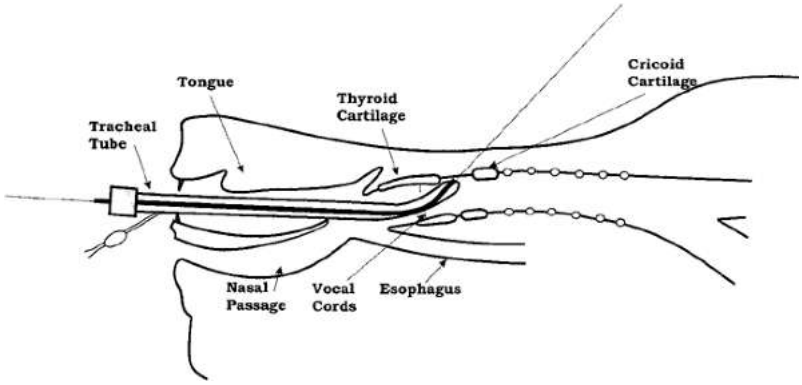

Figure 21.7 The tracheal tube is advanced over the airway exchange catheter.

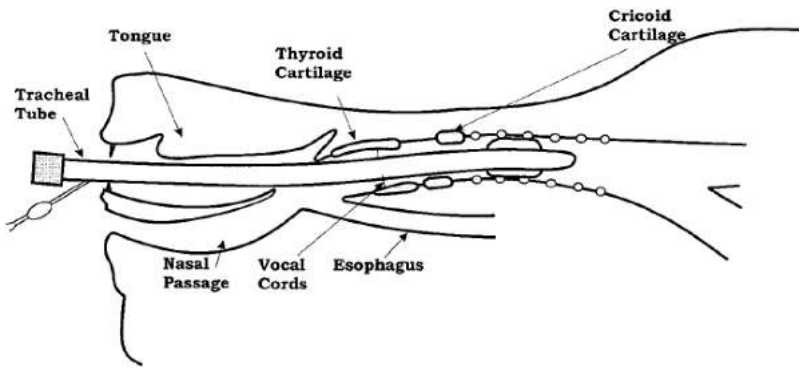

Figure 21.8 The guide wire and airway exchange catheter are removed, and the tracheal tube is advanced into the trachea.

Large-gauge intravenous catheters have been used successfully (162). Most authors recommend a 14-gauge or larger catheter for adult patients (147,163,164,165). Use of a catheter with side holes may lessen the risk of tracheal damage (163).

Catheter length is important. If the catheter is too short, it may come out, and gas will be injected into the subcutaneous neck tissues. However, the longer the catheter, the greater the resistance to flow. For the adult patient, the catheter should be at least 4 cm in length. For the patient with a thick neck, a greater length may be necessary (166).

Other devices used include a Tuohy needle (167,168), the

vessel dilator of an intravenous introducer kit (169,170), a triple-lumen central venous catheter (171), and a suction catheter (172).

To connect the cricothyrotomy device to a means of ventilation, either a Luer lock (Fig. 21.9) or a 15-mm connector is required. Many kits provide both. Some have the Luer lock attachment inside a 15-mm connector.

Ventilation Techniques

The catheter diameter often does not allow an adequate tidal volume to be delivered at the pressures provided by conventional ventilators. A source of high-pressure oxygen and robust connections are required.

Jet Ventilation

Injection of high-velocity gas into the airway through a narrow cannula without a seal is termed *jet ventilation*. It can be performed automatically or manually. Jet ventilation is conventionally carried out at rates up to 60 cycles/minute. Above 60 cycles/ minute, the technique is referred to *high-frequency jet ventilation* (173).

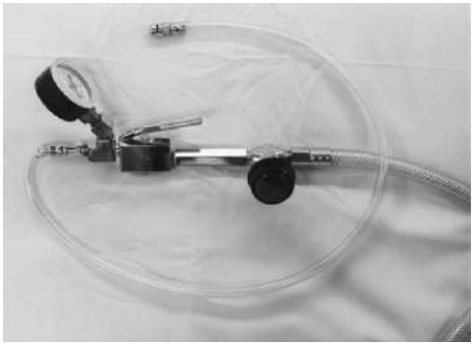

Figure 21.9 This device is designed to deliver oxygen at a high flow through a small tubing. The pressure tubing is attached to a 50-psi oxygen source, such as the outlet of a piped oxygen system. The pressure delivered can be adjusted by turning the knob. The pressure is measured by the pressure gauge at left. The flow is controlled by the toggle switch downstream of the knob. The tubing end at the top has a Luer lock connector and is attached to a large-bore needle or catheter placed percutaneously through the cricothyroid membrane.

A means of jet ventilation should be available in every anesthetizing area (174). Unfortunately, not all locations have the equipment readily available and ready for use (175). During an emergency is not the time to assemble these devices. All connections must be correct for the mode of ventilation anticipated and robust enough to withstand the pressures that will be used.

In a small patient, the peak pressure should be reduced to 5 pounds per square inch (psi) and then increased in increments of 5 psi until adequate chest excursions are observed (166,176,177). In adults, the jet ventilation device should be preset at 25 psi, then increased or decreased as indicated by the clinical response (178). The upper airway should be made maximally patent during jet ventilation by putting the patient in an optimal ĺ€sniffĺ€ position, by using bilateral jaw thrust and oropharyngeal airways, and by avoiding jet ventilation during phonation. If complete airway obstruction persists after jet ventilation is attempted, the airway needs to be converted to a tracheostomy as soon as possible.

The pattern of jet ventilation is important (142,162,179). The inspiratory volume depends on the gas flow rate, injection time, respiratory system compliance, and airway resistance. The expiratory volume will depend on the exhalation time, elastic recoil of the lungs, and airway resistance. Care must always be taken not initiate inspiration before the end of exhalation. End-tidal carbon dioxide can be monitored by placing a sample line through the mouth or nose (180). The inspired oxygen concentration will depend on the amount of air that is entrained, which depends on the ratio of the catheter to the trachea and the structure of the catheter (number of side holes).

If too much gas escapes from the trachea through the mouth or nose during inspiration, the patient's mouth and nose should be closed or the backflow blocked with a throat pack (181).

Devices

A number of jet ventilation devices are commercially available. One is shown in Figure 21.9. They are connected to a piped oxygen outlet or an oxygen cylinder with a regulator. Some have a means to regulate the delivered pressure and/or an alarm.

The jet may act as a Venturi and entrain adjacent gas to increase the volume delivered. The jet's efficiency depends on a number of factors (173). The amount of gas delivered increases as the driving pressure is raised.

Automatic Ventilator

Automatic ventilators that can deliver a jet of gas automatically while monitoring both delivery pressure and airway pressure are available and can be attached to the cricothyrotomy catheter (142,169,172,183,184,185,186). Some automatically pause ventilation when the end-expiratory pressure exceeds a preset limit, enabling detection of outlet obstruction (171).

Manual Jet Ventilation Device

A manually controlled jet ventilation device may be attached to the cricothyrotomy catheter and the patient ventilated by using an intermittent jet of oxygen. Tidal volume, inspired oxygen concentration, and airway pressures are not easily monitored. A check must be made for complete exhalation after each delivered tidal volume.

Flowmeter

Many anesthesia machines have an auxiliary (courtesy)

flowmeter. This or a flowmeter attached directly to a piping system outlet can be used as a source of oxygen (186,187). Noncompliant tubing should be used between the flowmeter and the cricothyrotomy catheter. A three-way stopcock or other device can be used at the patient end to convert the continuous flow of gas to intermittent bursts, or a hole can be cut in the tubing and the operator's finger placed over the hole to deliver a jet of oxygen.

Oxygen Flush

It may be possible to supply oxygen from the anesthesia machine by attaching noncompliant tubing to the common gas outlet and intermittently activating the oxygen flush (188,189,190,191). Alternatively, if there is a port near the patient end of the tubing, a second person can continuously depress the oxygen flush button while the anesthesia provider intermittently occludes the port (192).

Not all anesthesia machines have a common gas outlet that can be accessed, and not all anesthesia machines supply oxygen at a high enough pressure to drive the oxygen through the noncompliant tubing and a cricothyroid catheter (191,192). Before relying on this means of ventilation, the anesthesia department should ascertain what pressure will be delivered.

Anesthesia Breathing System

The 15-mm connector from a circle breathing system can be connected to the cricothyroid device and the oxygen flush intermittently activated. Because the reservoir bag and tubings absorb most of the pressure, the lungs will probably not be effectively ventilated by this method although adequate oxygenation may be achieved (188). Applying pressure to the reservoir bag will increase the delivered pressure.

Manual Resuscitation Bag

A manual resuscitator (Chapter 10) or a Mapleson system (Chapter 8) may be attached to the cricothyrotomy device. These cannot provide adequate ventilation unless a very large cannula is used (176,192,197).

Percutaneous Dilatational Cricothyrotomy

The elements of a percutaneous cricothyrotomy set are shown in Figure 21.10. A number of customized kits containing the necessary items are available (164,175,198,199,200,201,202,203,204,205,206,207,208,209). A needle-over-cannula or a simple needle with an attached syringe is inserted through the cricothyroid membrane and air aspirated (Fig. 21.11). A guide wire is then inserted through the catheter.

(Fig. 21.12), and the catheter is then removed. The hole in the skin around the guide wire is enlarged by using a scalpel (Fig. 21.13). The tract around the guide wire can be enlarged by using a series of progressively larger dilators (introducers) or a curved dilator (Fig. 21.14). The airway device is then inserted into the trachea over the wire guide or dilator, which is then removed

(Fig. 21.15). A cricothyrotomy tube may have a cuff (Fig. 21.16). The insertion assembly may differ (Fig. 21.17).

Figure 21.10 Elements of a cricothyrotomy set. At bottom is a syringe with needle. Next is the guide wire, which is advanced through the needle. The small scalpel is used to enlarge the hole in the skin at the site of the guide wire. The dilator is used to enlarge the opening into the airway. The tube is advanced over the dilator. The guide wire and dilator are then removed, and the tube is used to ventilate the patient.

This technique is fast and usually easy to perform, even in the patient with a short neck or spinal injury. An advantage is that most anesthesia providers are experienced in wire-guided techniques (210). Adequate ventilation can be achieved by using a conventional breathing system if the diameter of the device is at least 4 mm (147,208). However, it may result in more complications and less chance of correct positioning than a catheter-over-needle technique (211,212).

Surgical Cricothyrotomy

In surgical cricothyrotomy, a transverse skin incision is made at the level of the cricothyroid membrane (147,151,198,213,214,215,216). If the neck is edematous and the larynx cannot be palpated, the incision should be vertical and then deepened until the laryngeal cartilages are identified. An incision is then made in the cricothyroid membrane. A catheter may be placed as a guide. The incision in the membrane is then spread, and a tracheal or tracheostomy tube is placed through the opening. A bougie may facilitate insertion of a tracheal tube (217).

Surgical cricothyrotomy is more time consuming than the percutaneous methods and requires an experienced surgeon but provides a more definitive airway

than the other methods. However, if speed is particularly important and/or when equipment for less invasive techniques is

unavailable, it can be performed quite rapidly.

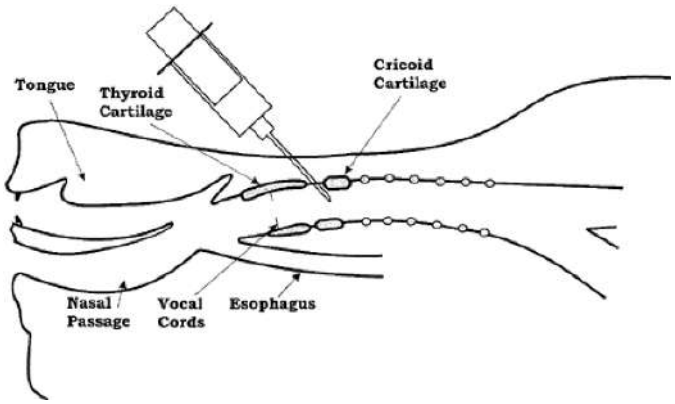

Figure 21.11 The needle-over-catheter is inserted through the cricothyroid membrane in a caudal direction.

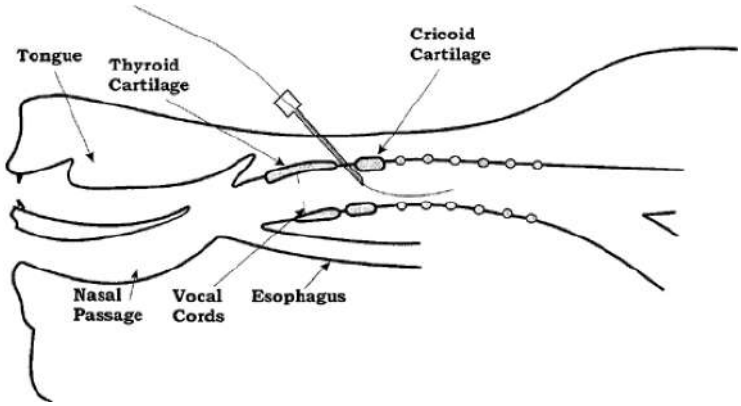

Figure 21.12 A guide wire is inserted through the catheter.

Indications

Upper Airway Obstruction with Inability to Ventilate or Intubate

A prime indication for cricothyrotomy is the inability to secure a patent airway by conventional techniques (154,170,194,218,219,220,221,222,223). These include foreign body aspiration and upper airway pathology or when a person skilled at intubation is not available or cannot intubate the patient and a supraglottic device cannot be inserted.

Anticipated Difficult Intubation

Cricothyrotomy may be used as an adjunct to fiberoptic or other intubation techniques where it is anticipated that intubation may

be difficult to perform (109,166,174,224,225,226,227). It provides a means to ventilate the patient if the intubation procedure is prolonged. This may be especially useful for patients who cannot tolerate an awake intubation. Jet ventilation may make subsequent tracheal intubation easier because the high tracheal pressure may open the collapsed

glottis (154,228,229). Leaving the cricothyrotomy device in place during the recovery period allows emergency oxygenation at a time when reintubation may be difficult or contraindicated.

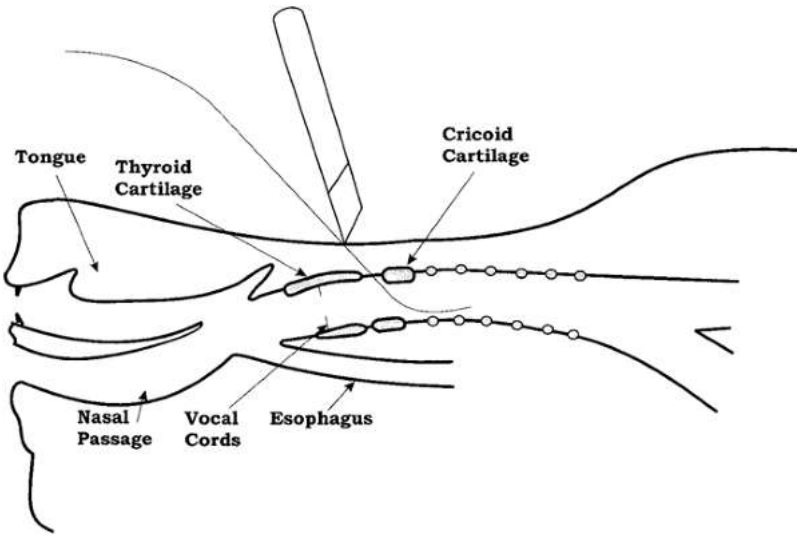

Figure 21.13 The hole in the skin around the guide wire is enlarged by using a scalpel.

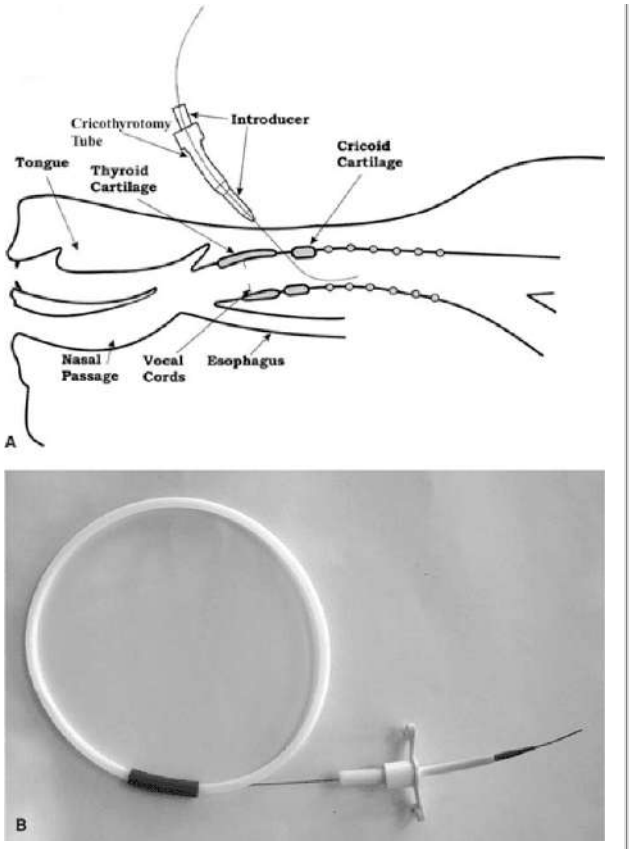

Figure 21.14 **A:** The tract around the guide wire is enlarged by using a curved dilator (introducer). **B:** The cricothyrotomy tube fits over the introducer and guide wire.

Procedures Involving the Airway

Jet ventilation through a cricothyrotomy device can be used during procedures involving the upper airway (168,171,174,182,230). This leaves the entire airway from the vocal cords to the face accessible to the surgeon. Since there is no tracheal tube, there is a reduced likelihood of fire (231) (Chapter 32). A disadvantage is that the airway is not protected from contamination by blood and surgical debris. However, the continuous egress of gas from the airway helps to reduce contamination.

Cervical Spine Injury

If cervical spine injury has occurred or has not been ruled out, cricothyrotomy may be a good way to establish an airway. Other methods of securing an airway with minimal neck movement are discussed in Chapters 17 and 19.

Contraindications

Intrathoracic Airway Obstruction

Cricothyrotomy is only useful for obstructions above the cricoid cartilage. Obstructions at or below this level may be pushed deeper. For obstructions at or below the level of the cricoid, tracheotomy will be necessary.

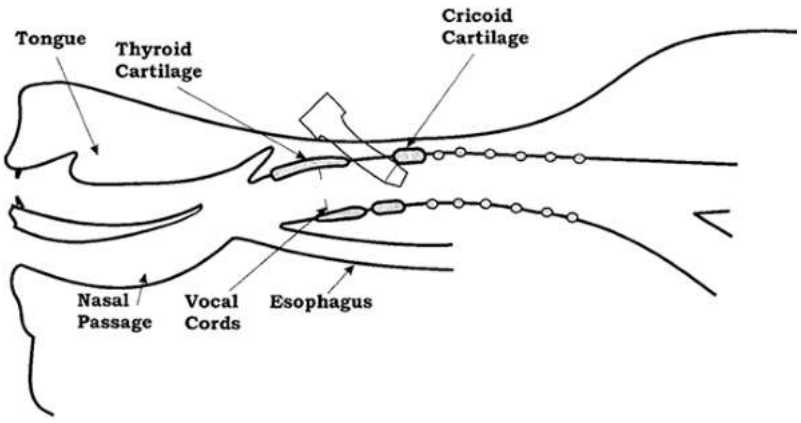

Figure 21.15 The introducer and guide wire are removed, and the cricothyrotomy tube is left in place.

Inability to Locate the Cricothyroid Membrane

This procedure should not be attempted if there is uncertainty about the location of the cricothyroid membrane.

Complete Airway Obstruction

If there is complete obstruction above the cricothy-rotomy catheter, there will be no exit path for exhalation. However, if a foreign body obstruction in the mouth or larynx is preventing respiration, there is the possibility that this could be blown out and the obstruction relieved. It may be possible to administer pressurized oxygen safely to patients with complete upper airway obstruction by using a Y-adaptor attached to the catheter hub (228). Oxygen can be administered through one limb while the other limb is used for passive expiration.

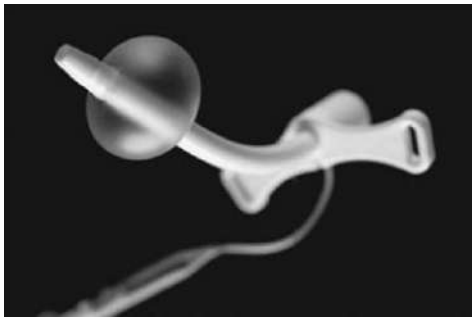

Figure 21.16 Cuffed cricothyrotomy tube. (Courtesy of Cook Critical Care.)

Pediatric Patients

Cricothyrotomy is technically difficult in the pediatric population and should be performed with extreme caution in children below 10 years of age (155). Pediatric patients have a higher incidence of complications from cricothyrotomy than do adults (232).

Laryngeal Pathology

Cricothyrotomy should not be used in the presence of laryngeal inflammation or infection.

Decreased Compliance

Patients with conditions such as emphysema and chronic bronchitis often have diminished compliance that may make ventilation less effective.

Complications

Barotrauma

If positive pressure is applied below the vocal cords, airway pressure may rise to a hazardous level with resultant barotrauma (175,182,183,228,230,233,234,235). Carefully monitoring chest movements, limiting inspiratory pressure and time, and allowing adequate time for expiration will decrease the risk of barotrauma. Airway pressure monitoring should be performed, if feasible. Some jet ventilators automatically pause when a preset pressure is reached (171,229).

Trauma

Placing a cricothyroid device can result in injury. Bleeding, hematoma, laryngeal cartilage injury, mucosal ulceration, and perforation of the posterior trachea and esophagus have been reported (175,205,213,220,236,237,238,239,240).

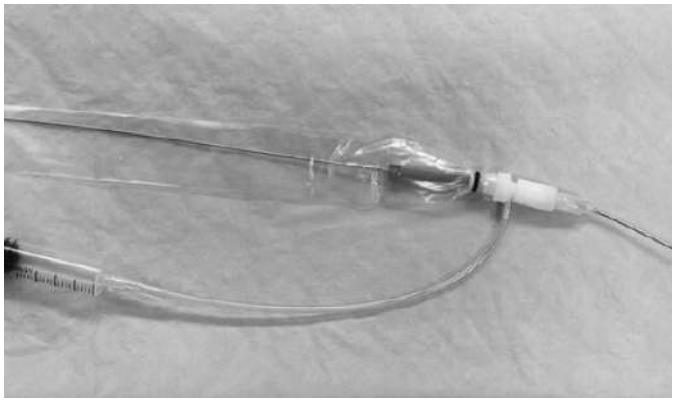

Figure 21.17 Cricothyrotomy set with the guide wire attached to the needle and a side tubing through which air can be aspirated.

If the catheter is incorrectly placed or slips out of the trachea or if there is a hole in the catheter near the surface of the neck, oxygen may be injected into the tissues, resulting in subcutaneous or mediastinal emphysema (183,228,241,242,243). Subcutaneous emphysema also may occur after decannulation (168,244). The cricothyrotomy device should be firmly secured to prevent dislodgment. Suturing the device in place should be considered if time permits. Neck movement should be limited. Î€Whippingî€ of the catheter with each breath can be minimizing by keeping a short length within the trachea and using a low driving pressure (171).

Late complications include granulation at the cuff site, excessive procedure time, tracheal stoma stenosis, persistent stoma, hemorrhage, subglottic stenosis, aspiration of blood, dysphonia, vocal cord paralysis or paresis, voice changes, and wound infection (220,236,239,245,246).

Kinked Catheter

If the catheter kinks, ventilation may not be possible (158,168,247). Adding a small curve to the tip may help prevent kinking (159). Precurved catheters are commercially available (248). If kinking occurs, it may be possible to change the catheter for one more resistant to kinking by using a guide wire (168).

Failure to Cannulate the Trachea

The reported failure rate for successfully placing catheters in the trachea varies from 0% to 40% (151,200,213,214,219,220,236,238,239,240,249,250,251). Practice with the technique during elective cases or a simulator increases familiarity with the method and facilitates its use in an emergency situation (156,247,252,253).

Advantages and Disadvantages

Cricothyrotomy is relatively simple, safe, easy to learn, and quick. The success rate is high even in inexperienced hands (151,152,214,219,220,238,239,250). Percutaneous jet ventilation may facilitate tracheal intubation by allowing identification of the glottis opening (154,228). The principal disadvantage is that it does not establish a definitive airway.

Percutaneous Dilatational Tracheostomy

Percutaneous dilatational tracheostomy entails insertion of a full-sized tracheostomy tube in the subcricoid area (254). It is an alternative to traditional surgical tracheostomy. It may be performed at the bedside in a critical care unit. Many institutions have adopted it as the technique of choice in critically ill patients who require a tracheostomy (255,256,257). It is most often performed electively but can be used in an emergency situation (258).

Technique

Ventilation can be maintained throughout the procedure by using a tracheal tube placed above the site of the proposed tracheostomy, a supraglottic airway device, a Combitube, a microlaryngeal tube, an airway exchange catheter, or a flexible or rigid bronchoscope (78,259,260,261,262,263,264,265,266,267,268,269,270,271,272,273,274,275,276). The Combitube may not be suitable if the longer lumen is in the trachea (79).

Endoscopy is often used during the procedure to avoid complications (261,265,275,277,278,279,280,281,282,283). An optical stylet may also be used (284). It allows confirmation of the position of the tracheal tube as well as correct placement of the needle (i.e., whether it is midline and

at the correct level), guide wire, dilator, and finally the tracheostomy tube. More severe complications occur when endoscopic visualization is not used (285). It also makes it relatively easy to perform a therapeutic or diagnostic bronchoscopy after the procedure is completed (286,287). Disadvantages of fiberoscopy include an increase in the time needed for the procedure, the need for a separate skilled person, and the potential for hypoventilation (288). A light wand may be used to guide the procedure (289,290).

A modification of this technique is to utilize endoscopic guidance during guide wire placement and then to insert an airway exchanger catheter (266,291). This produces less airway resistance, allows ventilation and administration of oxygen, and facilitates reintubation, if necessary.

The patient is placed in the supine position with the neck extended unless there is known or suspected cervical spine instability. Ultrasound scanning can be used to identify blood vessels and the correct level (269,292,293,294,295,296).

If the patient is intubated, the tracheal tube should be withdrawn to a point above the intended site of the tracheostomy. A bougie or airway exchange catheter may be inserted through the tracheal tube to facilitate reintubation if the tracheal tube is dislodged (291,297).

A short, shallow skin incision is made over the trachea, between the first and fourth cartilages (259,298). If the situation is urgent, the cricothyroid membrane may be punctured (202). A large gauge needle is then introduced into the tracheal lumen between two rings (Fig. 21.18). Position within the trachea is confirmed by aspiration of air, direct bronchoscopic visualization (preferred), or capnography (299,300). Local anesthetic can be injected into the lumen of the trachea. A guide is introduced through the needle into the trachea, and the needle is then removed.

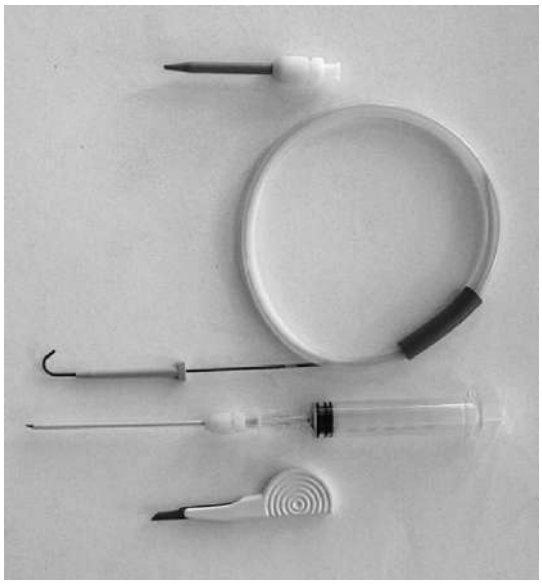

Figure 21.18 After the front of the trachea has been exposed, the needle with syringe attached is inserted into the trachea. Entry into the trachea is confirmed by the appearance of air bubbles on aspiration. A guide wire is then inserted through the needle, and the small dilator is inserted.

Different techniques are used to dilate the opening in the anterior tracheal wall over the guide (301,302,303,304). The first employs progressively larger tapered dilators (Fig. 21.19) or one large tapered or screwlike dilator (Fig. 21.20) introduced over the guide (305,306,307,308,309,310,311,312,313,314). Some dilators have a hydrophilic coating that helps to enlarge the entrance site. Another technique uses a dilating forceps (315,316,317). This technique is faster and may be

associated with fewer complications than sequential dilatation technique (318,319). Kits containing the necessary items for each method are available (254,309,320,321,322).

Figure 21.19 Progressively larger dilators can be used to enlarge the hole.

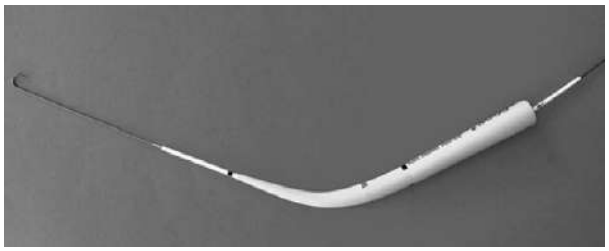

Figure 21.20 A large dilator is passed over the guiding catheter, which was passed over the guide wire.

The lubricated tracheostomy tube is inserted over the dilating device or guide, which is then removed (323) (Fig. 21.21). Special tracheal cannulas with obliquely cut tips that facilitate insertion have been developed (259). Capnography should be used to confirm correct placement (286,324).

Contraindications

Relative contraindications to percutaneous tracheos-tomy include infection at the site, inability to extend the neck, anatomical features interfering with identification of anatomic landmarks, tracheomalacia, and severe coagulopathies. Its use in children is controversial (259,325,326,327). However, percutaneous dilatational tracheostomy has been performed in all of these subgroups (255).

Advantages and Disadvantages

A major advantage of percutaneous tracheostomy is the ability to perform the technique at the bedside. This avoids delays, risks, and logistical problems of transfer to the operating room. Compared with a surgical tracheostomy, it is less expensive, faster, easier, and associated with less blood loss and is less likely to result in cosmetic deformity, infection, or bacterial contamination of neighboring structures (255,259,278,328,329,330,331,332,333,334,335,336,337,338). Short-term complication rates are less than for operative tracheostomy (316,329,331,334,339,340,341,342,343,344). It can be performed in most patients who cannot undergo neck extension (345,346) and in morbidly obese patients (306,347,348,349,350).

Complications

Studies indicate that there is a learning curve for percutaneous dilatational tracheostomy (351). The complication rate may be higher in obese patients (350). The use of ultrasound should reduce the number of serious complications (295,296).

Incorrect Placement

Some studies show that a significant number of tubes have been

placed in an improper location, usually higher in the airway than intended (352,353). A tube may end up moving cephalad rather than caudally (354).

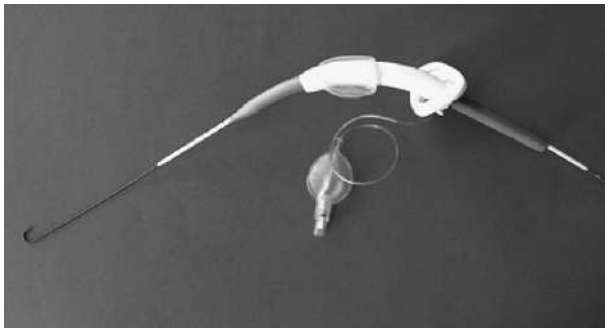

Figure 21.21 The tracheostomy tube is loaded over a small dilator, which is in turn loaded over a guiding catheter, which is then loaded onto a guide wire. After insertion into the trachea, the dilator, guiding catheter, and guide wire are removed.

Trauma

Trauma resulting from percutaneous tracheostomy can include formation of a false passage either anterior to or beside the trachea, injury to the posterior tracheal wall or tracheal cartilages, hematoma, hemorrhage, esophageal perforation, subcutaneous emphysema, mediastinal emphysema, pneumothorax, hemothorax, tracheoesophageal fistula, and tracheoinnominate fistula have all been reported (286,287,302,303,310,322,333,334,353,355,356,357,358,359,360,361,362,363,364,365,366,367,368,369,370,371,372,373,374,375,376,377,378,379,380,381,382

Tracheal Tube Damage

Tracheal tube damage, including puncturing the cuff, transfixing the tube, and inserting the guide wire through the Murphy eye, may occur during percutaneous tracheostomy (301,383,384,385,386,387). Damage to the endoscope may also occur.

Tracheal Stenosis

The incidence of tracheal stenosis as a long-term complication varies from less than 1% to 10% (259,286,325,329,339,342,388,389,390,391). Thickening of the lateral tracheal wall has been reported (392).

Hypoventilation

Hypoventilation can occur when the tracheal lumen is obstructed from external pressure, a dilator, or the endoscope (255,288). The tidal volume and/or respiratory rate can be increased to compensate for the leak created by the hole in the trachea.

Foreign Body in Trachea

Cases have been reported of a fractured guide wire and the dilator lodged in the trachea following percutaneous dilatational tracheostomy (393,394,395). A case has been reported where the blade of the forceps broke away and entered the trachea (396).

Other Complications

Other complications reported with percutaneous tracheostomy include inadvertent extubation, persistent stoma, cellulitis, bacteremia, a change in voice, airway obstruction, dysphagia, ongoing severe cough, and skin tethering (301,321,342,388,397,398,399,400). Damage to the endoscope may occur (401).

Translaryngeal Tracheostomy

This technique is unlike others in this chapter in that the tracheal cannula is inserted from inside the tracheal lumen to the outside (402,403). A kit based on this technique is available. It may be advantageous in patients who have serious hypoxemia and in those who are considered difficult to intubate or who have cervical spine injuries (177).

TABLE 21.1 Equipment for Difficult Airway Cart

Fiberscope
Fiberoptic light source
Video head
VCR
Defogging solution
Swivel fiberoptic adaptors
Local anesthetic spray
Endoscopic mask
Fiberoptic intubating airways (e.g., Ovassapian, Patil-Syracuse, Williams, Berman)
Fiberoptic stylet laryngoscope
Lighted intubation stylet
Rigid indirect laryngoscope (e.g., Bullard, WuScope, Upsher Scope)
Bougies
Flexible suction catheters
Yankauer suction catheter
Supraglottic devices (LMAs, etc.) and tracheal tubes suitable for insertion through the supraglottic device
Cricothyrotomy device and device for jet ventilation
Combitubes
Retrograde intubation kit
Percutaneous dilatational tracheostomy kit
Binasal airway
Magill forceps
Water-soluble jelly and ointment
Airway exchange catheters
Difficult airway algorithm
Elevation pillow (Fig. 18.47)
Variety of face masks
Variety of rigid laryngoscope blades and handles
Nasal and oral airways
Tracheal tubes
Stylets

Under bronchoscopic guidance, a guide wire is passed via a percutaneous needle in the trachea (passed retrograde into the mouth). The guide wire is attached to a specially designed cone that is bonded to a tracheostomy tube. The conal dilator/tracheostomy tube is threaded over the guide wire and pulled through the oral cavity, larynx, and trachea and out through the anterior tracheal wall. The cone is then detached from the tracheostomy tube, which is rotated from a cephalad to a caudal direction by using an obturator, then advanced caudally to its final position. During the procedure, the patient is ventilated via a thin tracheal tube, the end of which is positioned distal to the tracheostomy site. The tracheal tube is removed after or just before the tracheostomy tube is rotated and secured (404,405).

The modified Fanconi technique involves the use of a fiberscope, insertion of a J-shaped wire, and the use of a small-diameter tracheal tube positioned coaxially to the original airway to ventilate the patient during introduction of the tracheostomy tube (177).

This technique can be performed at the bedside. Because dilation is achieved by the tracheal cannula itself, the cannula fits smugly with the tracheostomy wound edges. It has been used in patients with severe respiratory failure and coagulopathy (177,406).

This technique is technically more complicated than percutaneous tracheostomy. It requires three people to perform properly, one of whom is concerned solely with maintaining the airway and the patient's ventilation. Complications include bleeding, barotrauma, trauma, and misplacement of the tracheostomy tube (332,403,405,407,408). A study comparing this technique with forceps dilatational percutaneous tracheostomy found a higher complication rate and more technical difficulties with the translaryngeal technique (403). It takes longer than a percutaneous tracheostomy.

Difficult Airway Cart

A cart containing equipment that is useful when a difficult airway is encountered should be immediately available in every location where anesthesia is administered. It is important that each cart be nearly identical across all locations so that when faced with an emergency, the user is familiar with the location and operation of all the equipment. The equipment on this cart should fit the skills and preferences of the anesthesia provider. The list in Table 20-1 is given only as an example and should not be considered exhaustive.

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Questions

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

1. Which statements concerning Combitube placement are true?

A. The pharyngeal balloon should be inflated first

B. The use of a laryngoscope may lower the number of complications

C. The tip of the tube usually ends up in the trachea

D. The esophageal detector device is useful in verifying tube position

View Answer

2. Contraindications to using a Combitube include

A. Ingestion of corrosive agents

B. Known esophageal trauma

C. Active pharyngeal and laryngeal reflexes

D. Patients younger than 12 years of age

View Answer

3. Advantages of the Combitube include

A. It can be used by non-anesthesia personnel

B. Neck movement is not necessary

C. The pharyngeal balloon anchors it in place

D. There is no danger of bronchial intubation

View Answer

4. Disadvantages of the Combitube include

A. Fiberoptic bronchoscopy is not possible

B. It is not useful for patients with latex allergy

C. There is higher stress response than that from a tracheal tube during insertion or removal

D. The presence of blood or vomitus in the pharynx precludes its use

View Answer

5. Situations that lend themselves to retrograde intubation include

A. Oropharyngeal bleeding

B. Infant and child intubation

C. Limited neck mobility

D. Pretracheal abscess

View Answer

6. Conditions where cricothyrotomy may be indicated include

A. Cervical spine injury

B. Surgery involving the upper airway

C. Difficult intubation

D. Foreign body aspiration

View Answer

7. Contraindications to cricothyrotomy include

A. Complete airway obstruction above the cricothyroid membrane in the larynx

B. Decreased compliance

C. Laryngeal inflammation or infection

D. Obstructions below the thyroid cartilage

View Answer

8. Complications of cricothyrotomy include

A. Kinked catheter

B. Tracheal stoma stenosis

C. Subcutaneous or mediastinal emphysema

D. Esophageal perforation

View Answer

9. Barotrauma can be reduced by which mechanisms?

A. Limiting inspiratory time

B. Using airway maneuvers such as sniff position and jaw thrust

C. Watching chest movements

D. Limiting the peak pressure to a maximum of 35 psi in adults

View Answer

10. Relative contraindications to percutaneous tracheostomy include

A. Severe coagulopathies

B. Infection at the site

C. Tracheomalacia

D. Inability to extend the neck

View Answer

11. Advantages of percutaneous tracheostomy include

A. Faster than surgical tracheostomy

B. Can be performed on patients who cannot extend their necks

C. Lower incidence of infection

D. Fewer complications than surgical tracheostomy

View Answer

12. Complications of percutaneous tracheostomy include

A. Pneumothorax

B. Tracheal tube damage

C. Airway obstruction

D. Tracheal stenosis in up to 15% of patients

View Answer

Chapter 22
Gas Monitoring

Reliable, affordable, and user-friendly monitors to measure respiratory and anesthetic gas concentrations are now available. Some use more than one technology to measure different gases. Some combine gas analysis with other types of monitoring such as electrocardiograph, blood pressure, pulse oximetry, or spirometry (Fig. 22.1).

Definitions

1. *Delay time* (transit time, response time, transport delay, time delay, lag time) is the time to achieve 10% of a step change in reading at the gas monitor.
2. *Rise time* (response time) is the time required for a change from 10% to 90% of the total change in a gas value with a change in concentration at the sampling site.
3. *Total system response time* is the sum of the delay and rise times. A fast response time is necessary to obtain accurate values and waveforms. The use of an instrument with a slow response may result in incorrect end-tidal values during rapid ventilation (1).
4. The *sensor* (measuring head or chamber) is the part of a respiratory gas monitor that is sensitive to the gas being measured.

Figure 22.1 Multipurpose monitor. Most gas monitors are now part of a physiologic monitor that includes other monitoring such as electrocardiograph, blood pressure, pulse oximetry, and the like. A gas monitor may also be part of the anesthesia machine. Newer anesthesia machines have one or more screens to display monitored functions, and the gas concentrations and waveforms may also be displayed.

5. A *nondiverting* (mainstream, direct probe, flow through, in-line, on airway, nonsampling monitor) *monitor* measures the gas concentration at the sampling site.
6. A *diverting* (sidestream, withdrawal, sampling, aspirating, sniffer, sampled system *monitor*) transports a portion of the gas being measured from the sampling site through a sampling tube to the sensor, which is remote from the sampling site.
7. The *sampling site* (sensing site) is the location from which gas is diverted for measurement in a diverting monitor or the location of the sensor in a nondiverting monitor.
8. The *sampling tube* (inlet line, sample gas transport tube, sample capillary tube, sampling catheter or tube, transport tube, aspirating tube, sample line) is the conduit for transferring gas from the sampling site to the sensor in a diverting gas monitor.
9. *Gas level* is the concentration of a gas in a gaseous

mixture. It may be expressed either as partial pressure or volumes percent.

10. The *partial pressure of a gas* is the pressure that a gas in a gas mixture would exert if it alone occupied the volume of the mixture at the same temperature.
11. The *volumes percent* (%, V/V, vol %) of a gas is the volume of a gas in a mixture, expressed as a percentage of the total volume.

Monitor Types

There are two general types of monitors in clinical use: diverting (sidestream) or nondiverting (mainstream) (2,3). These refer to the measurement site of the gases and not to the technology being used. Both can be integrated into a single module.

Nondiverting

A nondiverting gas monitor measures the gas by using a sensor located directly in the gas stream. Only oxygen and carbon dioxide (CO_2) can be measured by nondiverting monitors.

Carbon dioxide is measured by infrared technology with the sensor located between the breathing system and the patient (Figs. 22.2, 22.3). A nondiverting monitor is available for the non-intubated patient, in which the sensor attaches to a disposable oral and nasal adaptor.

The mainstream oxygen sensor uses electrochemical technology. It is usually placed in the breathing system inspiratory limb. If the technology is fast enough to measure both inspired and exhaled oxygen, it should be placed between the patient and the breathing system. Chapter 9 discusses possible locations of the oxygen monitor sensor in the circle breathing system.

Advantages

1. Mainstream CO_2 monitors have fast response times because there is no delay time. The CO_2 waveform generated has better fidelity than one generated by a diverting monitor.
2. Because no gas is removed from the breathing system, it is not necessary to scavenge these devices or to increase the fresh gas flow to compensate for gas removed from the

breathing system.

3. Water and secretions are seldom a problem with this type of analyzer, although secretions on the windows of the cuvette used for mainstream CO_2 monitoring can cause erroneous readings. Water and secretions

are generally not a problem with oxygen sensors, as they are usually on the inspiratory side of the breathing system.

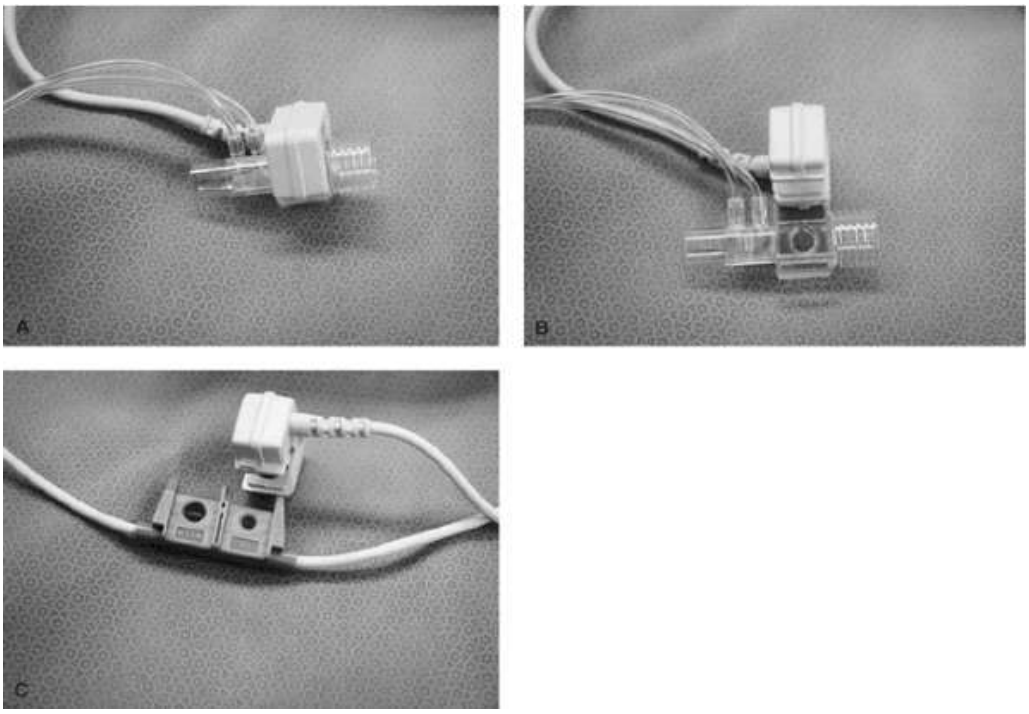


Figure 22.2 Nondiverting gas monitor. **A:** The sensor is in position over the cuvette, which is placed between the patient and the breathing system. The two clear tubings to the left are for spirometry loops (Chapter 23). **B:** The sensor is separated from the cuvette, which contains the window through which the infrared light passes. **C:** Calibration cells. For convenience, they are attached to the cable to the sensor. During calibration, the sensor is placed over each cell in sequence.

4. Sample contamination by fresh gas is less likely than with a diverting monitor.
5. A standard gas is not required for calibration. Oxygen sensors are usually calibrated by using room air.

6. These monitors use fewer disposable items than diverting monitors.

Disadvantages

1. To obtain accurate end-tidal CO_2 values, the airway adaptor must be placed near the patient. The sensor will add weight to the breathing system and may cause traction on the airway device or breathing tubes.
2. The use of an adaptor between the patient and the breathing system will increase dead space. However, studies show that end-tidal CO_2 values obtained by using a mainstream analyzer with a pediatric adapter in healthy neonates and infants are close to arterial values (4).
3. Leaks, disconnections, and circuit obstructions can occur (5,6,7,8).
4. With a mainstream CO_2 monitor, condensed water, secretions, or blood on the windows of the cuvette will interfere with light transmission.
5. With a mainstream CO_2 monitor, the sensor may become dislodged from the cuvette. If it is completely dislodged, no waveform will be seen. If it is slightly dislodged (Fig. 22.4), the reading may be incorrect although the waveform will appear normal (9,10,11).
6. The expensive optical sensor for CO_2 is vulnerable to costly damage.
7. At present, mainstream monitors can measure only oxygen and CO_2.
8. The adaptor for the CO_2 sensor must be cleaned and disinfected between uses. There is potential for cross contamination between patients if this is not done properly. Disposable adaptors are available but increase the cost.
9. Thermal burns have been reported with a mainstream CO_2 analyzer despite use of multiple layers of gauze, which kept the sensor from direct contact with the skin (12). To prevent this, it may be necessary to interpose a piece of aluminum foil between two pieces of soft material to reflect the radiant energy.

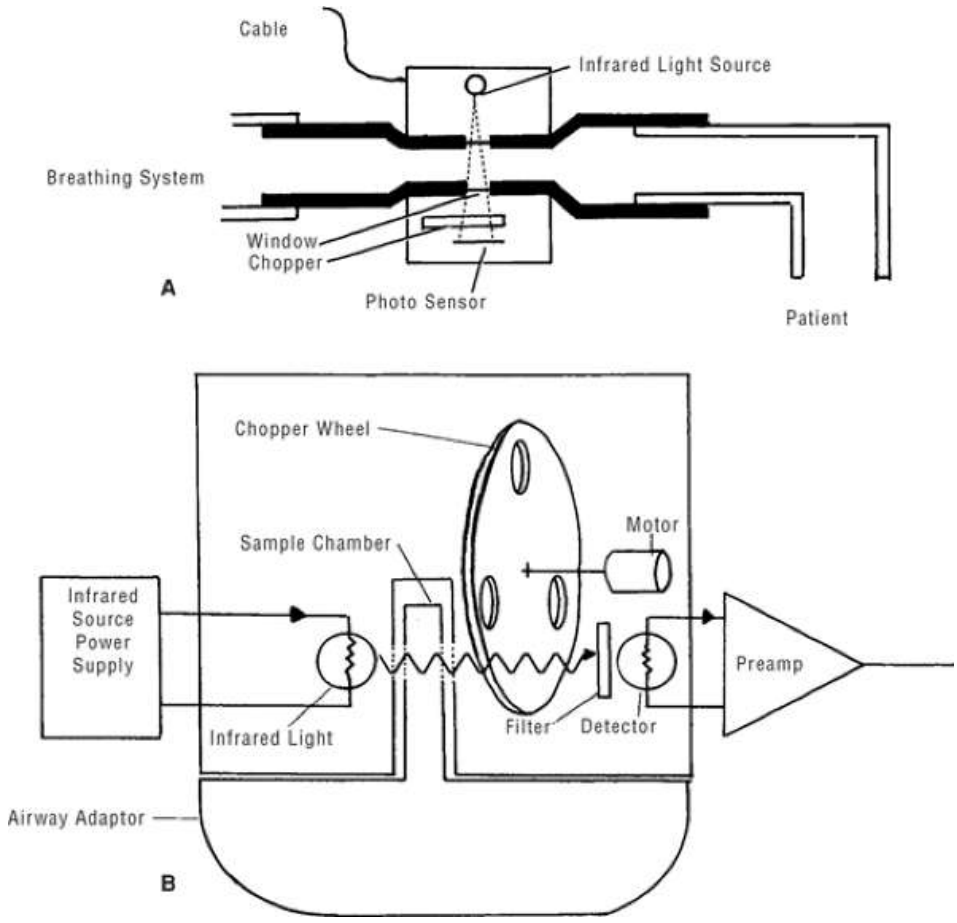


Figure 22.3 Mainstream infrared analyzer. **A:** Side view. The light source and detector are housed in the sensor, which fits over the cuvette. The infrared light shines through the windows of the cuvette and is detected by the photosensor. **B:** Cross-sectional view. Gases pass through the airway adaptor (cuvette). The infrared light that is transmitted through the windows is filtered and then detected by the photodetector in the sensor.

10. Prolonged contact of the CO_2 sensor assembly with the patient could cause pressure injury.

Diverting

A diverting monitor uses a pump to aspirate gas from the sampling site through a sampling tubing to the sensor that is

located in the main unit. Keeping the sampling tube as short as possible will decrease the delay time and result in more satisfactory waveforms. These analyzers are usually zeroed using room air and calibrated using a gas of known composition. A mainstream monitor with diverting capability is shown in Figure 22.5. Gas is aspirated through a special cuvette and is analyzed by the sensor.

To avoid water or particulate contamination in the monitor, a number of devices have been used. These include traps (Fig. 22.6) (which must be emptied periodically), filters and hydrophobic membranes (which must be changed periodically), and special tubing (which allows water to diffuse through its walls) (13,14).

Water droplets and secretions from the breathing system can enter the sampling tube and increase resistance in the tubing, affecting the accuracy. Some instruments either increase the sampling flow or, to clear the contaminant from the tube, reverse the flow (purge) when they sense a drop in pressure from a flow restriction (15). If this fails, the sampling port and/or the tube must be replaced.

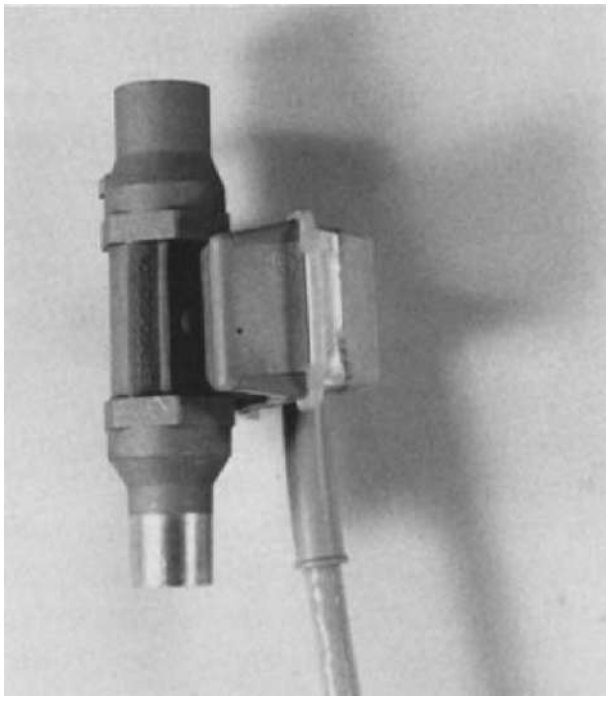


Figure 22.4 Mainstream infrared CO_2 analyzer with the sensor not completely covering the windows of the cuvette. This can result in falsely low CO_2 readings.

Accuracy decreases with increasing respiratory rate and longer sampling lines (16). Most diverting capnometers are accurate at those respiratory rates that are normally encountered in clinical practice (20 to 40 breaths per minute). At higher respiratory rates, accuracy is lower.

The sampling flow rate should be proportional to the size of the patient. It has been recommended that a flow rate less than 150 mL/minute should not be used because a low sampling flow may result in an elevated baseline, erroneously low peak readings, and absence of an end-tidal plateau (Fig. 22.36), especially when the respiratory rate is fast and tidal volume is small (17). A high flow rate will decrease the delay and rise times but may cause fresh gas to be entrained into the sample line with some breathing systems. This will result in incorrect end-tidal readings and a capnogram with a decrease in CO_2 at the end of the expiratory plateau (Fig. 22.37).

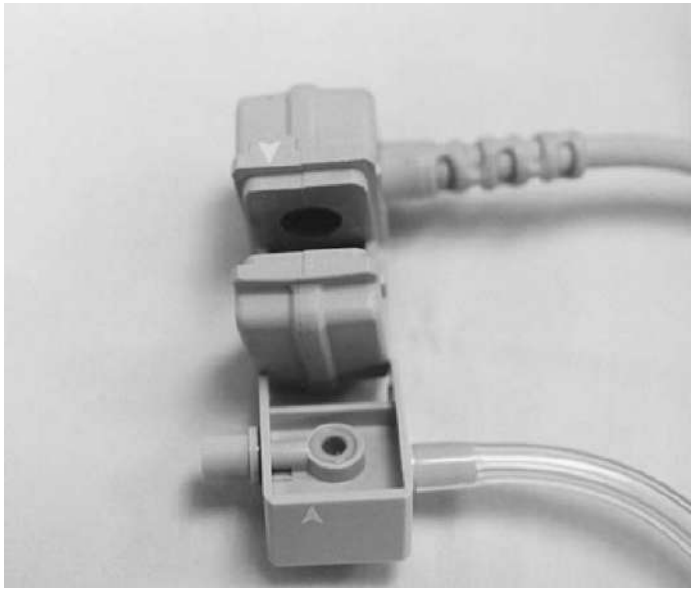


Figure 22.5 Mainstream infrared CO_2 analyzer used as a diverting monitor. Gas is drawn through the cuvette by a pump.

Devices

Face Mask

A face mask has a relatively large dead space relative to tidal volume, making it more difficult to obtain accurate end-tidal values. Figure 22.7 shows a mask with a sampling line for CO_2.

A sampling catheter can also be attached to the upper lip or placed in the patient's nares or the lumen of an oral or nasopharyngeal airway under the mask (18). With a breathing system, the sampling tube is most often attached to a component between the mask and the breathing system (Fig. 22.8), or the

sampling tube may be inserted through the right-angle connector that attaches to the mask (19,20).

Figure 22.6 Water trap. This should be emptied periodically to prevent water from entering the monitor.

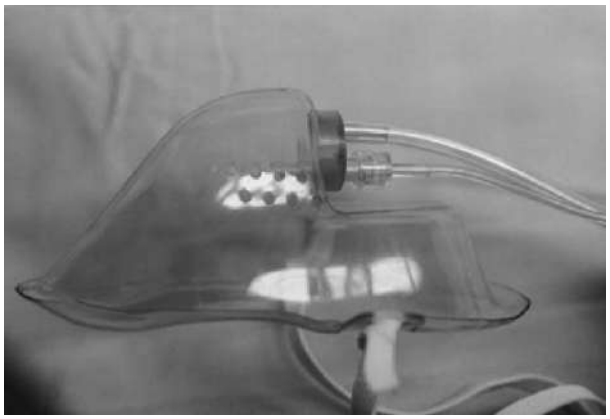


Figure 22.7 Face mask with lines for oxygen administration and gas sampling.

Tracheal Tube

To measure both inspired and exhaled gases, the sampling site must be between the patient and the breathing system. Most disposable breathing systems and heat and moisture exchangers (HMEs) have built-in sample ports (Fig. 22.8).

The sampling site should be away from the fresh gas port. When a Mapleson breathing system is used, continuous inflow of fresh gas that is close to the sampling site can cause erroneous readings and an abnormal waveform (Fig. 22.37).

Tracheal tubes that incorporate a sampling lumen that extends to the middle or patient end of the tube are available (Chapter 19). Tracheal tube connectors with an attachment or hole for a sampling tube are available or can be created (21). These may result in measurements that more closely approximate alveolar values, especially in small patients and with breathing systems in which the fresh gas flow can mix with exhaled gases (22,23,24,25,26).

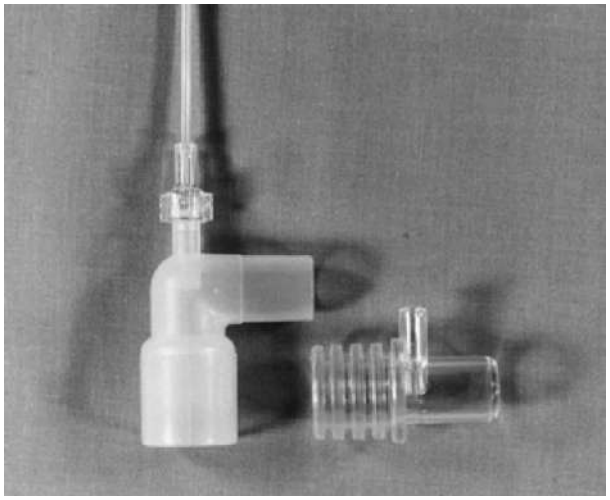


Figure 22.8 Ports for gas sampling in breathing system components.

Supraglottic Device

With a supraglottic airway device, a sampling tube can be inserted through the connector (27,28). The preferred sampling site is the distal end of the shaft (29,30), but in most patients, sampling at the connection to the breathing system will result in satisfactory readings (31,32,33,34,35).

A sampling tubing may be inserted into a nasal airway (36,37,38).

Oxygen Supplementation Devices

A relatively new device, the OxyArm, allows simultaneous administration of oxygen and carbon dioxide monitoring (39,40). It consists of a headset that traverses across the top of the head, oxygen supply and CO_2 sampling lines attached to an adjustable boom and a disposable arm diffusor. It can be used to administer oxygen and monitor CO_2 in both nose and mouth breathers. A nasal cannula can be modified to accept a sampling tubing (39,40,41,42,43,44,45,46,47,48,49,50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67). They are available in several configurations (Figs. 22.9, 22.10). Mouth breathing, airway obstruction, and oxygen delivery through the ipsilateral nasal cannula can affect accuracy (68). Caution should be observed in adapting a nasal cannula; a piece may become dislodged and present a choking hazard (69).

A plastic oxygen mask may be fitted with a sampling port (39,70) (Fig. 22.7). Alternatively, the sampling tube may be connected to the mask outlet (71), inserted through a vent hole (42,57,72,73,74,75,76) or a slit in the mask (77), or slipped under the mask and attached near the nostrils (37,78,79,80).

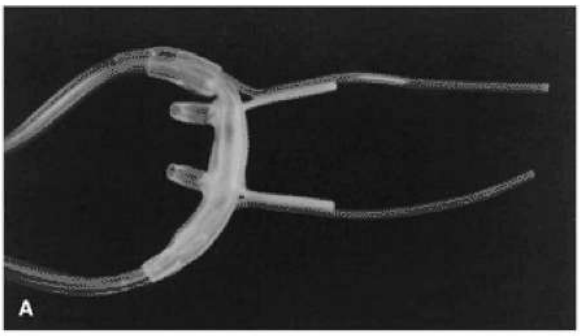
Jet Ventilation

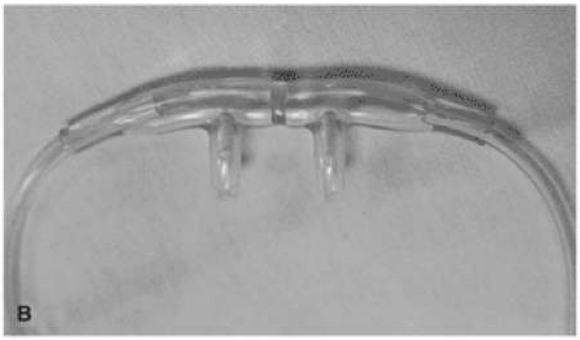
During jet ventilation, an injector incorporating a sampling lumen (81,82,83,84) or a sampling tube placed in the airway (85,86) may be used. The ventilatory frequency may need to be lowered to measure the end-tidal CO_2 (83,87,88).

Other

The end of a sampling line can be placed in front of or inside the patient's nostril (89,90) or a nasopharyngeal airway (91). If the patient is a mouth breather, the sample line can be placed in front of the mouth or in the nasopharynx (89,92) or hypopharynx (93,94). A catheter can be placed in the trachea after extubation for CO_2 monitoring (95). A bite block can be modified to accommodate a sampling line (96). A sampling line can be placed over a tracheostomy stoma (97).

Optimal placement should be determined by the CO_2 waveform. Mucosal irritation, catheter blockage, and mechanical interference sometimes cause problems.





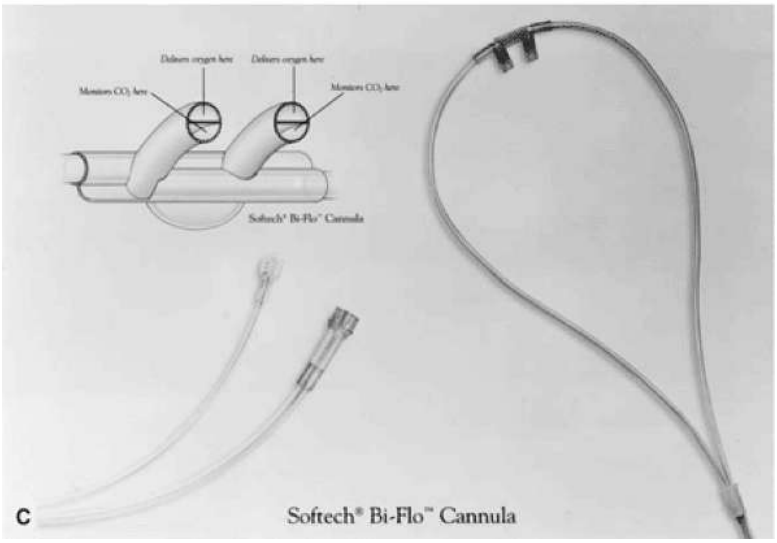


Figure 22.9 Devices for simultaneous administration of oxygen and gas sampling. **A:** This device is designed for patients who are predominantly mouth breathers. The longer oral sampling prongs can be cut and shaped to suit individual patients. (Courtesy of Biochem International, Inc.) **B:** One prong is used for administration of oxygen and one for gas sampling. There is a septum between the two prongs. **C:** With this device, the two prongs are divided so that oxygen is delivered and gas is sampled through each prong.

Advantages

1. Calibration and zeroing are usually automatic. Occasional calibration is necessary but is usually easily accomplished.
2. The added dead space is minimal.
3. The potential for cross contamination between patients is low.
4. Depending on the technology being used, several gases can be measured simultaneously. This allows automatic correction for nitrous oxide and/or oxygen.
5. The sampling port can be used to administer bronchodilators (98) (Chapter 7).
6. These devices can be used when the monitor must be remote from the patient (e.g., during magnetic resonance imaging [MRI]) (99,100).

Figure 22.10 This device is used for CO_2 sampling in nonintubated patients who are either exhaling by mouth or nose.

Disadvantages

1. Problems with the sampling system (leaks, sampling tube obstruction, or failure of the aspirator pump) can occur. Particulate matter, blood, secretions, or water can obstruct the tubing (102). The sampling line can be connected to the wrong place (103,104). If there is a leak in the sample line, air will be added to the sample. This will dilute the sample and reduce the values of end-tidal CO_2 and anesthetic agents (105,106,107) (Fig. 22.29). The sampling tube can kink, but this can be prevented by using an elbow connector near the attachment to the patient end (108).
2. The aspirated gases must be either routed to the scavenging system or returned to the breathing system. If scavenging is employed, the fresh gas flow may need to be increased to compensate for the gas removed or negative pressure will be created in the breathing system (109).
3. In some diverting monitors, room air used in the calibration process is added to the gas exiting the monitor. If this air is returned to the breathing system, it will create problems during closed circuit anesthesia.
4. Some delay time is unavoidable.
5. A supply of calibration gas must be available.
6. A number of disposable items (adaptors and catheters) must be used.
7. There may be deformation of the waveform and erroneously low CO_2 readings from the fresh gas dilution (Fig. 22.37).
8. Compared with mainstream monitoring, sidestream measurements produce more variable differences between arterial and end-tidal CO_2 levels (110).

Technology

There are a number of different technologies available to measure respiratory and anesthetic gases.

Infrared Analysis

Infrared analysis is by far the most common technology in use today (3,111,112).

Technology

Infrared (IR) analyzers are based on the principle that gases with two or more dissimilar atoms in the molecule (nitrous oxide, CO_2, and the halogenated agents) have specific and unique infrared light absorption spectra. Since the amount of infrared light absorbed is proportional to the concentration of the absorbing molecules, the concentration can be determined by comparing the infrared light absorbance in the sample with that of a known standard. The nonpolar molecules of argon, nitrogen, helium, xenon, and oxygen do not absorb infrared light and cannot be measured using this technology.

There are two general types of infrared technology available today.

Blackbody Radiation Technology

The most commonly used infrared technology utilizes a heated element called a blackbody emitter as the source of infrared light (113). This produces a broad infrared spectrum. The majority of the emitted radiation is redundant and must be removed. Filters block radiation that is outside the desired range. This method cannot remove the radiation that falls between discrete absorbing lines because of the continuous emission nature of the blackbody. The optical detectors must be calibrated to recognize only infrared radiation that is modulated at a certain frequency by using a spinning chopper wheel.

The analyzer selects the appropriate infrared wavelength, using an individual filter or a filter wheel to maximize absorption by the selected gas at its peak wavelength and to minimize absorption by other gases and vapors that could interfere with measurement of the desired component. Some older infrared units are equipped with a dial or switch to select the anesthetic agent being measured, while others require a different filter and scale to measure each agent. Most units in use today can recognize the agents that can be monitored with this technology. After the sensor detects the transmitted infrared energy, an electrical signal is produced and amplified, and the concentration is displayed.

Monitors that identify and quantify halogenated agents use a separate chamber to measure absorption at several wavelengths. Typically, these are single-channel, four-wavelength infrared filter photometers. There is a filter for each anesthetic agent and one to provide a

baseline for comparison. Each filter transmits a specific wavelength of infrared light, and each gas absorbs differently in the selected wavelength bands (114).

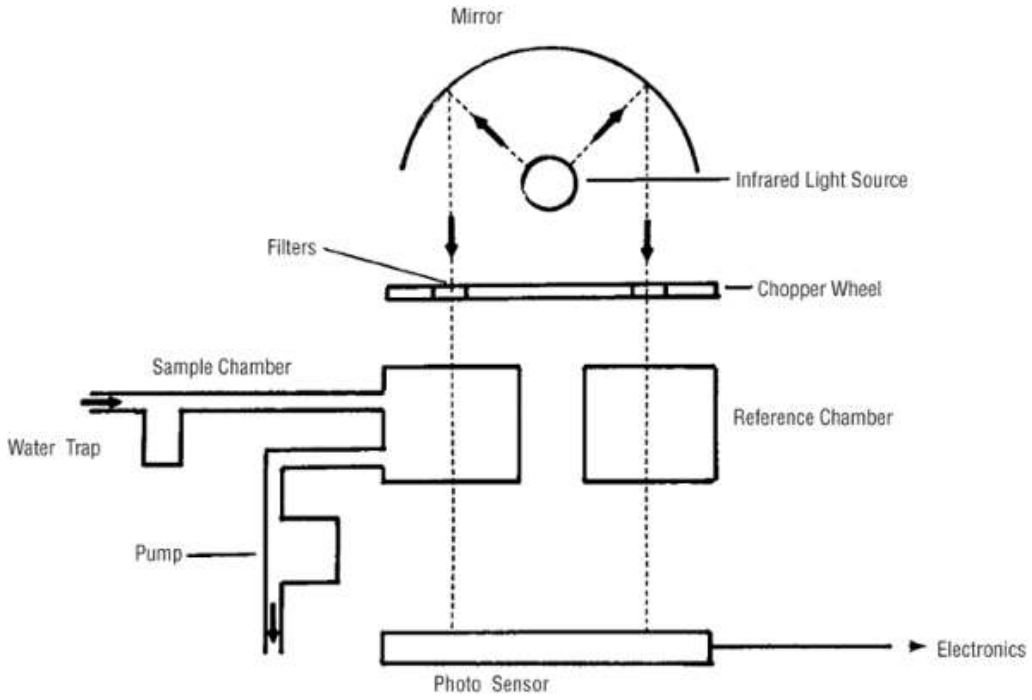


Figure 22.11 Sidestream optical infrared analyzer. A beam of infrared light is at one end, and a photodetection device is at the other. The chopper wheel contains several filters, which are divided into sections that will allow passage of only the frequencies most readily absorbed by the gases to be measured. The filtered and pulsatile infrared light is directed through both the sample chamber and a reference chamber with no absorption qualities. The amount of infrared light absorbed at each frequency depends on the gas level in the sample chamber.

Most infrared instruments have an accuracy of ยฑ0.2% for CO_2 concentrations over the range of 0% to 10% and ยฑ2.0% for nitrous oxide concentrations from 0% to 100%. For typical halogenated agents, the accuracy is ยฑ0.4% over a range of 0% to 5% (115). Most investigators believe that these monitors are sufficiently accurate for clinical purposes (116,117,118), although they tend to underestimate the inspired level and overestimate end-tidal values at high respiratory rates.

Diverting

Figure 22.11 shows a diverting (side-stream) infrared analyzer. Infrared light is continuously focused on a spinning (chopper) wheel. The wheel has holes with filters specially selected for the gases to be measured. The gas to be measured is pumped continuously through a measuring chamber. The filtered and pulsed light is passed through the sample chamber and also through a reference chamber with no absorption characteristics. The light is then focused on an infrared photosensor. The amount of light absorbed by the sample gas is proportional to the partial pressures of gases whose infrared light absorption patterns correspond to the wavelengths selected by the filters on the chopper wheel. The changing light levels on the photosensor produce changes in the electrical current that runs through it. Rotating the wheel thousands of times per minute provides hundreds of readings for each respiratory cycle. For practical purposes, the waveform on the display is continuous.

Monochromatic sidestream optical infrared analyzers use one wavelength to measure potent inhalational agents and are unable to distinguish between agents or to detect a mixture of agents (119). When such an analyzer is used, the clinician must select which agent is to be monitored. If an incorrect agent is selected, incorrect values will be reported (120,121,122). Polychromatic infrared analyzers use multiple wavelengths to both identify and quantify the various agents (123). This eliminates the need for the user to select the agent to be monitored and allows a mixture of agents to be detected.

Most sidestream analyzers have a fixed sampling flow rate, although some permit selection of the flow rate. The measuring cell is calibrated to zero by using gas that is free of the gases of interest (usually room air) and to a standard level by using a calibration gas mixture.

Nondiverting

With a nondiverting (mainstream) CO_2 monitor, the gas stream passes through a chamber (cuvette) with two windows that are transparent to infrared light (Fig. 22.2). The cuvette is placed between the breathing system and the patient. The sensor, which houses both the light source and detector, fits over the cuvette. To prevent water condensation, the sensor is heated slightly above body temperature. Infrared light shines through the window on one side of the adaptor, and the sensor receives the light on the opposite side. After passing through the sample

chamber, the light goes through three ports in a rotating wheel, which contains (a) a sealed cell with a known high CO_2 concentration,(b) a chamber vented to the sensor's internal atmosphere, and (c) a sealed cell containing only nitrogen (Fig. 22.2B). The radiation then passes through a filter that screens the light to the correct wavelength to isolate CO_2 information from interfering gases and onto a photodetector. The signal is amplified and sent to the display module.

Calibration is performed by using two sealed cells in a plastic unit that attaches to the control unit (Fig. 22.2C). It is shaped so that the sensor can clip over either cell. The low calibration cell contains 100% nitrogen, while the high cell contains a known partial pressure of

CO_2. Corrections for nitrous oxide and/or oxygen must be entered manually.

The sensor may become dislodged from the cuvette. If it is completely dislodged, no waveform will be seen. If it is slightly dislodged (Fig. 22.4), the readings may be incorrect although the waveform appears normal (9,10). Condensed water, secretions or blood on the cuvette windows will interfere with light transmission and cause erroneous readings (124).

Microstream Technology

Microstream technology utilizes laser-based technology to generate infrared emission that precisely matches the absorption spectrum of CO_2 (113). It utilizes a smaller sample cell and a low flow rate (50 mL/minute).

The emission source is a glass discharge lamp without an electrode that is coupled with an infrared transmitting window. Electrons that are generated by a radio frequency voltage excite nitrogen molecules. Carbon dioxide molecules are then excited by collision with the excited nitrogen molecules. As the excited CO_2 molecules drop back to their ground state they emit the signature wavelength of CO_2.

The emission is split so that one part is directed to the main optical detector via the gas sample cell while the other part passes through a reference detector. This channel is used as a continuous reference detector, compensating for changes in infrared output.

The infrared source is electronically modulated so that

measurements are made every 25 msec. This provides a rapid response time. The amplitude of the signals received by the detector depends on the amount of radiation absorbed from the gas sample. The absorbed radiation is proportional to the CO_2 concentration.

The airway adaptor has three channels with narrow hydrophobic openings, each facing a different direction. This permits the adaptor to be used in any orientation and prevents the sample line from being occluded by water or secretions. The sample line has a hydrophobic filter. A water trap is not necessary.

Because of the low sample flow and small sample cell, this technology is useful for measuring CO_2 in very small patients, high respiratory rates, low-flow applications, and unintubated patients. Readings are not affected by high concentrations of oxygen or anesthetic gases.

Advantages of Infrared Analysis

Multigas Capability

Infrared analyzers are capable of measuring CO_2, nitrous oxide, and all of the commonly used potent volatile agents.

Volatile Agent Detection

Although monochromatic analyzers are unable to identify anesthetic agents and mixtures of agents, most newer models provide agent detection and can detect and quantify mixtures. Analyzers handle mixtures of agents in different ways. They may give a display saying that there is a mixture of agents or may compensate for the additional agent.

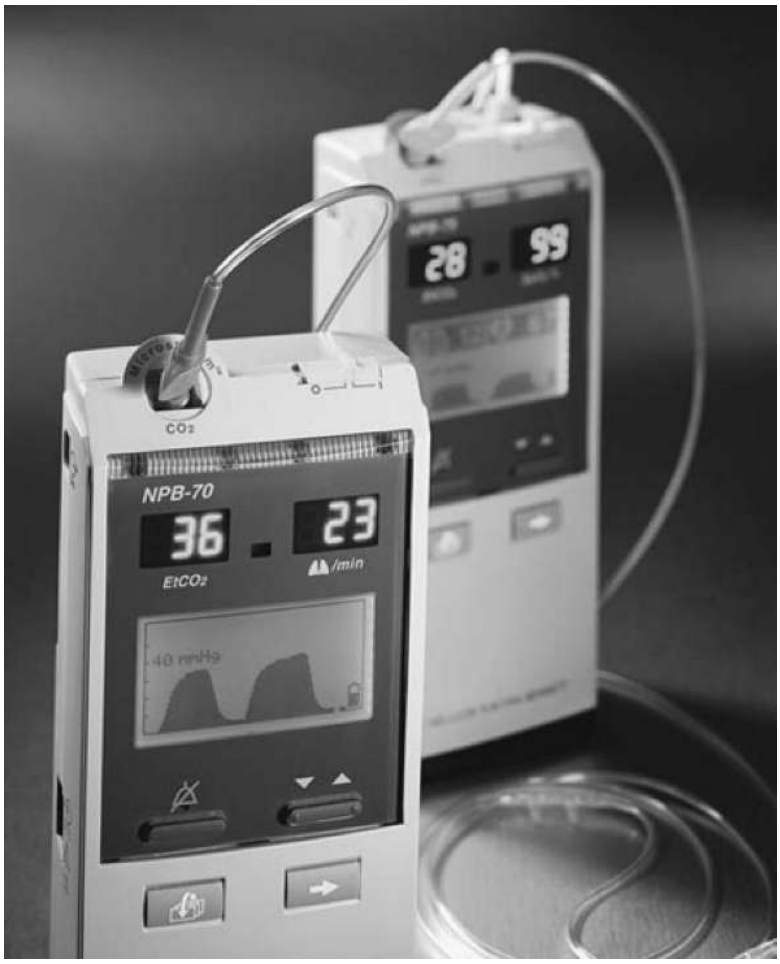


Figure 22.12 Microstream infrared analyzer. Small handheld device. (Picture courtesy of Oridion Medical.)

No Need to Scavenge Gases

After measurement, the gases can be returned to the breathing system, if desired.

Portability

The units (Fig. 22.12) are small, compact, and lightweight. They may be incorporated into an anesthesia machine or physiologic monitor and be used in remote areas of the facility.

Quick Response Time

The response time is fast enough to measure both inspired and

exhaled concentrations. Response times for anesthetic agents and nitrous oxide are longer than for CO_2 (115).

Short Warm-up Time

The warm-up time is short. The instruments do not need to be kept in a standby mode.

Convenience

Although early units required a complicated calibration with test gases with each use, newer units only require periodic calibration with a standardized gas mixture.

Lack of Interference from Other Gases

Argon or low concentrations of nitric oxide do not interfere with volatile agent monitoring by infrared analyzers (125,126). Infrared spectrometry is accurate in the presence of 5% CO_2 (127).

Detecting Anesthetic Breakdown

Agent-identifying infrared analyzers may provide warning of desflurane breakdown that produces carbon monoxide by displaying wrong or mixed agents (128).

Disadvantages

Oxygen and Nitrogen not Measured

Oxygen and nitrogen cannot be measured by infrared technology.

Gas Interference

While oxygen is not absorbed by infrared light, it causes broadening of the CO_2 absorption spectra, which results in lower CO_2 readings (115). In a typical infrared CO_2 analyzer, 95% oxygen causes a 0.5% decline in measured CO_2 (101). Some units have a user-actuated electronic offset for oxygen.

There is some overlap of the CO_2 and nitrous oxide infrared absorption peaks so that nitrous oxide can cause falsely high CO_2 readings, with an increase of 0.1 to 1.4 torr per 10% nitrous oxide. Most infrared analyzers that measure both CO_2 and

nitrous oxide automatically correct for nitrous oxide's effect on the CO_2 reading. Some require the user to indicate when nitrous oxide is present.

If the analyzer is set to measure a volatile agent different from that present in the gas mixture being analyzed, CO_2 and nitrous oxide as well as agent readings will be incorrect (129). A mixture of agents can cause erroneous readings (130). Desflurane may disturb the infrared CO_2 sensor so that it reads higher-than-expected concentrations (131).

Helium in the gas mixture may cause the infrared analyzer to underestimate the concentration of CO_2 (132).

Inaccuracy from Other Substances

Ethanol, methanol, isopropanol, diethyl ether, acetaldehyde, or acetone in sampled gases can cause spuriously high volatile agent readings (122,133,134,135,136,137,138). Ether that is used to soak gauze that packed a prosthesis can cause a monitor to incorrectly identify isoflurane (139). Polychromatic analyzers are less affected, and some display a warning that the interfering agent has been detected (118,123,140,141). Some analyzers detect halogenated propellants as anesthetic gases (142,143,144,145,146).

Methane, which can accumulate during low-flow anesthesia, causes inaccuracies with monitors that use the 3.3 ยต๓ wavelength range (147,148).

Interference from Water Vapor

Water vapor absorbs infrared light at many wavelengths and will cause increased CO_2 and volatile agent readings (115). Monitors use special tubing, water traps, filters, and/or hydrophobic membranes to minimize this. Water that gets into the monitor can cause expensive or irreversible damage (102).

Slow Response Time

With rapid respiratory rates, the response time may be too slow to measure inspired and end-tidal levels of volatile agents accurately (149).

Radio Frequency Interference

Handheld two-way radios in use near an infrared analyzer may cause CO_2 readings to be increased (150).

Difficulty Adding New Volatile Agents

As new volatile agents are added to the anesthetic armamentarium, these monitors need to be revised to accept the new agents. This revision may require anything from a software change to an expensive change to the analyzing bench. In some cases, a correction factor can be used to convert one channel of a monitor to monitor another agent (151). In some cases, it will be necessary for the user to manually select the agent being used (152,153).

Paramagnetic Oxygen Analysis

When introduced into a magnetic field, some substances locate themselves in the strongest portion of the field (154,155). These substances are termed *paramagnetic*. Oxygen is the only paramagnetic gas that is important in anesthesia.

When a gas that contains oxygen is passed through a switched magnetic field, the gas will expand and contract, causing a pressure wave that is proportional to the oxygen partial pressure.

To obtain a high degree of accuracy, it is necessary to compare the pressure in the gas sample with a reference signal that is obtained by using air or oxygen. When air is used as a reference gas, nitrogen may accumulate in the breathing system during closed-circuit anesthesia if the reference gases are redirected to the anesthesia circuit. If oxygen is used as the reference gas, the accumulation of nitrogen is significantly reduced (156).

A paramagnetic oxygen analyzer is shown in Figure 22.13. Reference and sample gases are pumped through the analyzer. The two gas paths are joined by a differential pressure or flow sensor. If the sample and reference gases have different partial pressures of oxygen, the magnet will cause their pressures to differ. This difference is detected by the transducer and converted into an electrical signal that is displayed as oxygen partial pressure or volumes percent.

The short rise time allows both inspired and end-tidal oxygen levels to be measured even at rapid respiratory rates. Many monitors combine infrared analysis of CO_2,

volatile anesthetic agents, and nitrous oxide with paramagnetic oxygen analysis in the same monitor using the same diverted gas (Fig. 22.1). This allows most gases of interest to be

monitored by a single monitor.

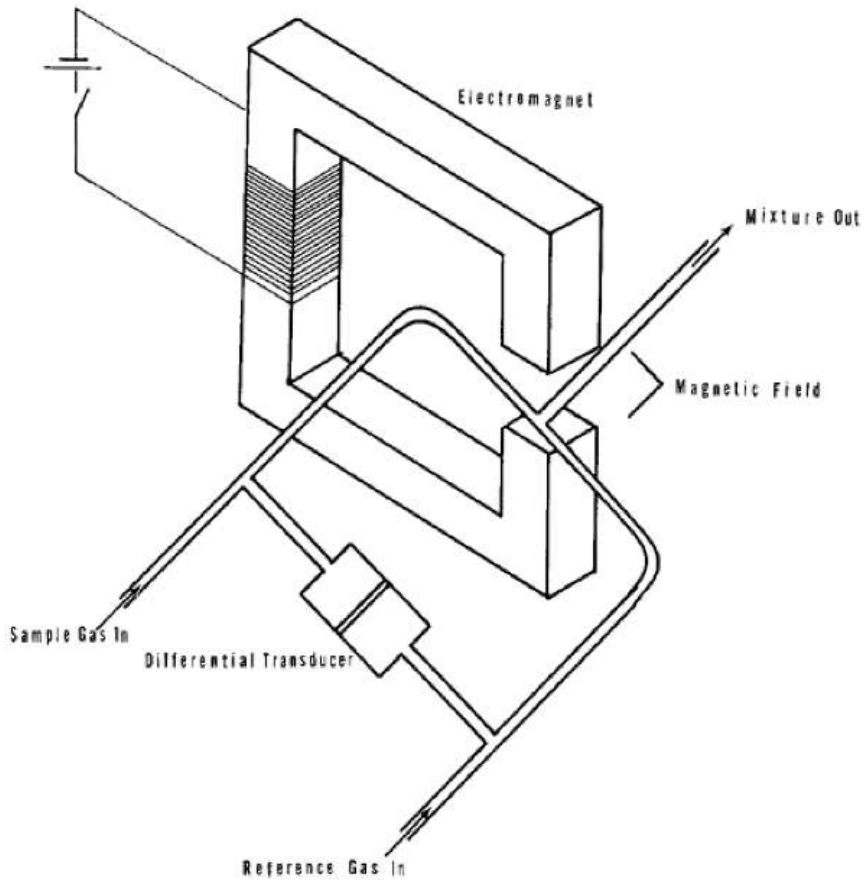


Figure 22.13 Paramagnetic oxygen analyzer. A reference gas of known or no oxygen content and the gas whose oxygen level is to be measured are pumped through the analyzer and converge into a tube at the outlet. The two gas paths are joined at their midpoints by a differential pressure or flow sensor. The magnet is switched on and off at a rapid rate. Because the reference and sample gases have different oxygen levels, the pressures in the paths will differ. The pressure difference is detected by the sensor.

If the sample gas from the analyzer is returned to the breathing system and air was used as a reference gas, it will dilute the other gases and cause an increase in nitrogen (101). This is especially a problem during closed-circuit anesthesia. If oxygen is used as the reference gas, the accumulation of nitrogen is significantly reduced (156). Desflurane may disturb the

paramagnetic oxygen sensor so that it reads higher than expected (131). Failure of a paramagnetic oxygen analyzer has been reported (157).

Electrochemical Oxygen Analysis

An electrochemical oxygen analyzer consists of a sensor, which is exposed to the gas being analyzed, and the analyzer box, which contains the electronic circuitry, display, and alarms (Fig. 22.14). The sensor contains a cathode and an anode surrounded by electrolyte. The gel is held in place by a membrane that is nonpermeable to ions, proteins, and other such materials, yet is permeable to oxygen. The membrane should not be touched, because dirt and grease reduce its usable area. In most cases, the sensor is placed in the inspiratory limb of the breathing system.

Most of these analyzers respond slowly to changes in oxygen pressure, so they cannot be used to measure end-tidal concentrations. Some newer sensors can analyze oxygen quickly enough to measure inspired and exhaled concentrations.

Technology

Galvanic Cell (Fuel Cell, Microfuel Cell)

Oxygen diffuses through the sensor membrane and electrolyte to the cathode, where it is reduced, causing a current to flow (114,158,159,160). The rate at which oxygen enters the cell and generates current is proportional to the partial pressure of oxygen in the gas outside the membrane. For convenience, however, the display scale is usually marked in percent oxygen. A gain control allows the analyzer to be calibrated with gas with a known partial pressure of oxygen (usually air).

A galvanic cell sensor is shown in Figure 22.15. It consists of an anode and two cathodes surrounded by electrolyte. The cathode acts as the sensing electrode and is not consumed. The hydroxyl ions formed there react with the lead anode, forming lead oxide. The anode is gradually consumed.

Cathode: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

Anode: $4OH^- + 2Pb \rightarrow 2PbO + 2H_2O + 4e^-$

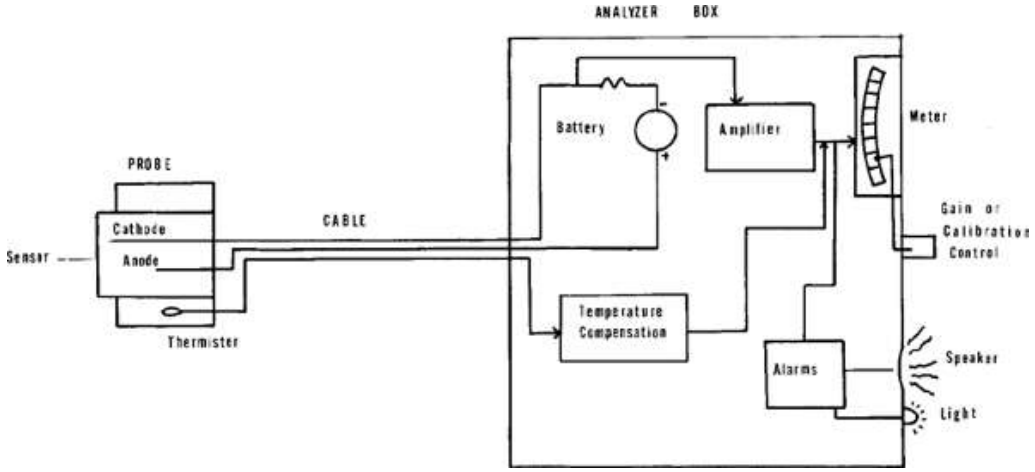


Figure 22.14 Electrochemical oxygen analyzer. The sensor is connected by a cable to the analyzer box, which contains the meter, alarms, and controls. A thermistor compensates for changes in oxygen diffusion caused by temperature. An amplifier is present in the polarographic analyzer. Those monitors with manual calibration require adjustment of a gain control until the correct reading is obtained for a standard oxygen concentration. Those with automatic calibration simply require a button to be pressed in the presence of a gas of standard concentration (usually air). This puts the monitor into calibration mode, and it returns to normal readings automatically when calibration is complete.

Since there are two cathodes, two voltages are generated. These are compared, and if a certain amount of difference is present, the operator is prompted to check the cell. Because the current is strong enough to operate the meter, a separate power source is not required to operate the analyzer. A power source (either battery or mains current) is required to power the alarms.

The chemical reaction is temperature dependent. In order to compensate for temperature differences, a temperature-dependent resistor (thermistor) may be connected in parallel with the sensor.

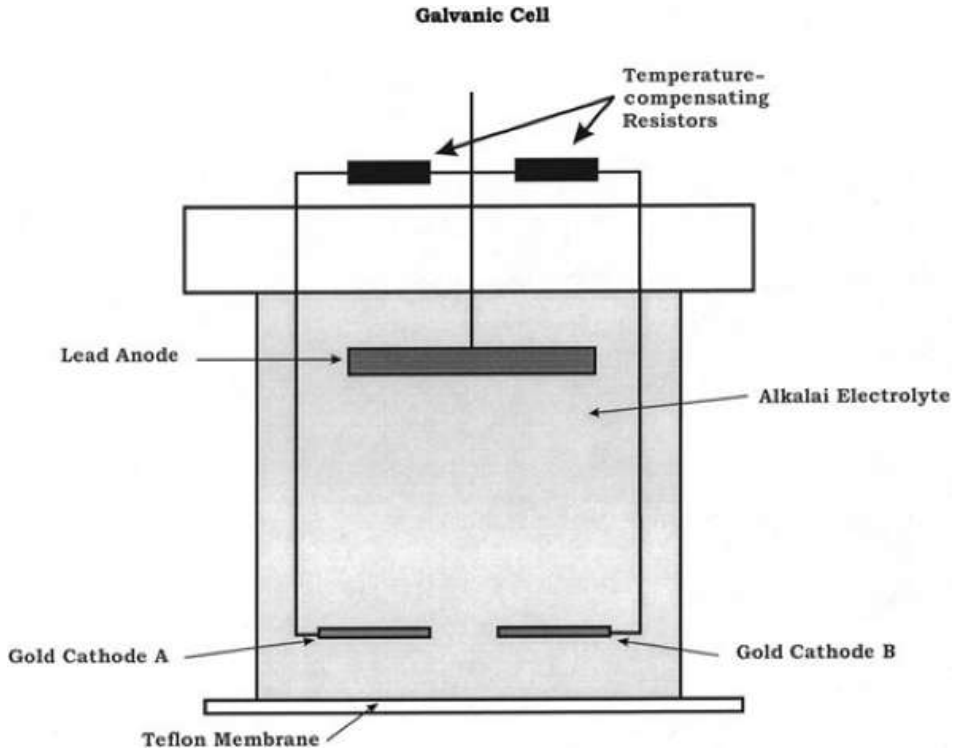


Figure 22.15 Galvanic cell sensor. The membrane is permeable to gases but not to liquids. At the cathode, oxygen molecules are reduced to hydroxide ions. At the anode, hydroxide ions give up electrons. An electron flow between the anode and cathode is generated, which is directly proportional to the partial pressure of oxygen in the sample gas.

Figure 22.16 The life of a galvanic (fuel cell) electrochemical oxygen analyzer can be prolonged by leaving it exposed to room air when not in use.

The sensor comes packaged in a sealed container that does not contain oxygen. Its life span begins when the package is opened. Its useful life is cited in percent hours, which is the product of hours of exposure and oxygen percentage. If it is exposed to a high oxygen concentration, its life expectancy will be decreased. Sensor life can be prolonged by removing it from the breathing system and exposing it to air when not in use (Fig. 22.16). Galvanic sensors require no membrane or electrolyte replacement. The whole sensor cartridge must be replaced when it becomes exhausted (Fig. 22.17).

Polarographic Electrode

A polarographic (Clark electrode) sensor is shown in Figure 22.18. It consists of an anode, a cathode, an electrolyte, and a gas-permeable membrane. There is a power source (battery or alternating current [AC] line) for inducing a potential between the anode and the cathode.

Oxygen molecules diffuse through the membrane and electrolyte. When a polarizing voltage is applied to the cathode, electrons combine with the oxygen molecules and reduce them to hydroxide ions. A current that is proportional to the oxygen partial pressure in the sample flows between the anode and cathode.

Polarographic sensors may be either preassembled disposable cartridges or units that can be disassembled and reused by changing the membrane and/or electrolyte.

Use

Calibration

Calibration should be performed daily before use and at least every 8 hours after that. Some instruments remind the user when calibration is needed and will not give a reading until calibration is performed (Fig. 22.19). The calibration can be checked by exposing the sensor to room air and verifying that it indicates approximately 21% oxygen.

Checking the Alarms

The sensor should be put in room air and the low oxygen alarm set above 21%. The visual signal should flash, and the audible alarm should sound. If the unit has a high oxygen alarm, the setting for that should be moved below 21%. Both visual and audible signals should be activated. If the visual signal fails or the audible signal is weak, the batteries should be replaced and the alarms rechecked. If this fails to remedy the problem, the unit should not be used.

Figure 22.17 Galvanic cell sensor. The entire sensor must be replaced when it becomes exhausted.

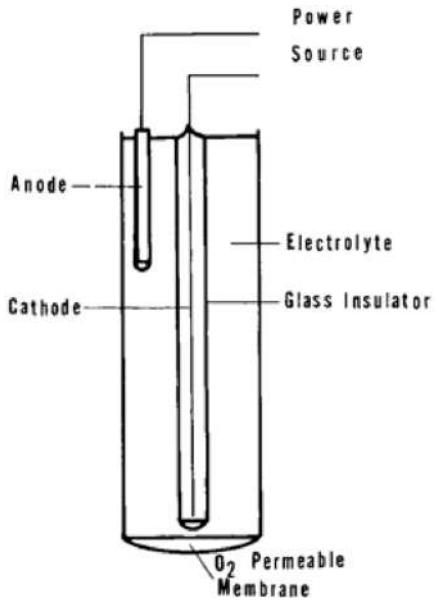


Figure 22.18 Polarographic sensor. Oxygen diffuses through the membrane and electrolyte to the cathode. When a polarizing voltage is applied to the cathode, the oxygen molecules are reduced to hydroxide ions. The current flow between cathode and anode will be proportional to the partial pressure of oxygen. (Redrawn from Bageant RA. Oxygen analyzers. Respir Care 1976;21:415.)

Placement in the Breathing System

Sites for placing the sensor in breathing systems are discussed in Chapter 9. The sensor service life of some galvanic cell analyzers is reduced by exposure to CO_2, so locating the sensor on the inspiratory side of the system may be preferable. The sensor should be upright or tilted slightly to prevent moisture from accumulating on the membrane. The junction between the cable and the sensor should not be under strain.

Setting Alarms Limits

The low oxygen alarm should be set a little below the minimum and the high oxygen level alarm a little above the maximum acceptable concentrations. There should be places on the anesthesia record for recording the alarm set points and oxygen percentage.

Advantages

Easy to Use

Electrochemical oxygen analyzers are dependable, accurate, and user-friendly. Galvanic analyzers may be more reliable than polarographic analyzers (161).

Low Cost

These instruments cost less than other means of oxygen analysis.

Compact

Compared with other technologies for measuring oxygen, the electrochemical analyzer takes up little space.

No Effect from Argon

Argon does not affect galvanic cell monitoring (126).

Disadvantages

Maintenance

While maintenance on newer models has been simplified, some instruments need frequent membrane and electrolyte changes. Polarographic monitors require more maintenance than the galvanic cell monitors (161).

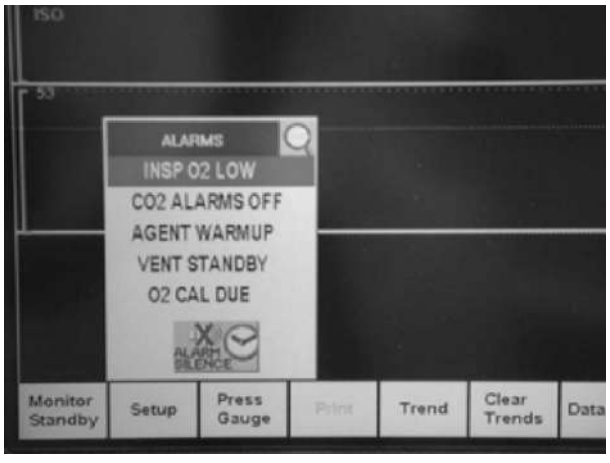


Figure 22.19 The display on the anesthesia machine provides a reminder that the oxygen analyzer needs to be calibrated.

Calibration

These instruments need to be calibrated before use each day and at least every 8 hours.

User Enabling

Instruments that are not an integral part of anesthesia machines need to be turned on by the user.

Slow Response Time

Most of these analyzers cannot be used to measure end-tidal oxygen.

Piezoelectric Analysis

Technology

The piezoelectric method uses vibrating crystals that are coated with a layer of lipid to measure volatile anesthetic agents (158,162,163,164) (Fig. 22.20). When exposed to a volatile anesthetic agent, the vapor is adsorbed into the lipid. The resulting change in the mass of the lipid alters the vibration frequency. By using an electronic system consisting of two oscillating circuits, one of which has an uncoated (reference) crystal and the other a coated (detector) crystal, an electric signal that is proportional to the vapor concentration is generated. Piezoelectric analyzers are diverting devices. Some piezoelectric-based units have a separate nondispersive infrared sensor to differentiate inspiration and expiration.

Advantages

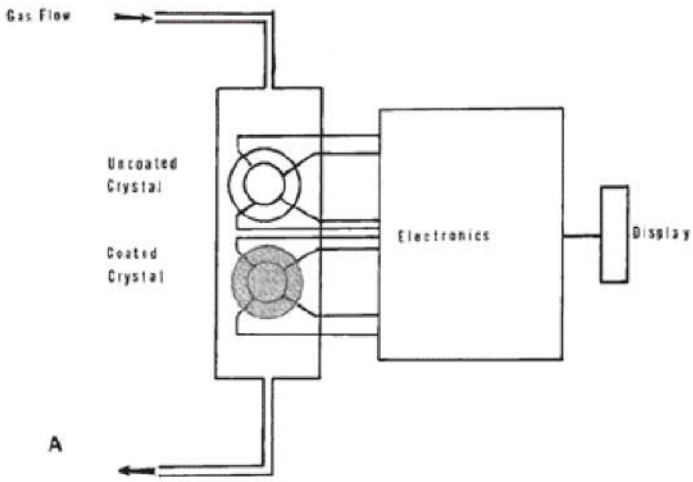
Accuracy

Investigations show an accuracy of better than 0.1% (162,163). Water vapor and nitrous oxide affect the reading, but the worst-case interference is less than 0.1%. The analyzer does not give artifactual results in the presence of aerosol propellants that are used to administer bronchodilators (142).

Fast Response Time

These analyzers can measure inspired and expired levels of

halogenated agents.



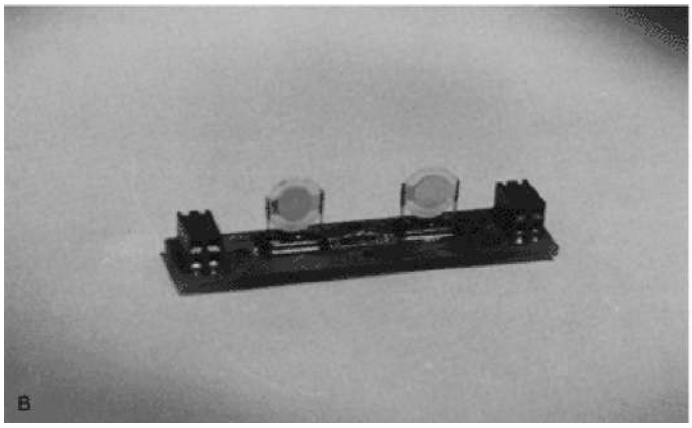


Figure 22.20 Piezoelectric analyzer. **A:** One vibrating crystal is coated with lipid, and the other is uncoated. By comparing the vibration frequencies of the crystals, the level of anesthetic agent in the gas being analyzed can be measured. **B:** Piezoelectric crystals. (Courtesy of Biochemical International, Inc.)

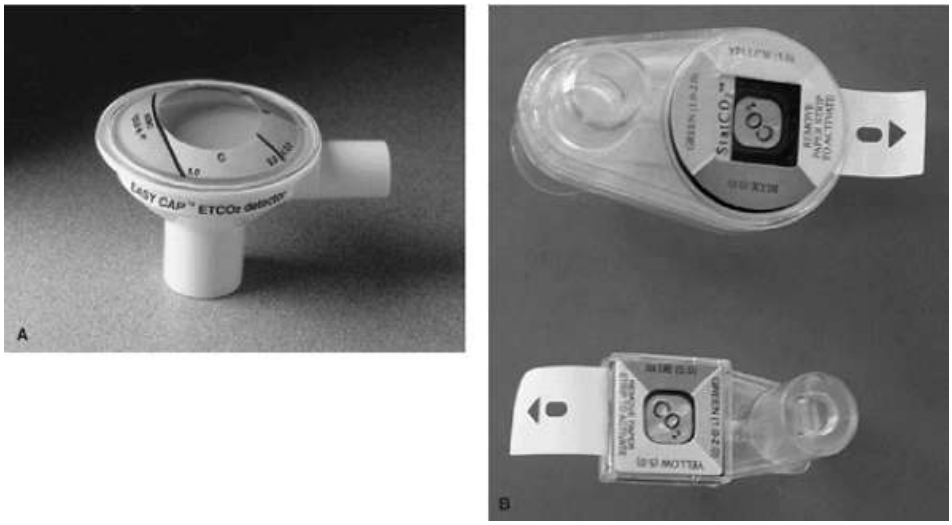


Figure 22.21 Colorometric carbon dioxide detectors. A color code around the outside provides a reference. **A:** Adult size. The device is supplied with caps that must be removed before use. (Reprinted by permission of Nellcor Puritan Bennett, Inc., Pleasanton, CA.) **B:** Adult and pediatric versions. The paper strip must be removed to activate the device.

No Need for Scavenging

Because the agents are not altered, the gas removed can be returned to the breathing system.

Short Warm-up Time

The warm-up period is shorter than with an infrared analyzer.

Compact

These units are small.

Disadvantages

Only One Gas Measured

This analyzer cannot measure oxygen, CO_2, nitrogen, or nitrous oxide.

No Agent Discrimination

This device cannot discriminate between agents. The user must tell the monitor which agent is being measured. If the wrong

agent is selected, the reading can be in error by as much as 118% (162).

Inaccuracy with Water Vapor

Water will cause errors with the piezoelectric monitor. In one case, the lines to the pump were reversed so that water vapor was removed after its passage rather than before (165). This caused erroneously high readings.

Chemical Carbon Dioxide Detection

A chemical (colorimetric) detector (Fig. 22.21) consists of a pH-sensitive indicator enclosed in a housing (3,166,167,168,169). When the indicator is exposed to carbonic acid that is formed as a product of the reaction between CO_2 and water it becomes more acidic and changes color. During inspiration, the color returns to its resting state unless it is used with a breathing system that allows rebreathing.

The inlet and outlet ports are 15 mm, so the device can be placed between patient and the breathing system or resuscitation bag. With the Mapleson F system (Chapter 8), it may be placed between the expiratory limb and the bag (170). Pediatric versions are available (Fig. 22.21B).

Technology

Hygroscopic

The hygroscopic CO_2 detector contains hygroscopic filter paper that is impregnated with a colorless base and an indicator that changes color as a function of pH. The filter paper is visible through a clear window. The color chart on the dome was designed to be read under fluorescent light. An auxiliary color chart that is included in each package should be consulted if other lighting is encountered. A purple or mauve (A) color indicates a low CO_2 (<0.5%) level. A beige (B) color indicates a moderate level (0.5% to 2%). A yellow color

(C) indicates a high level (>2%) (171,172). The mean minimum concentration of CO_2 needed to produce a color change is 0.54%, with a range from 0.25% to 0.60% (169).

The hygroscopic CO_2 detector's useful life may last from a few minutes to several hours, depending on the humidity of the gas being monitored (173). Reducing the relative humidity of exhaled

gases by using an HME to trap moisture before it reaches the device prolongs the detector's useful life.

Hydrophobic

A hydrophobic indicator in a colorimetric device shows a color change from blue to green to yellow when exposed to CO_2 (173,174). Liquid water may cause the device to not function properly. If the device is allowed to dry, it will recover its activity. It has a faster response time, performs better at high respiratory frequencies, and is less affected by humidity than the hygroscopic model (173,174).

Use

A chemical CO_2 detector is useful for confirming successful tracheal intubation when a capnometer is not available. It is useful for intubations that are performed out of the hospital, in the emergency department, or on the wards (175,176,177,178). It can be used to determine the position of the Combitube (179) (Chapter 21). It can be used during an intubation in a hyperbaric chamber (180). A manual resuscitator may have a built-in colorimetric CO_2 detector (181,182). Because it is disposable, it may be especially useful to confirm tracheal intubation in patients with respiratory diseases such as severe acute respiratory syndrome (SARS) (183).

Advantages

1. The device is easy to use.
2. Its performance is not affected by nitrous oxide or anesthetic vapors.
3. Its small size, portability, and lack of need for a power source allow it to be used in locations where use of a CO_2 monitor is not possible.
4. The cost is low compared with other methods of CO_2 analysis.
5. Studies show the device to be accurate in diagnosing esophageal intubation (166,167,168,171,176,177,178,182,184,185,186,187,188,189,190,191,192,193).
6. The device can serve to evaluate resuscitation or as a prognostic indicator of successful short-term resuscitation after the tracheal tube has been correctly positioned

(186,188,194).

7. It offers minimal resistance to flow.
8. It is always ready for use, does not require cleaning, and minimizes the risk of transmission of infection.
9. Carbon monoxide does not interfere with the chemical CO_2 detectors (127).

Disadvantages

1. It may take several breaths before conclusions can be drawn about the tracheal tube location to avoid errors caused by false-positive results, as discussed below. It is usually recommended to wait six breaths before making a determination.
2. False-negative results may be seen with very low tidal volumes and low end-tidal CO_2 concentrations, such as in cases of compromised lung perfusion (190,192). During cardiopulmonary resuscitation, a positive test indicates that the tracheal tube is in the airway, but a negative result (suggesting esophageal placement) requires an alternate method of confirming tracheal tube position. If there is little or no circulation to the lung, CO_2 will not be available for the detector to verify correct tracheal tube placement. Failure to inflate the tracheal tube cuff may cause equivocal color change (167). Other methods to determine tracheal tube position are discussed in Chapter 19.
3. Drugs instilled in the trachea or gastric contents can cause irreversible damage to the device (195,196).
4. False-positive results can occur if there is CO_2 in the stomach (from ingested carbonated beverages or antacids or mask ventilation) (197,198,199,200). The display may initially turn color and only slowly revert to its original color.
5. Difficulty in distinguishing color changes has been reported (197). It may be difficult to determine whether a subtle color change is due to the patient's low end-tidal CO_2 or a misplaced tracheal tube.
6. There is no alarm or CO_2 waveform.
7. This device may not be cost effective for routine use when

compared with use of a capnometer (201). Its cost-effectiveness may be greater with a small number of applications (202).

8. Airflow obstruction from a manufacturing defect has been reported (203).
9. This device is semiquantitative and cannot give accurate measurement of CO_2. For this reason, its application is limited to tracheal tube position verification.

Refractometry

In an optical interference refractometer (interferometer), one portion of a split light beam passes through a chamber into which the sample gas has been aspirated, while the other portion passes through an identical chamber containing air (204,205,206,207). Because vapor slows the velocity of light, the portion passing through the vapor chamber is delayed. The beams are then recombined to form an interference pattern that consists of dark and light bands. The position of these bands, observed through an eyepiece against a scale superimposed on the pattern, yields the vapor concentration. In

order to use this device, one must know the refractivity number of the gas being analyzed. Refractivity is a nonlinear function of the partial pressure of the gas.

This instrument is used primarily for vaporizer calibration. It cannot be used to measure vapor levels of halogenated agents in a typical anesthetic gas mixture of oxygen and nitrous oxide because of its sensitivity to nitrous oxide (208).

Gas Measurement

Oxygen

The standards for basic anesthesia monitoring of the American Society of Anesthesiologists (ASA) and American Association of Nurse Anesthetists (AANA) state that the concentration of oxygen in the patient breathing system shall be measured by an oxygen analyzer with a low oxygen concentration alarm in use. The use of more than one device to monitor oxygen is desirable.

Standard Requirements

International and U.S. standards on respiratory gas monitors

analyzers was published in 2004 and 2005 (209,210). The following requirements are in those standards.

1. Oxygen readings shall be within ±2.5% of the actual level. This accuracy shall be maintained for at least 6 hours of continuous use.
2. The high and low oxygen level alarms must be at least medium priority. A high-priority alarm is required for an inspired oxygen concentration below 18%. Alarm prioritization is discussed in Chapter 26.
3. It shall not be possible to set the low oxygen alarm limit below 18%.

An oxygen analyzer with an alarm that can be set below 18% is dangerous (211).

Technology

Oxygen levels may be measured by using electrochemical or paramagnetic technology. In most cases, electrochemical analysis provides only mean concentrations. Paramagnetic technology has a sufficiently rapid response time to measure both inspired and end-tidal levels. It may be desirable to measure the inspired oxygen with non-intubated, spontaneously breathing patients. This is possible with a diverting device such as a paramagnetic analyzer but not with an electrochemical monitor. End-tidal oxygen can be measured during jet ventilation (212).

Applications of Oxygen Analysis

Detecting Hypoxic or Hyperoxic Mixtures

The first line of defense against hypoxemia is to avoid a hypoxic inspired gas mixture. An oxygen monitor provides an earlier warning of inadequate oxygen than pulse oximetry. In a study of 2000 critical incidents, 1% were first detected by the oxygen monitor (213). Hypoxia is discussed in Chapter 14.

Oxygen analysis can also help prevent problems resulting from hyperoxygenation, such as patient movement during surgery, awareness, damage to the lungs and eyes, and fires. Fires are discussed in detail in Chapter 32.

Detecting Disconnections and Leaks

Disconnection of the tubing to an oxygen mask may be detected by using a diverting oxygen analyzer (214).

An oxygen monitor can detect disconnections in the breathing system (215,216,217). However, oxygen monitoring cannot be depended on for this purpose (218,219). Whether or not the oxygen level falls at the point being monitored depends on several factors, including the type of breathing system in use, position of the sensor, site of disconnection, alarm set points, if the patient is breathing spontaneously or ventilation is controlled, and the type of ventilator in use. If oxygen is the driving gas and there is no physical barrier between the driving oxygen from the ventilator and the breathing system gas, a disconnection at the common gas outlet will result in a rising percentage of oxygen (220). Disconnections are discussed in Chapter 14.

With a sidestream analyzer, a decrease in inspired and expired oxygen may result from a leak in the sampling system (221).

Detecting Hypoventilation

Normally, the difference between inspired and expired oxygen is 4% to 5%. A difference of more than 5% after a steady state has been reached is a sensitive indicator of hypoventilation (222,223,224). Hypoventilation is discussed in detail in Chapter 14.

Other

End-tidal oxygen has been used to measure the adequacy of preoxygenation (225,226,227,228,229).

Knowing the expired oxygen concentration allows an estimate of the patient's oxygen consumption and can aid in the diagnosing malignant hyperthermia. Oxygen consumption can be estimated from the difference between the inspired and exhaled oxygen concentrations (230,231).

The concentration of nitrous oxide can be estimated from the concentration of oxygen.

End-tidal oxygen has been used to detect air embolism. When a significant amount of air enters the

vascular bed, there is an increase in end-tidal oxygen and a decrease in the difference between inspiratory and end-tidal oxygen concentrations (232).

Carbon Dioxide Analysis

ASA guidelines for basic anesthetic monitoring state that when a tracheal tube or supraglottic airway device is inserted, its correct positioning must be verified by identifying CO_2 in the expired gas. Continual end-tidal CO_2 analysis shall be performed until the device is removed or the patient is transferred to a postoperative care location. In 2005, an audible alarm was added to the monitoring standard (233).

A court case has held that a reasonably prudent health care facility would supply a CO_2 monitor to a patient undergoing general anesthesia (234). Some states have mandated the use of CO_2 monitors (158).

Carbon dioxide analysis provides a means for assessing metabolism, circulation, and ventilation and can detect many equipment- and patient-related problems that other monitors either fail to detect or detect so slowly that patient safety may be compromised. A closed claims analysis found that capnography plus pulse oximetry could potentially prevent 93% of avoidable anesthetic mishaps (235). In one study, 10% of intraoperative problems were initially diagnosed by CO_2 monitoring (236). In another study, end-tidal CO_2 was useful in confirming 58% of already suspected anesthesia-related critical incidents and was the initial detector of 27% (237). In yet another study, it was estimated that a capnometer used on its own would have detected 55% of critical incidents if they had been allowed to evolve and 43% would have been detected before any potential organ damage (238). Carbon dioxide monitoring detects acute complete airway obstruction and extubation more rapidly than pulse oximetry or vital sign monitoring (239). In major trauma victims, using capnography to guide prehospital ventilation resulted in less hypoventilation on hospital admission (240,241).

The respiratory cycle (i.e., inspiration vs. expiration) is defined in terms of CO_2 measurement, so end-tidal values for other gases depend on CO_2 measurement.

Terminology

Capnometry is the measurement of CO_2 in a gas mixture, and a *capnometer* is the device that performs the measurement and displays the readings in numerical form. *Capnography* is the recording of CO_2 concentration versus time, while a *capnograph*

is the machine that generates the waveform. The *capnogram* is the actual waveform (242). It may be possible to connect a capnometer to another patient monitor and/or recorder to generate a waveform. Waveforms are available on all modern physiologic monitors.

The Capnometer

Standards Requirements

An international and a U.S. standard on capnometers have been published (209,210). They contain the following specifications.

1. The CO_2 reading shall be within ยฑ12% of the actual value or ยฑ4 mm Hg (0.53 kPa), whichever is greater, over the full range of the capnometer.
2. The manufacturer must disclose any interference caused by ethanol, acetone, methane, helium, tetrafluoroethane, and dichlorodifluoromethane as well as commonly used halogenated anesthetic agents.
3. The capnometer must have a high CO_2 alarm for both inspired and exhaled CO_2.
4. An alarm for low exhaled CO_2 is required.

Technology

Methods to measure CO_2 levels include infrared and chemical colorimetric analysis. A wide variety of display formats are available on CO_2 monitors. The CO_2 level may be reported as either partial pressure or volumes percent and may be displayed continuously or as the peak (normally end-tidal) value. Other parameters such as respiratory rate and I:E ratio may be displayed.

Portable, battery-operated CO_2 monitoring devices are available (243,244,245,246,247,248,249,250) (Figure 22.12). These are useful in emergency medicine and patient transport (Fig. 22.12). At least one has been reported to not give correct values during rebreathing (251). MRI-compatible infrared CO_2 monitors are available.

Many capnometers are included in multipurpose physiologic monitors with other parameters such as blood pressure, pulse

oximetry, and analysis of other gases. The CO_2 waveform may be one of several on a display.

Atmospheric Pressure Effects

Atmospheric pressure can influence CO_2 readings (111,112,252,253,254,255). Some instruments incorporate a barometer to compensate for changes in atmospheric pressure. Others require the user to enter the atmospheric pressure manually. Still others do not correct for atmospheric pressure. The capnometer standards (209,210) require that the manufacturer disclose the quantitative effects of barometric pressure on capnometer performance in the instructions for use.

Sidestream Analyzers

When a sidestream infrared reports results in volumes percent, the atmospheric pressure at measurement time must be known to correctly compute the CO_2 value.

TABLE 22.1 Capnography and Capnometry with Altered Carbon Dioxide Production[a]

	Waveform on Capnograph	*End-tidal Carbon Dioxide*	*Inspiratory Carbon Dioxide*	*End-tidal to Arterial Gradient*
Absorption of CO_2 from peritoneal cavity	Normal	↓	0	Normal
Injection of sodium bicarbonate	Normal	↓	0	Normal
Pain, anxiety, shivering	Normal	↓	0	Normal
Increased muscle tone (as from muscle relaxant	Normal	↓	0	Normal

reversal)				
Convulsions	Normal	↑	0	Normal
Hyperthermia	Normal	↑	0	Normal
Hypothermia	Normal	↓	0	Normal
Increased depth of anesthesia (in relation to surgical stimulus)	Normal	↓	0	Normal
Use of muscle relaxants	May see curare cleft	↓	0	Normal
Increased transport of CO_2 to the lungs (restoration of peripheral circulation after it has been impaired, e.g., after release of a tourniquet)	Normal	↑	0	Normal

[a]Normal end-tidal CO_2 is 38 torr (5%). Inspired CO_2 is normally 0. The arterial to end-tidal gradient is normally less than 5 torr.

For example:

$FetCO_2$ = partial pressure (atmospheric pressure - water vapor pressure) × 100

At 760 mm Hg atmospheric pressure and a CO_2 level of 38 mm Hg,

$FetCO_2$ = 38(760 - 47) ÷ 100 = 5%

If the atmospheric pressure is reduced to 500 mm Hg,

$FetCO_2$ = 38(500 - 47) ÷ 100 = 8%

If a correction for atmospheric pressure is not made, the capnometer will read erroneously high volumes percent at increased altitude. Other options are to calibrate at altitude with a gas that has a known CO_2 concentration or to set the device to read partial pressure.

Mainstream Infrared Analyzers

Mainstream infrared instruments are calibrated from sealed gas cells of known partial pressure. These instruments will report measurements in units of partial pressure correctly (252). If such an analyzer reports results in volumes percent, the atmospheric pressure at measurement time must be known.

Clinical Significance of Capnometry

Carbon dioxide is produced in the body tissues, conveyed by the circulatory system to the lungs, excreted by the lungs, and removed by the breathing system. Therefore, changes in respired CO_2 may reflect alterations in metabolism, circulation, respiration, or the breathing system. Tables 22.1 to 22.4 list some sources of changes in CO_2 levels.

TABLE 22.2 Capnographic and Capnometric Alterations as a Result of Circulatory Changes

	Waveform on Capnograph	*End-tidal Carbon Dioxide*	*Inspiratory Carbon Dioxide*	*End-tidal to Arterial Gradient*
Decreased transport of CO_2 to the lungs (impaired peripheral circulation)	Normal	↓	0	Normal
Decreased transport of CO_2 through	Normal	↓	0	Elevated

the lungs (pulmonary embolus, either air or thrombus; surgical manipulations)				
Increased patient dead space	Normal	↑	0	Elevated

TABLE 22.3 Capnometry and Capnography with Respiratory Problems

	Waveform on Capnograph	*End-tidal Carbon Dioxide*	*Inspiratory Carbon Dioxide*	*End-tidal to Alveolar Gradient*
Disconnection	Absent		0	
Apneic patient, stopped ventilator	Absent		0	
Hyperventilation	Normal	↑	0	Normal
Hypoventilation, mild to moderate	Normal	↑	0	Normal
Upper airway obstruction	Abnormal[a]	↑	0	Elevated
Rebreathing, e.g., (under drapes)	Baseline elevated	↑	↑	Normal
Esophageal intubation	Absent		0	

[a] See Figure 18.34.

Metabolism

Monitoring CO_2 elimination gives an indication of the patient's metabolic rate (256). An increase or decrease in end-tidal CO_2 is a reliable indicator of metabolism only in mechanically ventilated subjects. For spontaneously breathing patients, $PetCO_2$ may not increase with increased metabolism because of compensatory hyperventilation by the patient (257,258).

Table 22.1 lists some metabolic causes of increased or decreased CO_2 excretion. These include increased temperature, shivering, convulsions, excessive catecholamine production or administration (259), blood or bicarbonate administration (260), release of an arterial clamp or tourniquet (261,262,263,264,265), and parenteral hyperalimentation (266). Carbon dioxide production falls with decreased temperature and increased muscle relaxation.

Increased exhaled CO_2 can result from CO_2 used to inflate the peritoneal cavity during laparoscopy (267,268,269,270,271,272), the pleural cavity during thorascopy (273,274), a joint during arthroscopy (275), or to increase visualization for endoscopic vein harvest (276).

TABLE 22.4 Capnographic and Capnometric Alterations with Equipment

Problem	*Waveform on Capnograph*	*End-tidal Carbon Dioxide*	*Inspiratory Carbon Dioxide*	*End-tidal to Arterial Gradient*
Increased apparatus dead space	Baseline Elevated	↑	↑	Normal
Rebreathing with circle system: faulty or exhausted absorbent, bypassed absorber (may be masked by high fresh gas	Baseline Elevated See Figure 18.35	↑	↑	Normal

flow)				
Rebreathing with Mapleson system (inadequate fresh gas flow, misassembly, problem with inner tube of Bain system)	Baseline Elevated See Figure 18.35	↑	↑	Decreased
Rebreathing due to malfunctioning nonrebreathing valve	Baseline Elevated See Figure 18.35	↑	↑	Decreased
Obstruction to expiration in the breathing system	See Figure 18.34	↑	0	Decreased
Blockage of sampling line	Absent	0	0	
Leakage in sampling line	See Figure 18.39	↓	0	Increased
Low sampling rate with diverting device	See Figure 18.41	↓	↑	Increased
Too high a sampling rate with diverting device	See Figure 18.42	↓	0	Increased
Inadequate seal around tracheal tube	See Figure 18.44	↓	0	Increased

Malignant hyperthermia is a hypermetabolic state with a massive increase in CO_2 production. The increase occurs early, before the rise in temperature. Early detection of this syndrome is one of the most important reasons for routinely monitoring CO_2 (236,277). Capnometry can be used to monitor the effectiveness of treatment.

Circulation

Table 22.2 lists some of the circulatory changes that affect exhaled CO_2. A decrease in end-tidal CO_2 is seen with a decrease in cardiac output if ventilation remains constant (278,279,280,281,282). End-tidal CO_2 increases with increased cardiac output (283).

In addition to reduced cardiac output, reduced blood flow to the lungs can result from surgical manipulations of the heart or thoracic vessels (284), a dissecting aortic aneurysm compressing a pulmonary artery (285), wedging of a pulmonary artery catheter, and pulmonary embolism (thrombus, tumor, gas, fat, marrow, or amniotic fluid) (286,287,288,289,290,291,292,293,294,295). If the embolized gas is CO_2, the end-tidal CO_2 will initially increase and then decrease (296,297,298,299,300,301). Although not as sensitive as the Doppler for detecting air embolism, CO_2 monitoring is less subjective, is unaffected by electrosurgery apparatus, and can be used in major ear, nose, and throat (ENT) cases for which the Doppler method is not applicable. Capnometry may not be sufficiently sensitive to detect fat and marrow microemboli (302).

During resuscitation, exhaled CO_2 is a better guide to the effectiveness of resuscitation measures than the electrocardiogram (ECG), pulse, or blood pressure (303,304,305,306,307,308,309,310,311,312). The capnometer is not susceptible to the mechanical artifacts that are associated with chest compression, and chest compressions do not have to be interrupted to assess circulation. The colorimetric CO_2 detection device has also been shown to be an effective monitor during resuscitation. However, if high-dose epinephrine or bicarbonate is used, end-tidal CO_2 is not a good resuscitation indicator (313,314,315,316,317,318).

End-tidal CO_2 levels may be of use in predicting the outcome of resuscitation (186,304,307,310,319,320,321,322,323,324,325,326,327,328,329,330,331,332)

and the resolution of a pulmonary embolus (333).

Respiration

Carbon dioxide monitoring gives information about the rate, frequency, and depth of respiration. It can be used to evaluate the patient's ability to breathe spontaneously as well as the effect of bronchodilator or nitric oxide treatment or altered ventilation parameters. It allows control of ventilation with fewer blood gas determinations. End-tidal analysis is noninvasive, available on a breath-by-breath basis, and not affected by hyperventilation that is induced by drawing an arterial blood sample.

Table 22.3 lists some respiratory causes of increased and decreased end-tidal CO_2. A capnometer can warn of esophageal intubation, apnea, extubation, disconnection, ventilator malfunction, a change in compliance or resistance, airway obstruction, poor mask fit, or a leaking tracheal tube cuff.

A dependable means to determine when a tracheal tube has been correctly positioned in the tracheobronchial tree obviously is of great value. Esophageal intubation has been a leading cause of death and cerebral damage in the past. A discussion of ways to detect inadvertent esophageal placement is found in Chapter 19. Carbon dioxide monitoring is usually considered the most reliable method. Carbon dioxide measurement to detect esophageal placement has some drawbacks and limitations, so its use as the only means of correct tube placement should be strongly discouraged. Absence of circulation, severe bronchospasm, equipment malfunction, and application of cricoid pressure occluding the tracheal tube tip can result in failure to detect CO_2 (334,335,336,337,338,339,340,341,342,343,344). The analyzer may be in a calibration mode when the tube is placed.

With esophageal intubation, small waveforms may be transiently seen as a result of CO_2 that has entered the stomach during mask ventilation or from carbonated beverages or medications (197,199,345,346,347,348). This could give the impression that the tube is correctly placed in the trachea. However, rapidly diminishing concentrations and abnormal waveforms will usually differentiate esophageal from tracheal intubation (345,349,350).

A case has been reported where a normal capnogram was present despite an esophageal intubation (351). There was a cuffed oropharyngeal airway in place, and the patient was

breathing spontaneously. Carbon dioxide from the trachea was thought to have gotten under the cuffed airway and forced down the esophagus, where it was aspirated from the tracheal tube. Inflating the tracheal tube cuff interrupted the waveform.

While esophageal intubation will likely be detected by using end-tidal CO_2, there is no guarantee that the tube is in the trachea. Carbon dioxide can be sensed from a tracheal tube that is positioned above the vocal cords (352).

A diverting CO_2 monitor can be used to monitor respiratory rate and exhaled CO_2 in unintubated patients who are breathing spontaneously (50,51,52,53,54,55,67,72,78,89,90,353,354,355,356,357,358,359). Apnea, airway obstruction, or disconnection of the oxygen source may be detected. If ventilation of the breathing space under the surgical drapes is inadequate, rebreathing will occur and may be detected by a rising inspired CO_2 level (52,354,360).

Capnometry has been used to help determine the position of a double-lumen tube (361,362). Methods to determine proper double-lumen tube placement are discussed in Chapter 20. Correct placement can be checked by examining the waveform from each lung during clamping and unclamping procedures. However, that method

is less reliable than other methods that are used for this purpose (363,364,365). During independent lung ventilation, capnography can be used to determine the proper settings for ventilation of each lung (366). Capnography can be used to detect tracheobronchial injury during thoracoscopic procedures (274).

Carbon dioxide monitoring can serve as a warning of accidental bronchial intubation. This may result in a transient fall or rise in end-tidal CO_2 (367,368,369).

Carbon dioxide monitoring can be useful during weaning from artificial ventilation (370,371,372,373,374,375,376,377). However, end-tidal CO_2 monitoring alone may not be a reliable tool during weaning without knowing the arterial-$ETCO_2$ gradient. This is discussed in more detail later in this chapter. Carbon dioxide monitoring can assist with the decision to provide ventilatory support (378). It provides a means to measure the severity of bronchospasm (379,380).

Equipment Function

A problem with the breathing system can cause an inspired CO_2 level greater than zero. Examples of such problems are listed in Table 22.4 and include leaks, faulty or exhausted absorbent, channeling, a bypassed absorber, increased dead space, low fresh gas flow to a Mapleson system, a defect in the inner tube of a Bain system, accidental administration of CO_2, and a defective nonrebreathing valve (381,382,383,384,385,386,387,388).

Incompetent unidirectional valves are an inherent danger of the circle system. An incompetent expiratory valve allows reverse flow of gas that contains CO_2 from the expiratory limb during the inspiratory phase, resulting in an elevated baseline on the capnogram (389) (Fig. 22.30). If the inspiratory valve is incompetent, CO_2 will enter the inspiratory limb during exhalation. During the next inspiration, CO_2 will be rebreathed. This will cause the plateau on the capnogram to be lengthened and a decrease in the steepness of the inspiratory downslope (Fig. 22.32) (390). An increase in the baseline may not be seen. A spirogram that plots CO_2 against volume (Fig. 22.22) will illustrate the inspiratory valve leak by a decreased downslope on the inspiratory side of the loop (391).

Carbon dioxide analysis can be used to detect a disconnected oxygen tubing to a mask over the face during local or regional anesthesia (355). If the oxygen source becomes detached, there will be a rise in CO_2 because of rebreathing.

Rarely a ĺ€phantomĺ€ CO_2 wave may be noted despite a disconnection. One case was reported when the gas sample line from the CO_2 monitor was connected to the breathing system just upstream of the expiratory unidirectional valve (392). During inspiration, the inspiratory unidirectional valve opened, allowing fresh gas plus the gas (containing CO_2) from the monitor to pass to the patient, where it was detected during inspiration. This problem does not occur if the gas is either directed to the scavenging system or returned to the breathing system downstream of the expiratory valve. In another case, square wave capnographic tracings were observed after a patient was disconnected from a ventilator that had not been turned OFF (393). The gas analyzer aspirated CO_2 from the expiratory tubing, generating a series of diminishing tracings on the capnograph.

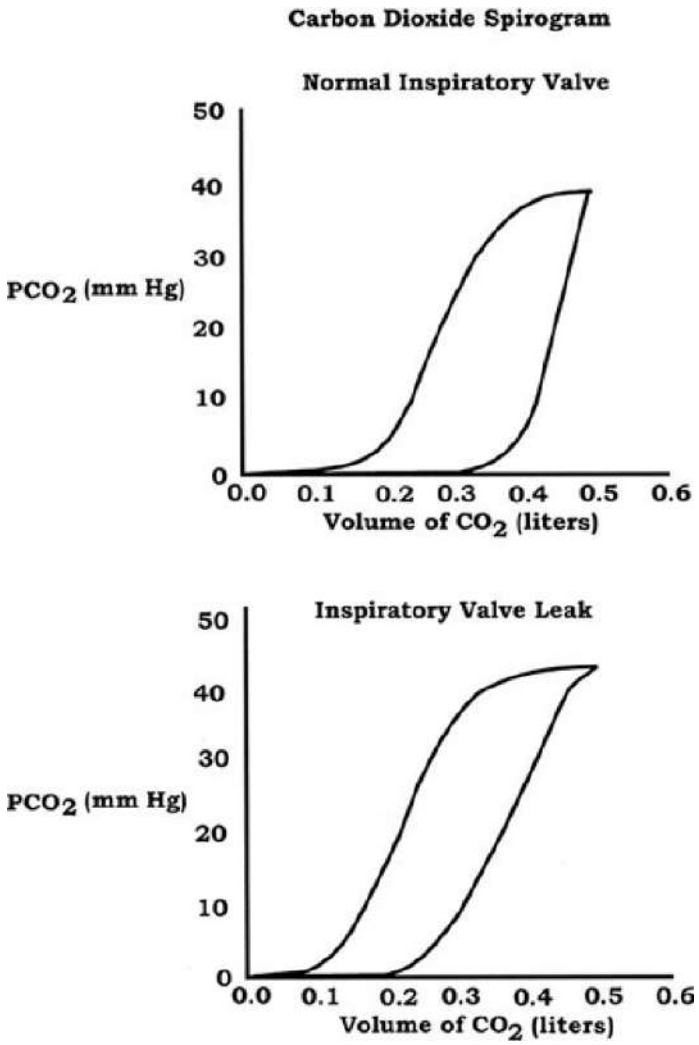


Figure 22.22 A spirogram that plots CO_2 against volume will illustrate the inspiratory valve leak by a decreased downslope on the inspiratory side of the loop better than a capnogram. (Redrawn from Breen PH, Jacobsen P. Carbon dioxide spirogram [but not capnogram] detects leaking inspiratory valve in a circle circuit. Anesth Analg 1997;85:1372–1376.)

Other Uses

A diverting capnometer can be used to localize the site of leaks in CO_2 insufflation equipment (394), diagnose a tracheoesophageal or bronchoesophageal fistula (395,396),

guide blind intubation (397,398,399,400,401,402,403,404,405), determine when the tip of an exchange catheter or fiberscope is in the trachea (406,407), or confirm that the needle or catheter is positioned in the trachea during a

cricothyrotomy or percutaneous dilatational tracheostomy (Chapter 21) (408,409,410).

Carbon dioxide analysis may be used to assess the position of an enteric tube (411,412,413,414,415,416,417,418,419,420,421,422,423). If the tube is placed into the trachea, CO_2 will be detected at the free end. If CO_2 is not detected, the tube is likely in the esophagus. If an enteric tube passes into the trachea in an intubated patient, the capnograph will show a downsloping alveolar plateau (424).

Correlation between Arterial and End-tidal Carbon Dioxide Levels

Numerous studies have shown that the correlation between arterial and end-tidal CO_2 tensions in children and adults without cardiorespiratory dysfunction is good enough to warrant routine monitoring (4,110,271,425,432). End-tidal CO_2 is usually lower than $PaCO_2$ by 2 to 5 torr (433). The gradient may be less or even negative if the functional residual capacity is reduced, as in pregnant or obese patients (428,434,435) and is reduced with rebreathing (436). Tables 22.1 through 22.4 show some conditions with altered end-tidal to arterial gradients.

Prediction of $PaCO_2$ from end-tidal CO_2 alone is unreliable in some patients and may be potentially deleterious in some patient subgroups. A study of neurosurgical patients found that end-tidal CO_2 did not accurately reflect changes in the arterial CO_2 tension (437), although in healthy patients during elective neurosurgical procedures, the $PaCO_2$-$PetCO_2$ difference remains stable over time (430). Transcutaneous CO_2 monitoring has been found to be more accurate in evaluating CO_2 levels during one-lung ventilation (438,439), in obese patients (440), during neurosurgical procedures in adults (441), and in older children (442,443).

The relationship between arterial and end-tidal CO_2 tension may be constant or vary, sometimes in different directions, both within and between patients (444). Although there usually is a linear relationship between end-tidal and arterial CO_2, the gradient may

be unexpectedly large or even negative (445,446,447,448,449,450). End-tidal CO_2 cannot replace the measurement of $PaCO_2$ in the intensive care unit or emergency room, although it is useful for trending or screening (430,450,451,452,453).

Problems with Sampling

Accurate measurement of end-tidal CO_2 is especially difficult with high ventilatory frequencies (16). In small patients, sampling at the patient end of the tracheal tube results in a closer approximation to arterial CO_2 than sampling at the breathing system end (22,23,24,25,26). While placing the gas sampling line on the machine side of an HME may avoid contamination and water logging of the sample, this may result in erroneous values and poor waveforms (454,455,456).

One source of sampling error is a leak at the interface between the patient and the equipment. Poor mask fit, using an uncuffed tracheal tube or a tube with a defective cuff, or a loose connection or leak in the sampling catheter may cause erroneously low end-tidal CO_2 readings (106). The correlation between arterial and end-tidal CO_2 tensions is better during ventilation with a supraglottic device than a face mask (457). The correlation can be improved by sampling at the patient end of the supraglottic device (30).

With unintubated, spontaneously breathing patients, poor correlation between end-tidal and arterial CO_2 is associated with partial airway obstruction, high respiratory rates, low tidal volumes, oxygen delivery through the ipsilateral nasal cannula, and mouth breathing (68,93,458). Results may be improved by isolating insufflated oxygen from exhaled gases, observing the waveform for normal configuration, and decreasing the oxygen flow rate (53,459).

When a sidestream capnometer is used with a Mapleson system, exhaled gas may be diluted by fresh gas during the latter portion of expiration if the expiratory flow rate is less than the sampling flow rate of the capnometer. This will cause the end-tidal CO_2 reading to be lowered even if the alveolar phase of the capnogram is flat or has a small positive slope. The amount that the end-tidal CO_2 is lowered will depend on several factors, including whether spontaneous or controlled ventilation is used, the type of ventilator and breathing circuit, the fresh gas flow,

the sampling rate, and the expiratory flow rate (22,460,461). Maneuvers to obtain a $PetCO_2$ reading that is closer to the $PaCO_2$ with Mapleson systems include using lower fresh gas flows, extending the time of expiratory flow, adding dead space between the breathing system and gas sampling point, and using a circuit that automatically interrupts the fresh gas flow after inspiration or prevents mixing of exhaled and fresh gases (460,462). A quick method of checking to see whether the $PetCO_2$ is artifactually low is to temporarily disconnect the fresh gas supply (463). If there is an abrupt rise in $PetCO_2$ when the diluting effect of the fresh gas is removed, then the first breaths that follow will give a better measure of the true $PetCO_2$.

During high-frequency ventilation, $PetCO_2$ is a poor index of $PaCO_2$ (88). In order to measure the end-tidal CO_2, the high-frequency ventilation should be interrupted to impose a few slow breaths (83,87,88,464,465,466).

Disturbances in the Ventilation:Perfusion Ratio

When there is ventilation-perfusion mismatching, the relationship between end-tidal and arterial tensions of CO_2 is disturbed. Clinical conditions that can alter the volume and/or distribution of pulmonary blood flow include pulmonary embolism, pulmonary artery stenosis or

occlusion, reduced cardiac output, pulmonary hypotension, hypovolemia, and certain heart lesions (433,467,468,469,470,471,472).

The end-tidal to arterial CO_2 gradient increases as venous admixture (right to left shunt) occurs. This can be caused by atelectasis, bronchial intubation, or certain heart conditions. The effect is less dramatic than that caused by an increase in dead space, but when the venous admixture is large (as in cyanotic congenital heart disease), its contribution can be considerable (425,469,473,474).

Changes in body position, such as the lateral or prone position, may cause an increase in the $Pa/PetCO_2$ gradient (475,476).

Patients with pulmonary disease have an uneven distribution of ventilation and, to a lesser extent, blood flow. This leads to an increased gradient (433,477,478,479). Since positive end-expiratory pressure (PEEP) may decrease the gradient

(480,482), the arterial-end-tidal CO_2 gradient can be a useful tool for optimizing PEEP (377,482). A patient who has a gradient that narrows while PEEP is gradually increased may have a widened gradient when the optimal level has been exceeded.

Capnometer Problems

If there is a leak or break in the sampling line or its connections, air will be added to the sample, and the end-tidal CO_2 reading will be lower than the actual value (483,484,485) (Fig. 22.37). An obstructed sampling catheter can cause the capnogram to be dampened and cause falsely high inspired and falsely low end-expired CO_2 values (486). An occluded sampling or exhaust line can result in no CO_2 being detected (344,487). An internal leak in the analyzer can result in artifactually high values (488).

Other problems that may result in an inaccurate $PetCO_2$ reading include increased sampling tube resistance, changes in atmospheric pressure, improper calibration, drift, signal noise, selectivity, pressure effects from the sampling system or patient environment, water vapor, and foreign substances (252). With some analyzers, the gas used for zeroing is obtained from room air. If CO_2-containing gas enters the zeroing sample, there will be falsely low CO_2 readings with a normal-looking waveform (489).

Other

A significant discrepancy between $PaCO_2$ and $PetCO_2$ may occur in patients taking acetazolamide, which delays the conversion of HCO_3^- to CO_2, causing a decrease in end-tidal CO_2 (490).

Gas solubility changes with temperature, so the arterial to end-tidal gradient may increase with hypothermia unless the $PaCO_2$ is corrected for hypothermia (491).

Inadvertent addition of CO_2 to the inspired gas from a CO_2 laser may cause elevated readings (492).

Capnography

Most CO_2 monitors include a waveform. Waveforms can be displayed on an oscilloscope or printed on paper (112,242,493,494). Slow speeds can be used to show trends. Faster speeds are used for examining individual waveforms.

Examination of the waveform will often explain readings that appear inaccurate. If the capnometer reads several peaks per breath or breaths that do not have a plateau, the respiratory rate and peak CO_2 readings will be inaccurate.

The waveform should be examined systematically for height, frequency, rhythm, baseline, and shape. Height depends on the end-tidal CO_2. Frequency depends on the respiratory rate.

The baseline is normally zero. An elevated baseline (Fig. 22.30) can result from deliberate administration of CO_2, rebreathing, exhausted absorbent, a contaminated sample cell, or an incompetent expiratory unidirectional valve. The baseline may or may not be elevated with an incompetent inspiratory unidirectional valve.

The shape of the normal waveform is illustrated in Fig. 22.23. Only one shape (top hat or sine wave) is considered normal. Phase I (inspiratory baseline) begins at E and is normally zero, reflecting inspired gas, which is normally devoid of CO_2.

Phase II (expiratory upstroke) begins at B and continues to C. This rapid S-shaped upswing represents the transition from gas from the dead space that does not participate in gas exchange and alveolar gas that contains CO_2.

Phase III begins at C and continues to just before D. As gas coming almost entirely from alveoli is exhaled, a plateau is normally seen. If a plateau is not seen, the maximum value obtained may not be equivalent to the end-tidal level and the correlation between arterial and end-tidal CO_2 is not likely to be good. The slope of this phase is increased by ventilation-perfusion abnormalities in the lung (495) as well as external factors such as a kinked tracheal tube.

The very last portion of Phase III, identified by D, is referred to as the end-tidal point. The CO_2 level here is normally at its maximum. In normal individuals, this is 5% to 5.5%, or 35 to 40 torr.

The angle between Phases II and III is called the ฮฑ (takeoff, elevation) angle (496). Normally, it is between 100 and 110 degrees. It is decreased with obstructive lung disease, as the dead space volume takes longer to be exhaled. The slope of Phase III depends on the lung's ventilation-perfusion status. Airway obstruction and PEEP cause an increased slope and a larger ฮฑ angle (379,380,496). Other factors that affect the

angle are the

capnometer's response time, sweep speed, and the respiratory cycle time (242).

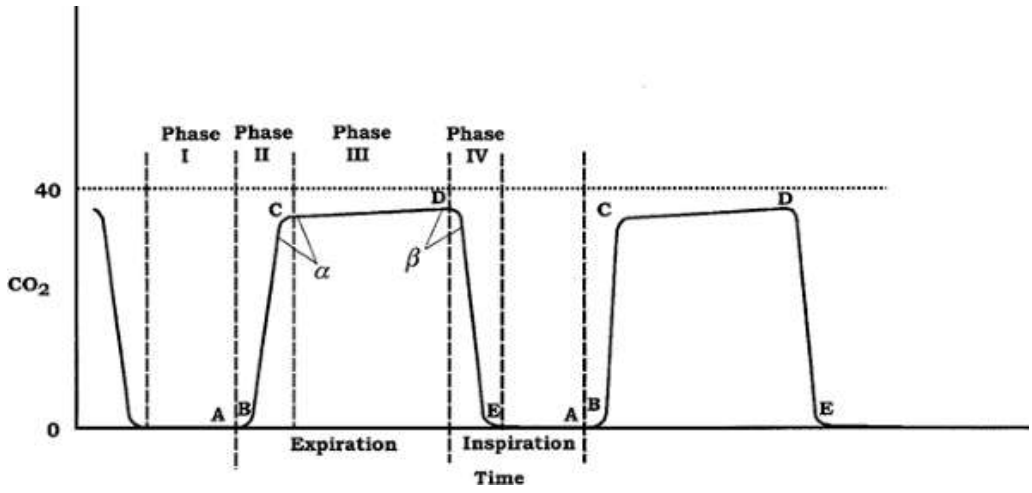


Figure 22.23 Normal carbon dioxide waveform. EA (Phase I) is the latter part of inspiration, during which the CO_2 level remains at zero. BC (Phase II) represents the emptying of connecting airways and the beginning of the emptying of alveoli. As exhalation continues, gas from alveoli in regions with relatively short conducting airways appears and mixes with dead space gas from regions with relatively long conducting airways, resulting in an increasing CO_2 level. CD (Phase III) shows the alveolar plateau. Because of uneven emptying of alveoli, the slope continues to rise gently. Point D shows the best approximation of alveolar CO_2 (end of expiration, beginning of inspiration). In DE (Phase IV), as the patient inhales, CO_2-free gas enters the patient's airway, and the CO_2 level abruptly falls to zero. Characteristics of the normal capnogram include (a) rapid increase from B to C, (b) nearly horizontal plateau between C and D, (c) rapid decrease from D to E to zero, and (d) a zero baseline (EA AB). A good alveolar plateau greatly increases the chances that the end-tidal reading is a reliable estimate of the alveolar level.

The angle between the end of Phase III and the descending limb of the capnogram is called the ฮฒ angle. Normally, it is approximately 90 degrees. The angle will be increased with rebreathing. Another possible cause of an increased ฮฒ angle is a prolonged response time compared with the respiratory cycle time, particularly in children (242). The angle will be decreased

if the slope of Phase III is increased.

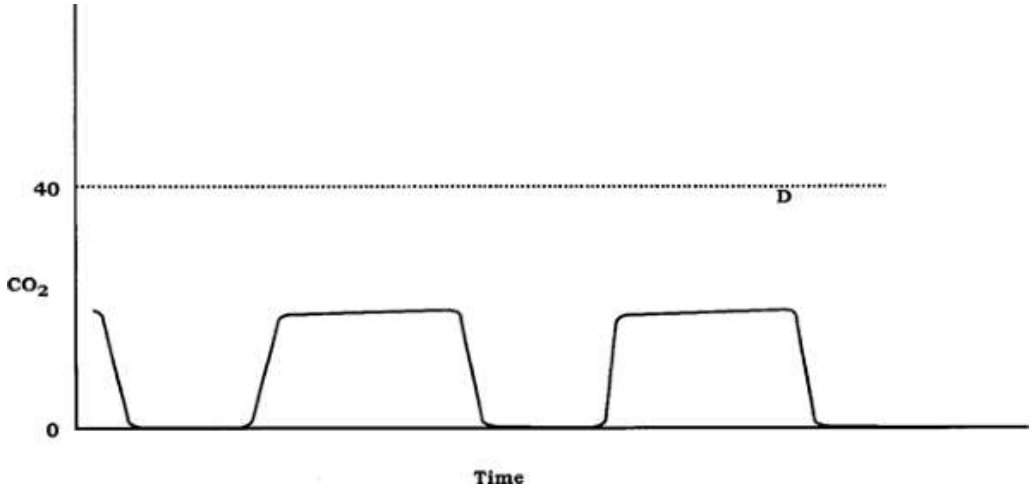


Figure 22.24 Low end-tidal CO_2 with a good alveolar plateau may be the result of hyperventilation or an increase in dead space ventilation. Comparison of $PetCO_2$ with $PaCO_2$ is necessary to distinguish these two conditions.

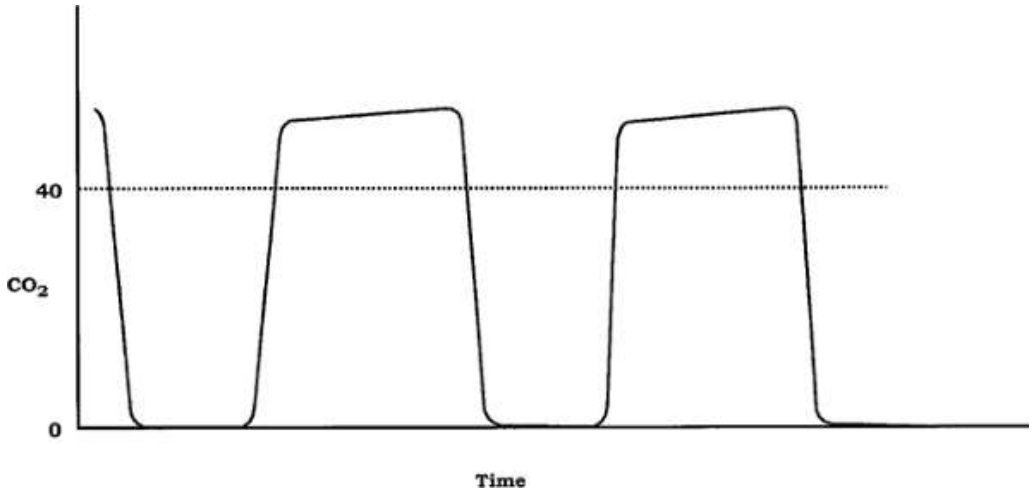


Figure 22.25 Elevated end-tidal CO_2 with good alveolar plateau may be caused by hypoventilation or increased CO_2 delivery to the lungs.

In Phase IV, the patient inhales. Normally, CO_2 falls abruptly to zero and remains at zero until the next exhalation.

A number of situations can cause unusual waveforms. Some are shown in Figures 22.24 to 22.42. There is an Internet website devoted to capnography (http://www.capnography.com).

If there is a leak in the sample line during positive-pressure ventilation or at the patient connection, the capnogram will have a brief peak at the end of the plateau (106,221,502,504,505,509,510,511,512,513) (Fig. 22.34). If there is a leak in a sampling line that runs through the lumen of the expiratory limb, the baseline will be elevated, falsely indicating rebreathing (514).

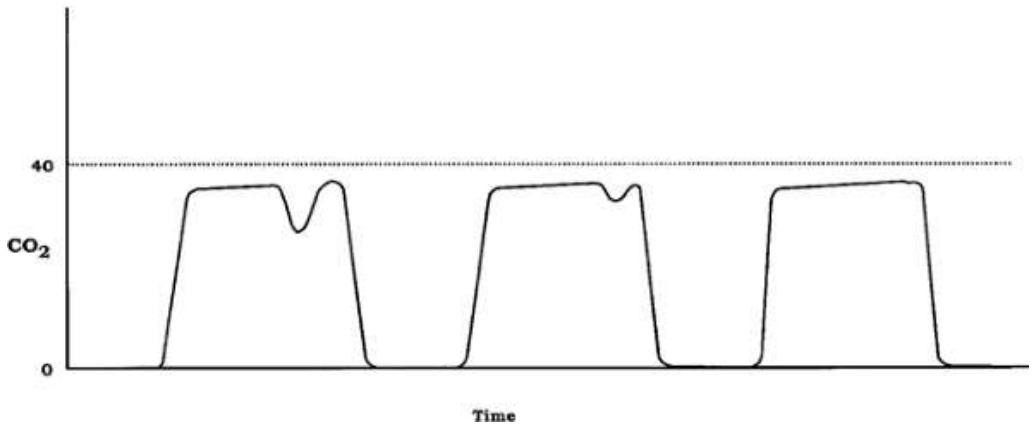


Figure 22.26 Curare cleft or notch, which is seen during spontaneous ventilation. The capnogram on the left shows the notch. As the muscle relaxant is reversed, the curve becomes normal in shape. The cleft is in the last third of the plateau and is caused by a lack of synchronous action between the intercostal muscles and the diaphragm, most commonly caused by inadequate muscle relaxant reversal. The depth of the cleft is proportional to the degree of muscle paralysis. The position of the cleft is fairly constant on the same patient but is not necessarily present with every breath. The notch also is seen in patients with cervical transverse lesions, flail chest, hiccups, and pneumothorax and when a patient tries to breathe during mechanical ventilation.

Patients who are partially paralyzed with muscle relaxants may make respiratory efforts anytime during the respiratory cycle with controlled ventilation (Fig. 22.27). If the patient is spontaneously breathing and the depression occurs in the later third of the waveform, it is referred to as a curare cleft (515) (Fig. 22.26).

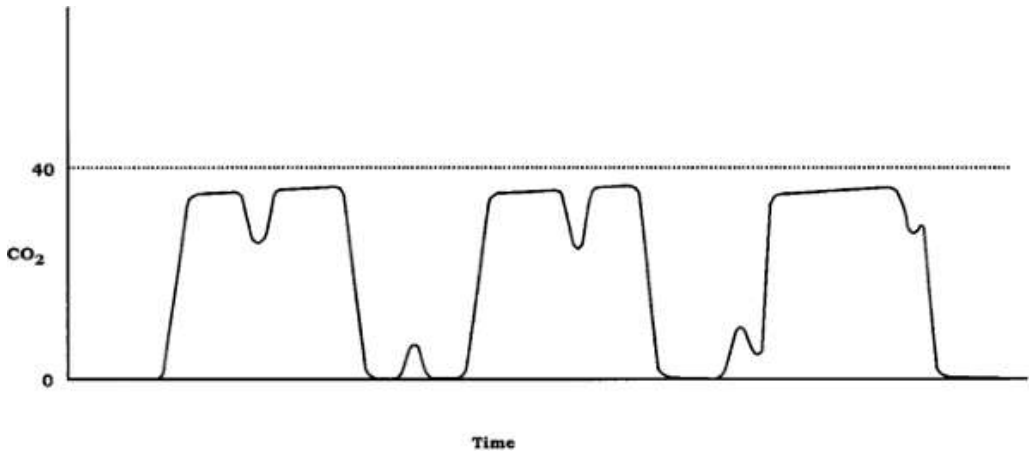


Figure 22.27 Spontaneous respiratory efforts during mechanical ventilation. The capnogram shows small breaths at various places during expiration and inspiration. Causes include maladjusted ventilator (hypoventilation), inadequate muscle paralysis, severe hypoxia, or the patient waking up. The end-tidal CO_2 may rise slightly because of increasing metabolism of the contracting respiratory muscles. This pattern may also be caused by pressure on the patient's chest or ventilator malfunction.

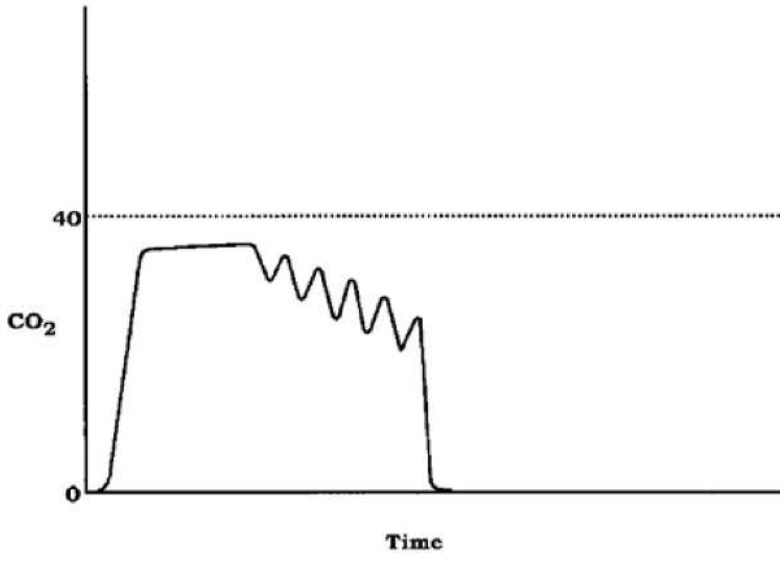


Figure 22.28 Cardiogenic oscillations appear as small, regular, toothlike humps at the end of the expiratory

phase. They may be single or multiple, and the heights may vary considerably. They are believed to be due to the heart beating against the lungs. A number of factors contribute to the appearance of cardiogenic oscillations, including negative intrathoracic pressure, a low respiratory rate, diminution in the vital capacity:heart size ratio, a low inspiratory:expiratory ratio, low tidal volumes, and muscular relaxation (268,269,497). In many cases, adjustment of the ventilator rate, flow, or tidal volume will remove this pattern from the screen. Other times, however, it cannot be corrected. Cardiogenic oscillations are the rule rather than the exception in pediatric patients because of the relative size of the infant's heart and thorax. Capnograms from patients with severe emphysema tend not to register cardiogenic oscillations. Less sophisticated capnometers may count each oscillation as a breath, displaying a respiratory rate higher than actual. Cardiogenic oscillations may result from the positions of the components in the breathing system in relation to the sampling site. Placing the sampling site on the patient side of an HME may remove the oscillations (454,498) The addition of low level positive end-expiratory pressure can also be used to eliminate these oscillations (499).

A capnogram with two peaks (biphasic) may be caused by unilateral conditions that cause unilateral hypoventilation or high airway resistance, single lung transplantation, bronchial intubation, or severe kyphoscoliosis (516,517,518,519,520).

Volatile Anesthetic Agents

Measuring concentrations of volatile anesthetic gases is common practice. In some countries (but not the United States at the time of this writing), agent monitoring is a standard of care (122). The anesthesia workstation standard (524) requires that the workstation be provided with a device to monitor the concentration of anesthetic vapor in the inspiratory gas.

An anesthetic agent monitor may be a stand-alone device or part of a multiparameter monitor.

Standard Requirements

International and U.S. standards for anesthetic gas monitors are available (209,210). The following are provisions of both standards.

1. For halogenated anesthetic gases, the difference between the mean anesthetic gas reading and the anesthetic gas level shall be within ±0.2% vol % + 15% of the anesthetic gas level.
2. A high concentration alarm is mandatory. A low concentration alarm is optional.

Measurement Techniques

The volatile anesthetic agents can be measured by using infrared analysis, refractometry, or piezoelectric analysis. When an agent is used for which an analyzer is not

programmed, it may be possible to apply a conversion factor so that the analyzer may be used to monitor that agent (525,526).

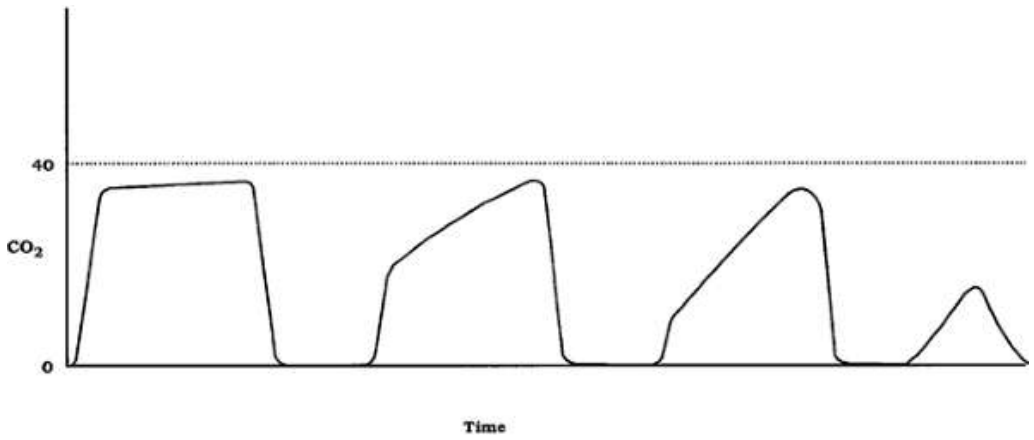


Figure 22.29 Prolonged expiratory upstroke. The left curve shows a normal waveform. The other three curves show progressive slanting and prolongation of the expiratory upstroke. As expiration is progressively prolonged, inspiration may start before expiration is complete so that the end-tidal PCO_2 reading is decreased. This is indicative of obstruction to gas flow caused by a partially obstructed tracheal tube or obstruction in the patient's airways (chronic obstructive lung disease, bronchospasm, or upper-airway obstruction).

Significance

Vaporizer Function and Contents

An advantage of monitoring potent agents is the ability to assess

vaporizer accuracy. It is recommended that vaporizer output be verified twice a year as well as at any time a vaporizer is disconnected from the anesthesia machine and then reinstalled (208). When a vaporizer is suspected of malfunction, it can be easily checked by placing the end of the sampling catheter in the fresh gas flow.

Agent-specific analyzers can detect an incorrect agent, and non-agent-specific analyzers will usually

exhibit unusual readings when an agent error is made (129,130).

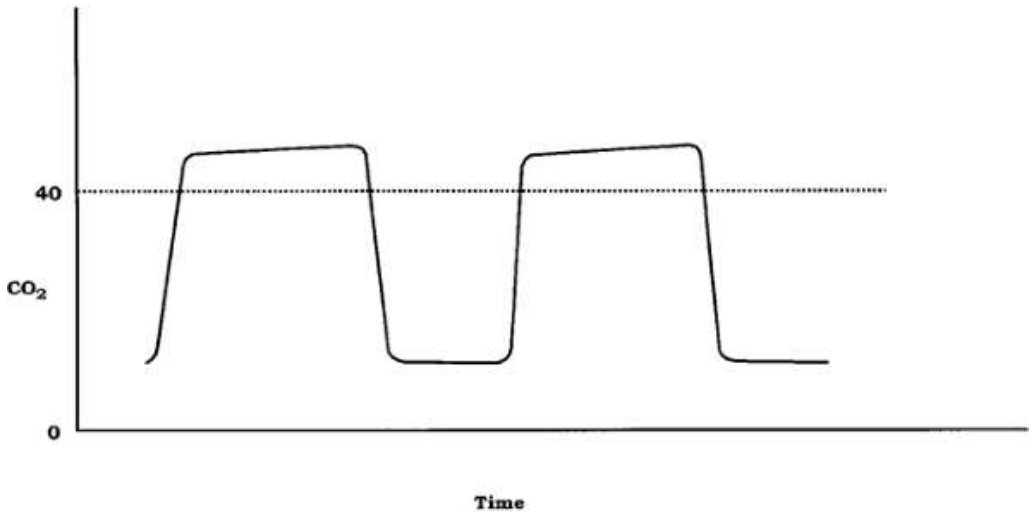


Figure 22.30 The baseline is elevated, and the waveform is normal in shape. This may be caused by an incompetent expiratory valve or exhausted absorbent in the circle system; insufficient fresh gas flow to a Mapleson system; problems with the inner tube of a Bain system; deliberate addition of CO_2 to the fresh gas; or in some cases, an incompetent inspiratory valve. It may also be the result of rebreathing under drapes in a spontaneously breathing patient who is not intubated.

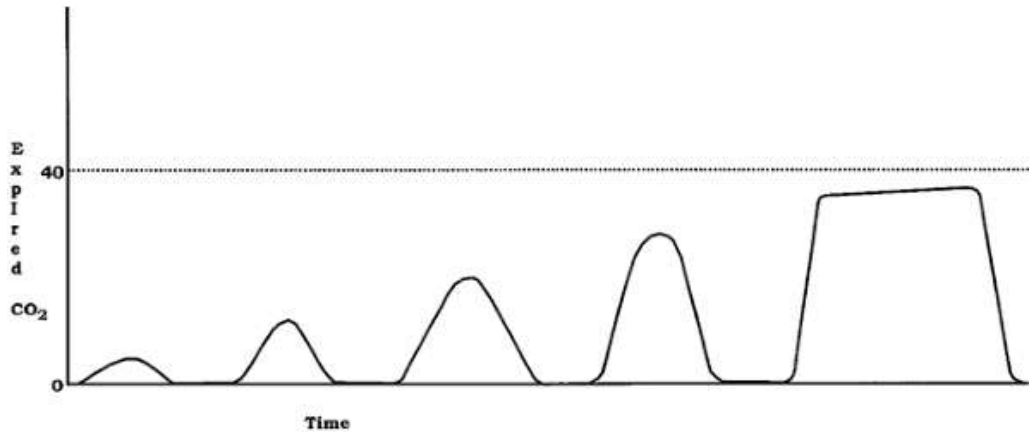


Figure 22.31 Return to spontaneous ventilation. The first breath is typically of small volume. Subsequent breaths show progressively higher peaks with gradual resumption of a normal waveform.

Anesthetic agent monitoring will alert the user when a vaporizer has become empty or is turned OFF, when it is inadvertently in the ON position, or when a vaporizer not in use is allowing significant amounts of vapor to leak into the fresh gas line (527).

The difference between the vaporizer setting and the measured inspired concentration of the agent puzzles many clinicians. There is usually a difference between the two values, with the inspired concentration being lower at the beginning of a case and higher at the end. This discrepancy results from the time needed to equilibrate the concentration in the relatively large volume of gas in the breathing system as well as by agent uptake by the patient. If low fresh gas flows are used, the time needed for equilibration will be longer. If the volatile anesthetic agent is reacting with desiccated absorbent (Chapter 9), the difference will be increased.

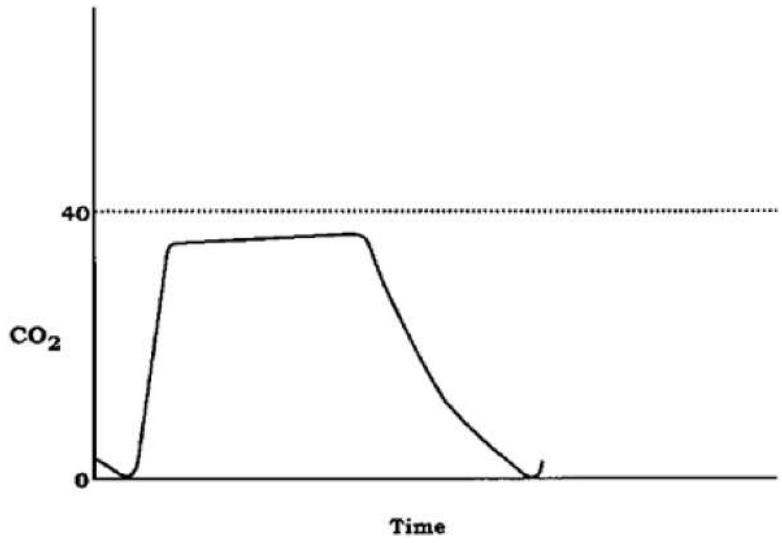


Figure 22.32 Incompetent inspiratory unidirectional valve. The waveform shows a prolonged plateau and a slanting inspiratory downstroke. The inspiratory phase is shortened, and the baseline may or may not reach zero, depending on the fresh gas flow. A similar pattern may be seen with suction applied to a chest tube.

Information on Uptake and Elimination

Monitoring volatile anesthetic agents provides information on uptake and elimination. The difference between inspired and expired levels provides a measure of patient saturation.

Teaching

Anesthetic agent monitoring can be used to demonstrate the relationship between agent concentration in the fresh gas line and that in the breathing system. This makes agent monitoring useful for teaching low-flow anesthesia.

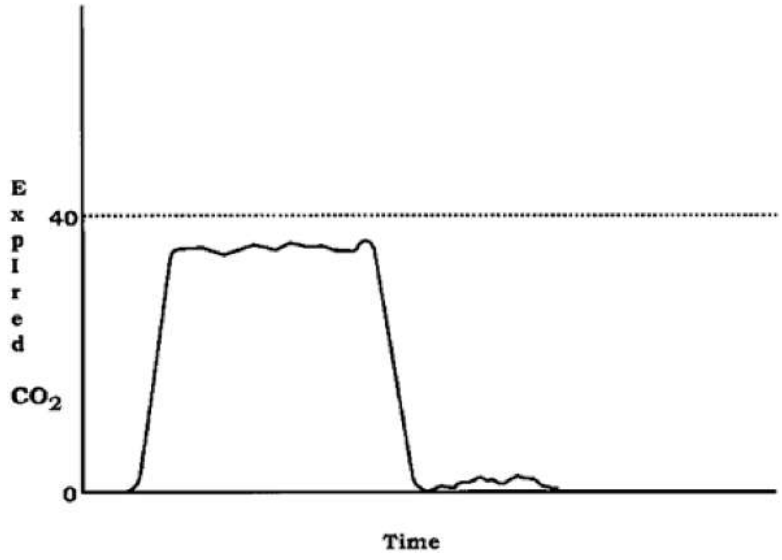


Figure 22.33 Irregular plateau and/or baseline may result from displacement of the tracheal tube into the upper larynx or lower pharynx with intermittent ventilation of the stomach and lungs or from pressure on the chest, which causes small volumes of gas to move in and out of the lungs.

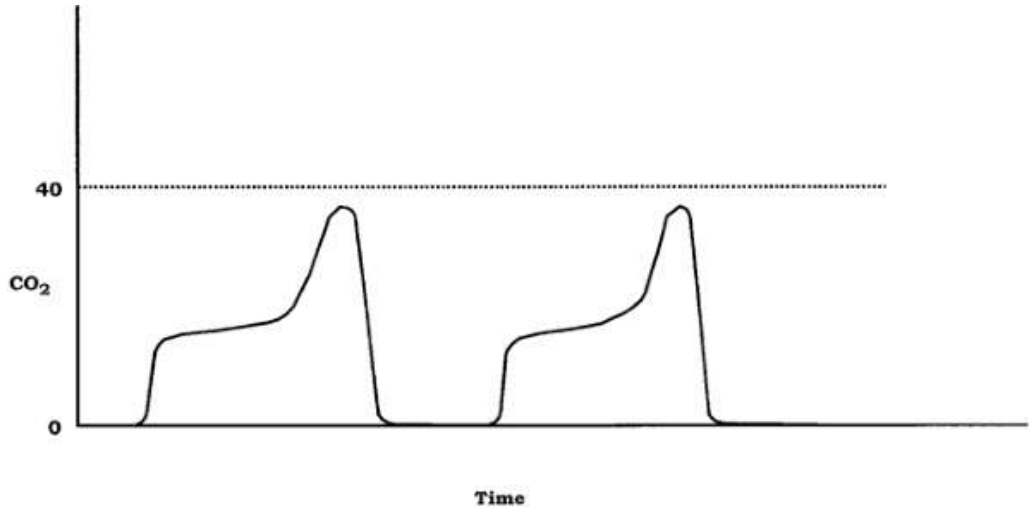


Figure 22.34 A leak in the sampling line during positive-pressure ventilation will result in an upswing at the end of Phase III (71,500,501,502). A plateau of long duration is followed by a peak of

brief duration. The height of the plateau is inversely proportional to the size of the leak. The brief peak is caused by the next inspiration, when positive pressure transiently pushes undiluted end-tidal gas through the sampling line. If the patient is breathing spontaneously a falsely low end-tidal carbon dioxide reading may be seen, owing to air entrainment, but no terminal hump is seen. An upswing at the end of Phase III may also be seen in obese and pregnant patients (242,503,504,505).

Information on Anesthetic Depth

Knowledge of volatile agent concentrations may provide evidence that the patient who is paralyzed is neither awake nor grossly overdosed, may permit more rapid awakening of the patient, and may aid in the diagnosis of delayed emergence. Awareness due to a low concentration of inhalational agent may be avoided (528). Measuring concentrations of volatile anesthetic agents may help to avoid cardiac arrests due to overdosage. This is particularly a problem in pediatric patients (529).

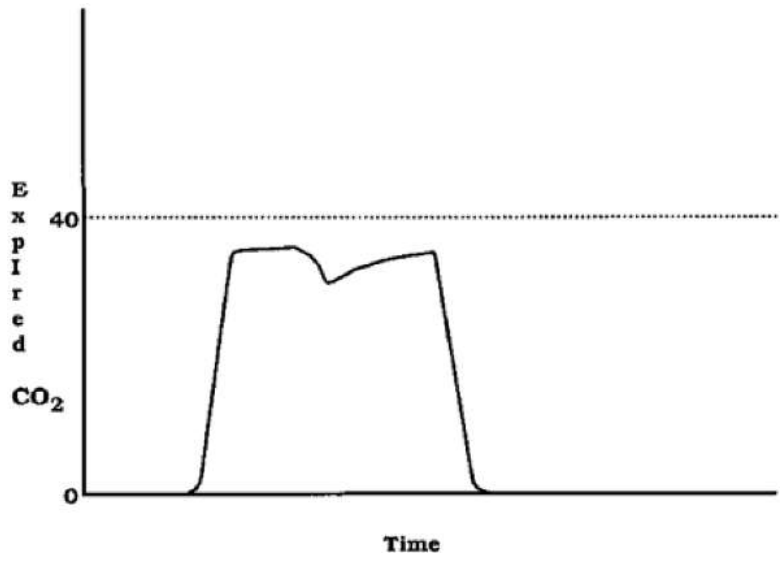


Figure 22.35 If the compliance, airway resistance, or ventilation-perfusion ratios in one lung differ substantially from the other lung, a biphasic expiratory plateaus may be seen (506). This type of capnogram has been reported in a patient with severe kyphoscoliosis (507) and following single-lung transplantation (508).

These devices are not true monitors of anesthetic depth, as the condition of the patient depends on many other things besides the inhaled anesthetic agent concentration. Anesthetic agent monitoring should not be regarded as a replacement for other means of measuring anesthetic depth but as an additional source of information. A study of anesthetized patients found that prediction of arterial levels from end-tidal concentrations was difficult (530). Agent monitoring has not been shown to result in an improvement in intraoperative hemodynamic stability or early recovery with either high or low total gas flows (531,532,533).

Detecting Contaminants

Contaminants in the nitrous oxide supply were detected with an agent monitor that indicated the presence of a volatile agent when no vaporizer was turned ON (534). An agent monitor indicated a warning that a foreign agent was present when a defective temperature-compensation device in a vaporizer released diethyl ether into the vaporizing chamber and the inspired gas (141).

Information for the Electronic Record System

With the expected increase in automated record keeping, the ability to automatically add information such as the concentration of volatile agent to the record is important (Chapter 28).

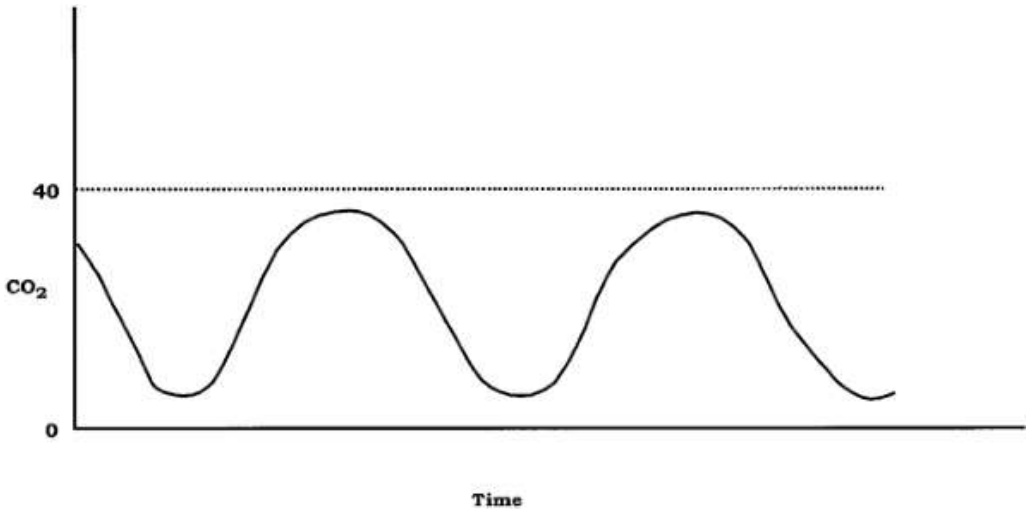


Figure 22.36 Too low a sampling rate with a sidestream capnometer will result in a low peak and, often, elevation of the baseline. Erroneous values for both inspired and end-tidal CO_2 will be reported.

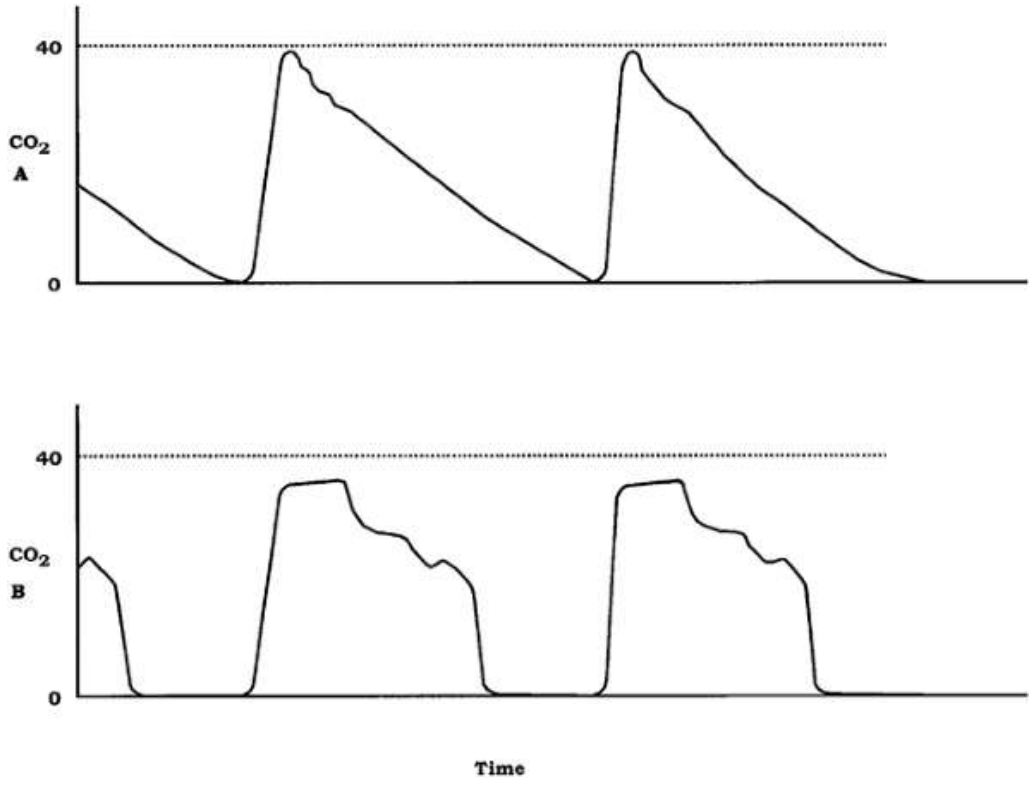


Figure 22.37 Contamination of expired sample by fresh gas or ambient air may be caused by placing the sampling site too near the fresh gas inlet, a leak, or too high a sampling flow rate. **A:** A large leak is indicated by the progressive decrease in the plateau. **B:** Here, the contamination is of lesser magnitude and a dropoff occurs at the end of the plateau.

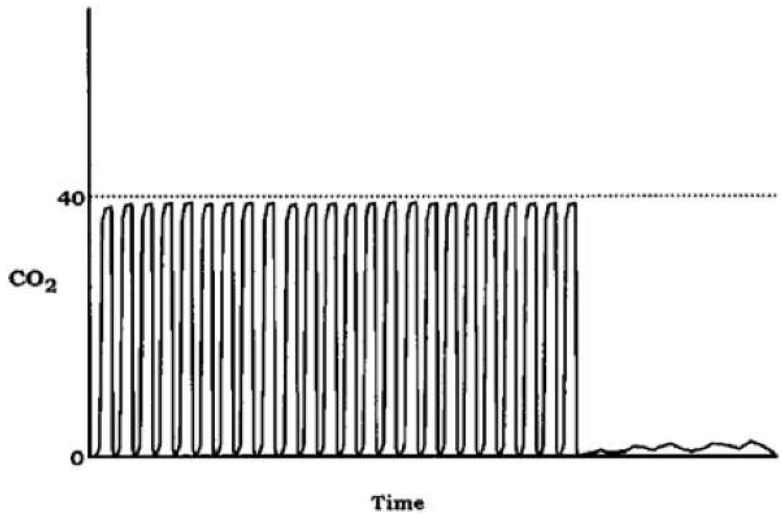


Figure 22.38 A sudden drop of end-tidal CO_2 to zero is usually caused by an acute event relating to the airway, such as extubation, esophageal intubation, complete breathing system disconnection, ventilator malfunction, or a totally obstructed tracheal tube. It may also be the result of a plugged gas sampling tube.

Detecting Disconnections

If a disconnection occurs between the CO_2 sensing site and the breathing system while the patient is spontaneously breathing, the agent concentration may drop while the end-tidal CO_2 level will be unchanged (535).

Nitrous Oxide

Technology

Nitrous oxide can be measured directly only by infrared technology. There are and international and U.S. standards covering the requirements (209,210). When oxygen and nitrous oxide are used together, the nitrous oxide concentration can be approximated by the oxygen analyzer.

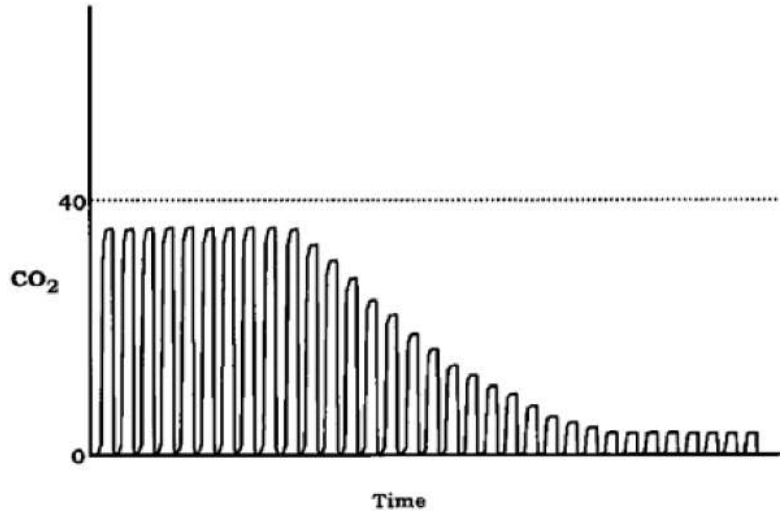


Figure 22.39 The causes of a sudden drop of end-tidal CO_2 to a low but nonzero value include a poorly fitting tracheal tube or mask, a leak or partial disconnection in the breathing system, and a partial obstruction of a tracheal tube.

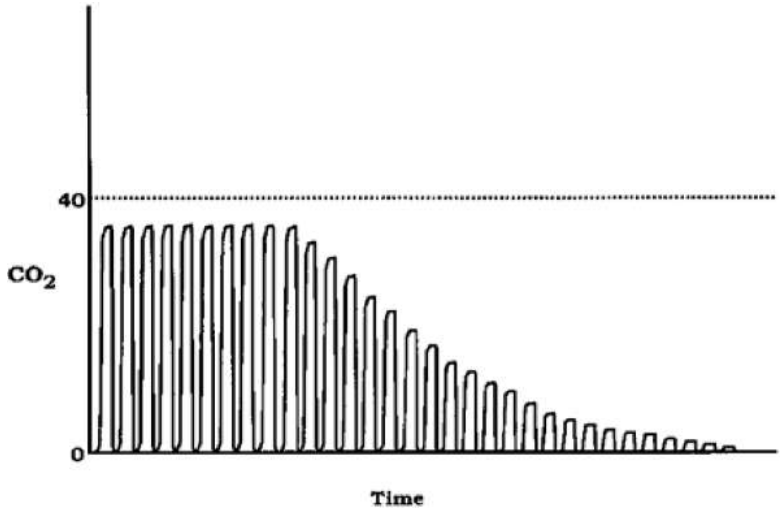


Figure 22.40 Events that cause an exponential decrease in end-tidal CO_2 include sudden hypotension owing to massive blood loss or obstruction of a major blood vessel, circulatory arrest with continued pulmonary ventilation, and pulmonary embolism (air, clot, thrombus, or marrow).

Significance

Analysis of nitrous oxide will show whether the flowmeters are functioning properly. At the end of a case, washout of nitrous oxide will avoid diffusion hypoxia.

Nitrogen

Previously, nitrogen could be measured by using Raman scattering or mass spectrometry. At the time of this writing, both of these technologies were no longer available for clinical use. This constitutes a loss for the clinician because there are advantages to monitoring nitrogen. These advantages are discussed (pp. 721â€“722) in hopes that in the future some technology will be developed that will allow this monitoring.

Verifying Adequate Denitrogenation

An important use of nitrogen monitoring is to ensure adequate denitrogenation before induction. This is especially a concern with pediatric patients, in patients with lung disease, and in patients with a reduced functional residual capacity

(e.g., obesity or pregnancy) as well as during a rapid sequence induction.

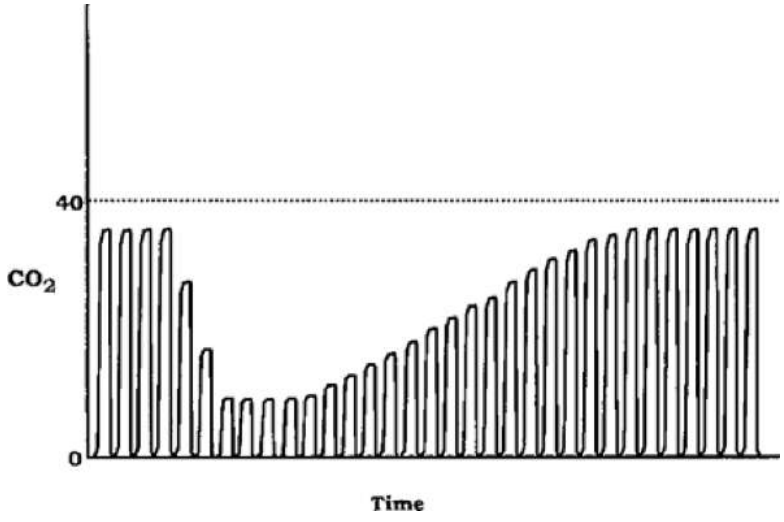


Figure 22.41 Small air embolus with resolution.

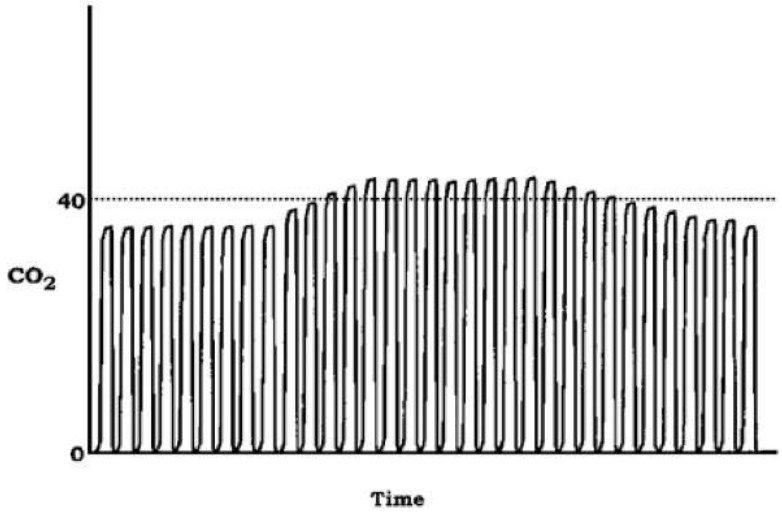


Figure 22.42 Release of a tourniquet or unclamping of a major vessel may result in a sudden increase in end-tidal CO_2 that gradually returns to normal.

Detecting Venous Air Emboli

A rise in exhaled nitrogen may indicate that air from some source has entered the breathing system (536). Nitrogen monitoring can provide information that is helpful in distinguishing air emboli from other events that cause reduced CO_2 elimination.

Monitoring Breathing System and Anesthesia Machine Integrity

Normally during general anesthesia, the level of nitrogen in the breathing system drops rapidly at first and then more slowly. A slow drop or a rise may be caused by room air entering through a leak, disconnection, poorly fitting mask, an uncuffed or leaking tracheal tube, or a change in vaporizers (537,538).

A leak in the sampling system can cause nitrogen to be detected. To determine if this is occurring, pure oxygen from the anesthesia machine should be sampled. If the monitor continues to show nitrogen, air is leaking into the sampling line.

Detecting Nitrogen Accumulation

Despite high initial gas flows, nitrogen can built up in the breathing system during low-flow anesthesia. This can cause a significant decrease in the levels of oxygen, nitrous oxide, and volatile agents.

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Questions

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

1. Advantages of a nondiverting monitor include

A. Quick response time

B. Water is less likely to cause problems

C. Scavenging of gases is not necessary

D. A standard calibrating gas can be used

View Answer

2. Disadvantages of a nondiverting monitor include

A. Only CO_2 and oxygen can be measured by this method

B. Blood on the curette will cause accuracy problems

C. The sensor can be damaged by mishandling

D. It cannot be used on patients who do not have a tracheal tube in place

View Answer

3. Possible sampling sites for a diverting monitor include

A. An HME

B. The base or inside of the nose

C. An elbow adaptor

D. The distal end of a tracheal tube

View Answer

4. If the sampling flow rate of a diverting monitor is too low,

A. The delay time and rise time will be decreased

B. The peak readings on the capnogram will be lowered

C. The baseline on the capnogram will be depressed

D. The plateau on the capnogram will be absent

View Answer

5. Advantages of a diverting gas monitor include

A. Calibration and zeroing are usually automatic

B. The patient connection is usually disposable

C. Remote monitoring is possible in the MRI suite

D. Low dead space

View Answer

6. Disadvantages of a diverting gas monitor include

A. Dead space in the breathing system is increased

B. Gases from the monitor must be returned to the

breathing system or scavenged

C. Warm-up is usually prolonged

D. The delay time is prolonged

View Answer

7. Advantages of infrared monitors include

A. They do not need to be kept on standby

B. Response time is fast enough to measure both inspiratory and end-tidal values

C. Units are small and lightweight

D. Periodic calibration with a standard gas is sufficient

View Answer

8. Disadvantages of infrared gas analysis include

A. Water vapor will cause interference

B. It is difficult to add new agents

C. Helium causes artifactually low CO_2 values

D. Sampled gases must be scavenged after analysis and cannot be added to the breathing system

View Answer

9. Which of the following definitions is correct?

A. Delay time is the time to achieve 10% of a step change in reading at the gas monitor

B. The partial pressure of a gas is the pressure that a gas in a gas mixture would exert if it alone occupied the volume of the mixture at the same temperature

C. Rise time is the time required for a change from 10% to 90% of the total change in a gas value with a change in concentration at the sampling site

D. The sampling site is the location from which gas is diverted for measurement in a diverting monitor or the location of the sensor in a nondiverting monitor

View Answer

10. Concerning microstream technology,

A. It utilizes laser-based technology

B. It provides a rapid response time

C. Readings are not affected by high concentrations of oxygen or anesthetic gases

D. The airway adaptor has two channels, each facing a different direction

View Answer

Chapter 23

Airway Volumes, Flows, and Pressures

Definitions

1. *Compliance*: Ratio of a change in volume to a change in pressure. It is a measure of distensibility and is usually expressed in milliliters per centimeter of water (mL/cm H_2O). Compliance commonly refers to the lungs and chest wall. Breathing system components, especially breathing tubes and the reservoir bag, also have compliance.
2. *Expiratory Flow Rate*: Rate at which gas is exhaled by the patient expressed as volume per unit of time.
3. *Expiratory Flow Time*: Time between the beginning and end of expiratory flow (Fig. 23.1).
4. *Expiratory Pause Time*: Time from the end of expiratory flow to the start of inspiratory flow (Fig. 23.1).
5. *Expiratory Phase Time*: Time between the start of expiratory flow and the start of inspiratory flow. It is the sum of the expiratory flow and expiratory pause times (Fig. 23.1).
6. *Inspiratory Flow Time*: Period between the beginning and end of inspiratory flow (Fig. 23.1).
7. *Inspiratory Pause Time*: That portion of the inspiratory phase time during which the lungs are held inflated at a fixed pressure or volume (i.e., the time of zero flow (Fig. 23.1). It is also called the *inspiratory hold*, *inflation hold*, and *inspiratory plateau*.
8. *Inspiratory Phase Time*: Time between the start of inspiratory flow and the beginning of expiratory flow (Fig. 23.1). It is the sum of the inspiratory flow and inspiratory pause times. The inspiratory pause time:inspiratory phase

time (T_{IP}:T_I) may be expressed as a percentage.

9. *Inspiratory:Expiratory Phase Time Ratio (I:E ratio)*: Ratio of the inspiratory phase time to the expiratory phase time. For example, an I:E ratio of 1:2 means that the inspiratory phase time is one third of the ventilatory cycle time.
10. *Inspiratory Flow Rate*: Rate at which gas flows into the patient expressed as volume per unit of time.
11. *Minute Volume*: Sum of all tidal volumes within 1 minute.
12. *Peak Pressure*: Maximum pressure during the inspiratory phase time (Fig. 23.1).
13. *Plateau Pressure*: Resting airway pressure during the inspiratory pause. There is usually a lowering of airway pressure from peak pressure when there is an inspiratory pause (Fig. 23.1). This lower pressure is called the *plateau pressure*.
14. *Positive End-expiratory Pressure* (PEEP): Positive pressure in the airway at the end of exhalation.
15. *Resistance*: Ratio of the change in driving pressure to the change in flow rate. It is commonly expressed as centimeters of water per liter per second (cm H_2O/L/second).
16. *Tidal Volume*: Volume of gas entering or leaving the patient during the inspiratory or expiratory phase time, respectively.
17. *Ventilatory (Respiratory) Rate or Frequency*: Number of respiratory cycles per unit time, usually per minute.
18. *Work of Breathing*: Energy expended by the patient and/or ventilator to move gas in and out of the lungs (1). It is expressed as the ratio of work to volume moved, commonly as joules per liter. It includes both the work needed to overcome the elastic and flow-resistive forces of the both respiratory system and apparatus.

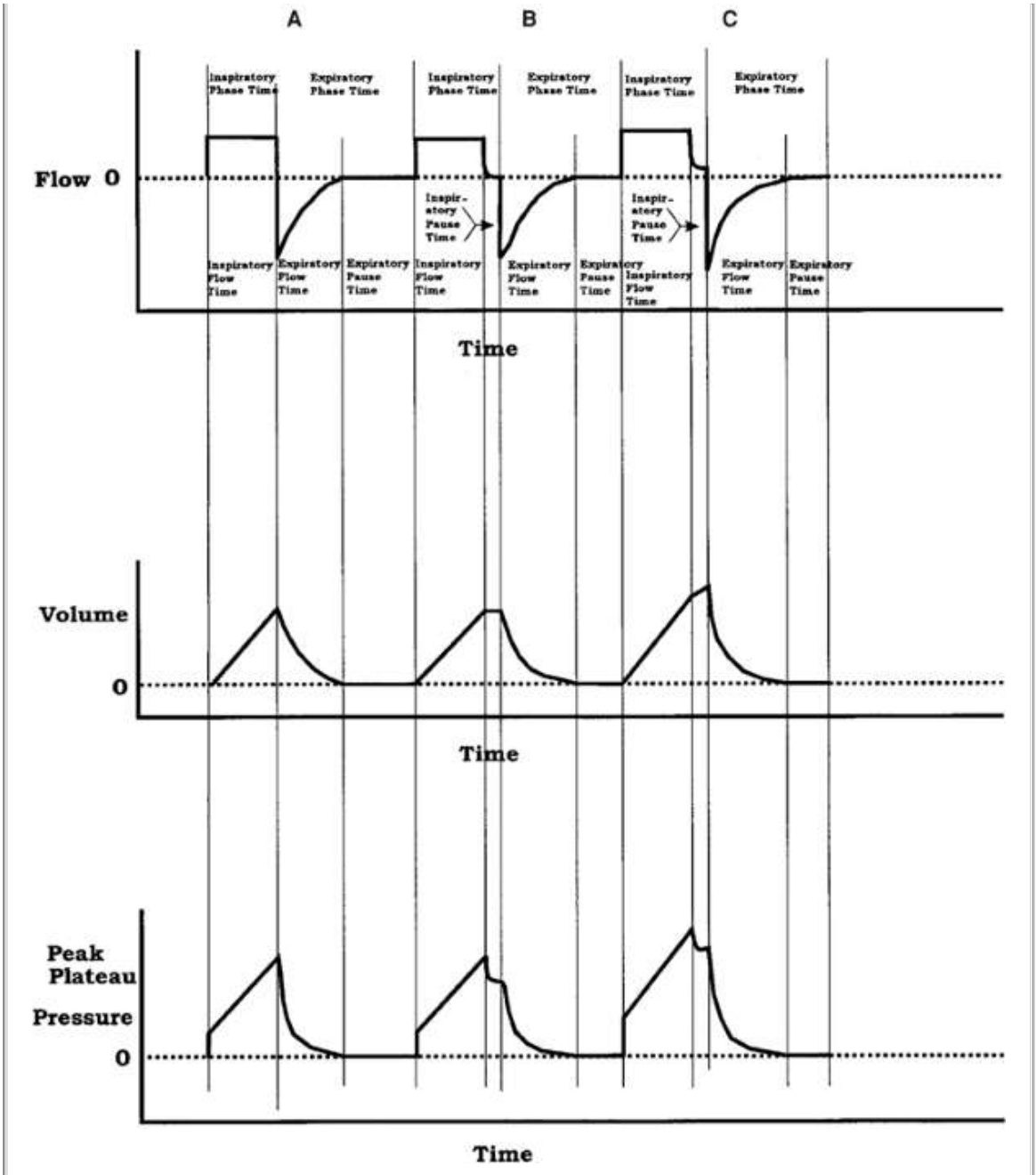

Figure 23.1 Flow, volume, and pressure curves from a ventilator that produces a rectangular inspiratory flow wave. **A:** This represents controlled ventilation with no inspiratory pause. The end-inspiratory pressure will equal the peak pressure. **B:** With an inspiratory pause, there is a decrease from peak pressure to a lower plateau pressure. **C:** This illustrates the effect of continuing fresh gas flow during inspiration. The inspired volume increases, and the peak pressure falls, then rises.

General Considerations

The Ventilatory (Respiratory) Cycle

Airway pressure with controlled ventilation is shown in Figure 23.1. There is a rise in pressure with no preceding negative pressure. A fast rise to peak pressure suggests too high a flow. The peak pressure will increase if tidal volume, inspiratory flow rate, or resistance increases or compliance decreases. A decrease in peak pressure may result from a leak, spontaneous inspiratory effort by the patient, a decrease in resistance, or an increase in compliance.

Figure 23.1B shows the respiratory cycle with an inspiratory pause. If the pause is long enough, a plateau pressure will occur at the end of inspiration. The plateau pressure is usually preceded by a higher peak pressure.

Plateau pressure depends on tidal volume and the total static compliance but is independent of resistance (2).

Compliance and Resistance

In the past, compliance and resistance measurements during anesthesia were difficult and involved bulky apparatus. They can now be measured accurately on a real-time basis with relatively compact equipment.

Compliance

Compliance measurement may be dynamic or static. Dynamic compliance is calculated by dividing the difference in volume by the difference in pressure at two points during the ventilatory cycle. This is not a true measure of total compliance, because the airway pressure includes the pressure needed to overcome resistance (3).

Static compliance is calculated by using the end-inspiratory occlusion pressure (4,5) (Fig. 23.22). Conditions of zero gas flow are achieved by employing an inspiratory hold or occluding the expiratory port long enough to allow airway pressure to reach a constant value. This pressure, commonly termed *plateau*

pressure, represents the elastic recoil of the total respiratory system at end-inflation volume.

Static Compliance = Tidal volume/Plateau pressure - Positive end-expiratory pressure (PEEP)

In adults, normal total static compliance is 35 to 100 mL/cm H_2O. In children, normal static compliance is greater than 15 mL/cm H_2O (6).

Total compliance reflects the elastic properties of the lungs, thorax, abdomen, and the breathing system. Using muscle relaxants will increase chest wall compliance but will not affect lung compliance, so in paralyzed patients, changes in compliance reflect mainly alterations in lung compliance.

Resistance

When gas flows through a tube, energy is lost. This is reflected by a decrease in pressure. The pressure drop can be expressed as the product of resistance and flow rate. For a given tidal volume, a high resistance may be overcome by using a lower flow for a longer time or a higher driving pressure. During controlled ventilation, if there is an increase in airway resistance, the pressure needed to deliver a given tidal volume will increase. This can usually be supplied by the ventilator or the person squeezing the reservoir bag so that inspiratory flow is not affected. Because exhalation is passive, expiratory flow depends on the elastic and resistive forces of the lungs and the resistance in the expiratory limb of the breathing system and airway device.

Total resistance, which may differ during inspiration and expiration, is determined predominantly by the resistance of the patient's airway, the tracheal tube, and the breathing system. Decreased airway caliber from bronchoconstriction, secretions, tumor, edema, a foreign body, or airway closure is associated with increased resistance. Tracheal tube resistance depends primarily on its internal diameter. Partial tube obstruction by secretions, kinking, or other problems will cause increased resistance. Breathing system resistance is affected by the length and internal diameter of its components and is increased by sharp bends and constrictions.

Total airway resistance can be estimated by using the difference

between peak and plateau pressures, which is normally 2 to 5 cm H_2O. If there is an increase in resistance, a higher peak pressure will be necessary to produce the same flow. Plateau pressure, however, depends only on compliance and will not be affected by resistance. Therefore, if the inspiratory flow and tidal volume remain constant but resistance increases, there will be a greater difference between the peak and plateau pressures.

Measured Gas Composition

The composition of the gas being measured will affect the accuracy of flow-measuring devices (7,8). Differences in density and viscosity of the gases can induce an error in flow measurement. The composition of carrier gas has a greater impact on viscosity than volatile anesthetic agents, whereas density is more influenced by volatile agent concentrations (9).

For accuracy, the flow-measuring device should be associated with a gas monitor that can make corrections to gas flow caused by changes in gas composition. If a gas such as xenon that is not measured is present, flow measurements may be inaccurate (8).

Respiratory Volume and Flow Measurement

A respirometer (spirometer, ventilation or respiratory meter or monitor, ventilometer, volume measuring device, flow monitor, respiratory flowmeter) is a device that measures the volume of gas passing during a period of time through a location in a flow pathway (10).

Monitoring respiratory volumes and flows can aid in detecting breathing system obstructions, disconnections, apnea, leaks, ventilator failure, and high or low volumes in spontaneously breathing patients as well as in those whose ventilation is controlled. Some can detect reversed flow, an indication of an incompetent unidirectional valve or a leak. A discrepancy between expired and inspired tidal volume should suggest a leak.

A decrease in tidal volume associated with the tracheal tube migrating into a bronchus may be detected (11). Although there are other ways of detecting these problems, such as observing

chest wall movements, monitoring breath sounds, capnometry, and airway pressure monitoring, the use of a volume monitor provides additional protection. One study found that for detecting and classifying breathing system faults, a volume monitor was better than airway pressure or carbon dioxide monitoring (12). In 1999, the American Society of Anesthesiologists (ASA) strongly encouraged qualitative monitoring of the volume of expired gas. The anesthesia workstation standard requires a device to monitor the patient's exhaled tidal or minute volume or both (13).

Respiratory volume monitoring may fail to detect some problems. With airway occlusion, there may be enough flow during expiration resulting from compression of gas within the breathing system during inspiration to prevent the respirometer alarm from being activated. If the sensor is attached to the patient's tracheal tube or supraglottic airway device, a disconnection between the sensor and the breathing system will not be detected if the patient is spontaneously breathing. If the sensor is in the exhalation side of the breathing system, the disconnection will be detected. It is possible to have fairly normal flow with esophageal intubation.

A high-volume alarm may be useful to detect unanticipated increases in tidal volume (14). This may be due to improper ventilator settings or increased gas flow into the breathing system during inspiration, resulting from a hole in the ventilator bellows, an increased inspiratory:expiratory (I:E) ratio, or from the flowmeters (if there is no fresh gas flow compensation or decoupling). During pressure control ventilation, a decrease in compliance will result in an increased tidal volume.

Older respirometers were strictly mechanical devices. Newer respirometers convert flow into an electronic signal that is processed and displayed. Electronic processing enhances alarm capability. Alarm limits should be set as close as possible to the displayed tidal or minute volume without producing an unacceptable incidence of false-positive alarms (15).

Equipment

Ventilator Bellows Scale

Ventilators that are used in anesthesia are discussed in Chapter 12. If the ventilator has a bellows, there is usually a scale on the

bellows housing. This scale can provide a rough estimate of tidal volume delivered into the breathing system but is not an accurate estimate of the volume delivered to the patient because of wasted ventilation secondary to gas compression and distension of components of the breathing system. If the fresh gas flow adds to the tidal volume during inspiration (see Chapter 12), this added volume will not be represented on this scale.

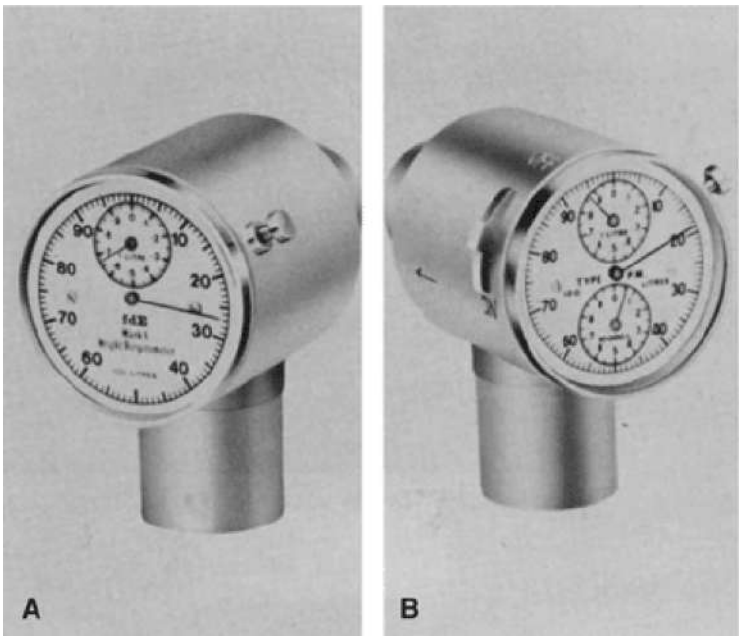

Figure 23.2 Wright respirometers. **A:** This small instrument can be handheld or inserted into the breathing system. It has two dials: a large peripheral one and a smaller one on the upper part of the main dial. The small dial indicates volumes up to 1 L and the large dial up to 100 L. Note the reset button on the side. **B:** This version has three dials. The top small dial reads up to 1 L, the large dial indicates volumes up to 100 L, and the bottom small dial reads up to 10,000 L. Note the on-off control and the directional flow arrow. (Courtesy of Ferraris Medical, Inc.)

Wright Respirometers

Description

Typical Wright respirometers are shown in Figure 23.2. They are supplied with adaptors to facilitate connection to a mask, airway device, or breathing system. There is an ON-OFF control in the form of a sliding stud and a spring-loaded reset button to set the hands of the scales to zero.

An infant version that can measure volumes down to 15 mL is available (Fig. 23.3). Its dead space is 15 mL. An electronic version is also available (15).

The internal construction is shown in Figure 23.4. Gas entering through the outer casing is directed through a series of tangential slots enclosed in a cylindrical housing and strikes a vane, causing it to rotate. The vane is connected by a mechanical gear system to the hands on the dial so that a reading corresponding to the volume of gas passing through the device is registered.

Evaluation

Most studies have found that the Wright respirometer over-reads at high flows and under-reads at low flows (16,17,18). Pulsatile flows can cause additional over-reading. It will give slightly higher readings with mixtures of nitrous oxide and oxygen than for air and will slightly over-read in the presence of xenon (8).

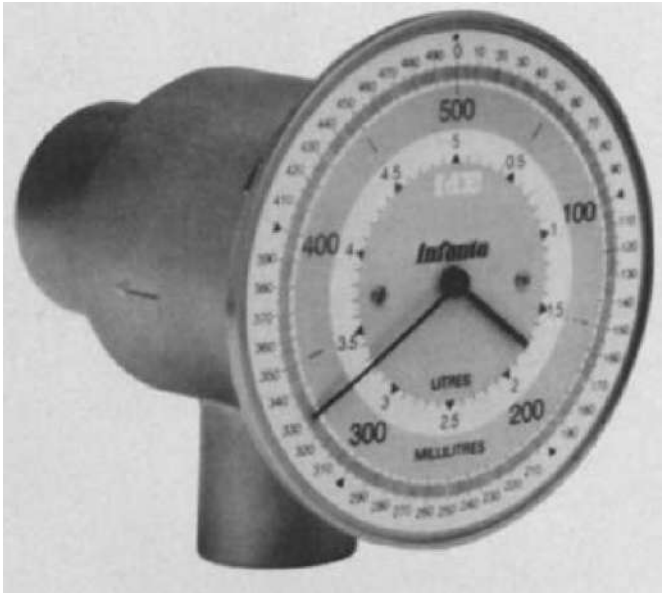

Figure 23.3 Infant version of Wright respirometer. The outer scale goes up to 500 mL, and the inner scale goes up to 5 L. (Courtesy of Ferraris Medical, Inc.)

Advantages of the Wright respirometer include its small size and light weight. Its low dead space makes it suitable for use between the patient and the breathing system.

The main disadvantage is that it has no alarms. It is somewhat difficult to read and does not give respiratory rate. A clock is necessary to determine minute volume. It does not read bidirectional flow. Maintenance can be expensive. Many instruments that are in use are inaccurate because of poor mechanical condition. Its portability can result in inaccuracy due to pocket dirt and a high incidence of damage from being dropped. Guards that are designed to reduce damage from physical abuse are available. It needs to be cleaned and disinfected between patients.

Spiromed

Description

The Spiromed is an electronic respirometer that is designed for use with North American Drager breathing systems (19,20). As

gas flows through the monitor, it forces a pair of rotors to counter-rotate (Fig. 23.5). Attached to the axle of one of the rotors is a four-pronged armature with a small magnet at the tip of each prong. As exhaled gas flows through the sensor, the rotor and armature spin in unison. Located at approximately the 12 and 7 o'clock positions are two transistors that turn ON in the presence of a magnetic field. As the armature that carries the magnets rotates, the transistors are turned ON and OFF. These paired pulses are transmitted through the sensor cable to the interface panel and then to the processor.

Figure 23.4 Internal construction of Wright respirometer. Gas entering the casing is directed through a series of tangential slots and strikes the vane in the center, causing it to rotate.

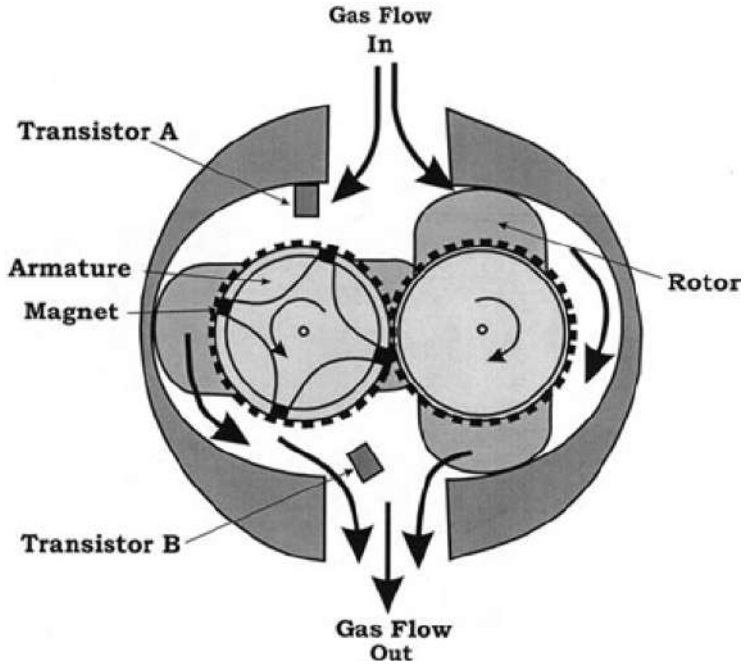

Figure 23.5 Spiromed. (See text for details.)

The number of paired pulses is related to the volume of gas that passes through the sensor over time. The total number of pulse pairs counted during each exhalation determines the tidal volume. The speed at which the exhaled gas flows through the sensor determines the duration of each pulse pair. Rapid gas flow causes the rotors and armature to spin quickly, and shorter pulses are produced as the transistors rapidly cycle. With slower gas flow, longer pulses are produced. The processor analyzes the pulse lengths and displays the information as the exhaled waveform.

Sixty seconds of continuous data is required for the initial display of the respiratory rate, and the displayed reading is recalculated after each exhalation. For an exhalation to be counted as a ĩ€valid breath,ĩ€ the processor must count at least 80 mL. All exhaled gas volumes, regardless of size, are counted and included in calculating the minute volume. The sensor in the breathing system is shown in Figure 23.6.

The Spiromed sensor recognizes the direction of gas flow by monitoring the phase relationship between the pulses in each

pulse pair. When the gas flows ‾€forward,‾€ the pulse from one transistor leads the pulse from the other transducer because of the armature's rotational direction. If gas flows in the wrong direction, the order

of the pulses is reversed and the processor recognizes this as reverse flow. If two consecutive pulse pairs are in reverse order, a reverse flow alarm is generated.

Figure 23.6 Spiromed in place in breathing system.

Evaluation

This instrument is programmed to measure tidal volumes equal to or greater than 150 mL. If the tidal volume is less than 150 mL, the instrument will automatically add two or more consecutive tidal volumes and reduce the recorded frequency accordingly. The minute-volume display remains correct.

The accuracy of tidal volume measurement is reported as

ยฑ0.04 L, minute volume as ยฑ10% of reading or 0.1 L, and respiratory rate as ยฑ8% of reading or 1 breath/minute.

D-Lite Gas Sampler and Flow Sensor

Description

The flow sensor (Fig. 23.7) for this device is a modified Fleisch pneumotach with a two-sided Pitot tube (21,22,23,24). The Fleisch pneumotach measures flow by measuring the pressure difference across a flow resistor (capillary tube) in a tube. The Pitot tube uses two sensing tubes to make a differential pressure measurement. One tube faces the direction of flow (total pressure), and the other faces the opposite direction to measure the static pressure. The difference in pressure between the total pressure and static pressure is the dynamic pressure, which is proportional to the square of gas flow.

The sensor body (Fig. 23.8) consists of a straight tube with a combined 15-mm female/22-mm male connector on the patient end and a 15-mm male connector on the machine end. Two small hollow pressure tubes perforate the side of the tube and extend into the lumen. Each makes a 90-degree turn inside the lumen so that the end of one tube faces the breathing system and the other end faces the patient. A gas sampling port is also present. A double-lumen tube conducts the flow signal as a pressure difference to the pressure sensor inside the monitor.

The sensor is placed between the breathing system and the patient. A filter or heat and moisture exchanger may be placed on either side of the sensor. If placed between the patient and the sensor, mucus and humidity will be prevented from entering the gas sampling tube. If the sensor is placed between the patient and the heat and moisture exchanger, a higher compliance will be observed than if it is placed between the heat and moisture exchanger and the Y-piece (25).

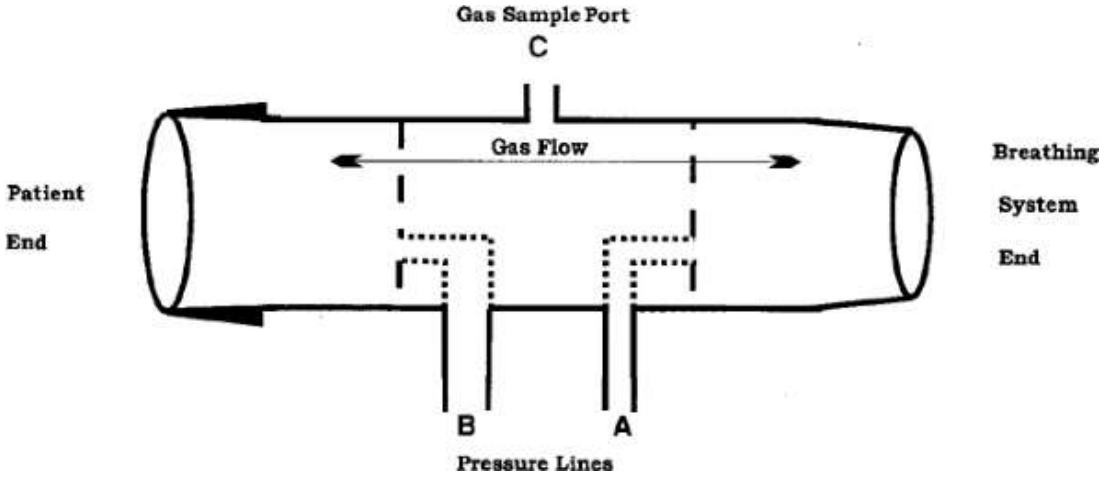

Figure 23.7 D-Lite flow sensor and gas sampler. The patient end has a 15-mm internal and 22-mm outside diameter connector to fit a mask or tracheal tube connector. The other end has a 15-mm outside diameter connector. Because the pressure tubes point in opposite directions, gas flows can be measured during both inspiration and exhalation. Note that one pressure tube is larger than the other to avoid misconnection of the tubings. There is a gas sampling port on the opposite site of the sensor.

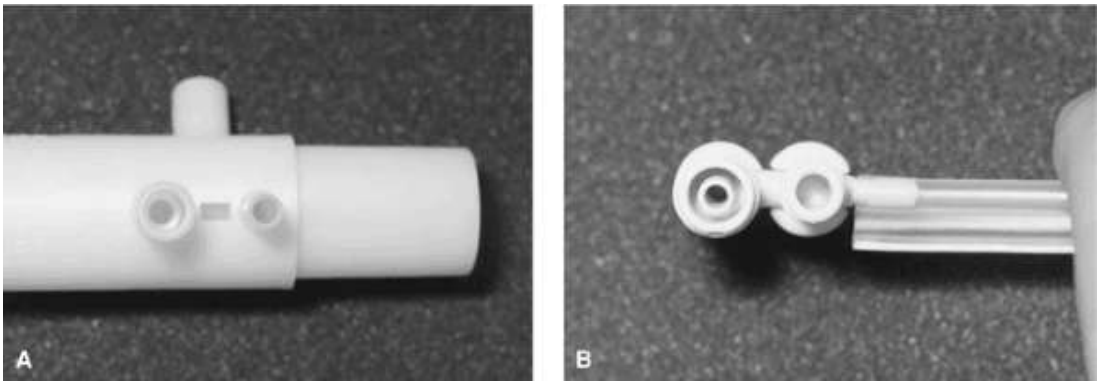

Figure 23.8 Sensor for D-Lite flow sensor and gas sampler **A:** The gas sample port is at the top. Note that the pressure line attachments utilize male and female connectors. **B:** Attachment for pressure tubings.

During inspiration, gas moves from the breathing system toward

the patient. The pressure in the hollow tube facing the breathing system and the pressure in the tube that faces away from the direction of gas flow are measured. Since the pressure tubings face in opposite directions, similar measurements can be made during exhalation, when the gas flow is reversed.

In the monitor (Fig. 23.9), concentrations of carbon dioxide, oxygen, and anesthetic agents are determined. The monitor utilizes the gas composition data to

compensate for changes due to density and viscosity (7). A correction factor must be applied if helium is in the respiratory mixture (26). From the derived flows (flow rate, peak flow) and measured pressures (end-expiratory, plateau, minimum, and maximum), the inspiratory and expiratory tidal and minute volumes, compliance, and resistance are calculated and displayed, and flow-volume and pressure-volume loops are displayed. Inspired and expired gas concentrations are also displayed.

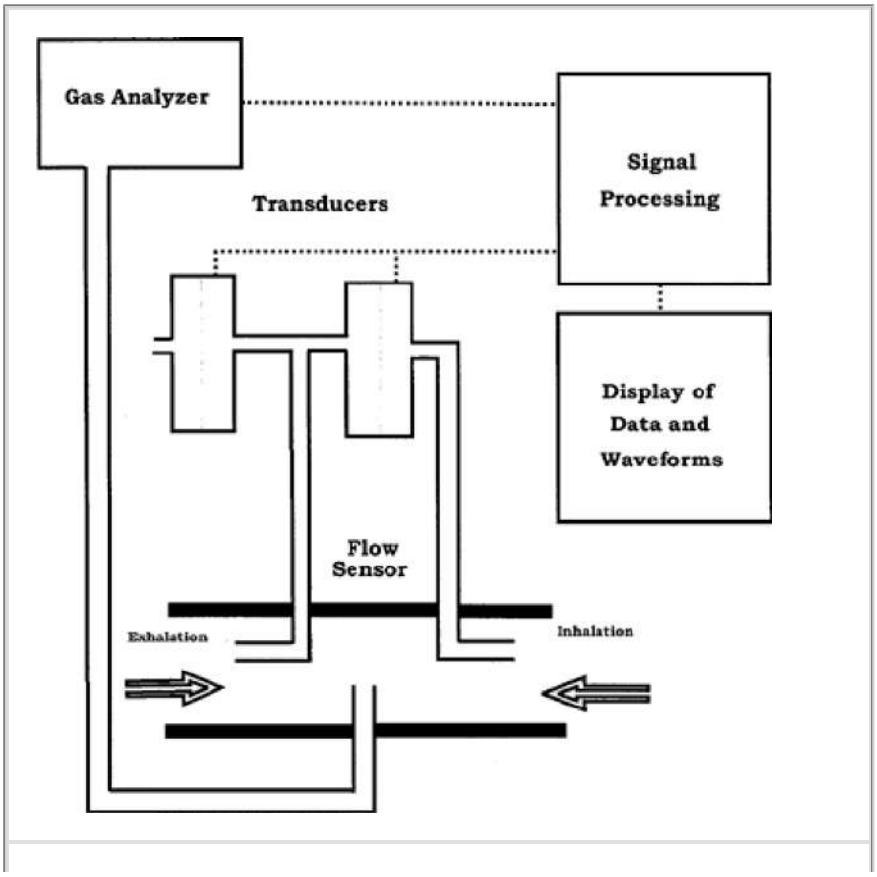

Figure 23.9 The monitor utilizes the gas composition data to compensate for changes due to density and viscosity. From the derived flows and measured pressures, the inspiratory and expiratory tidal and minute volumes, compliance, and resistance are calculated and displayed, and flow-volume and pressure-volume loops are displayed. Inspired and expired gas concentrations are also displayed.

Alarms include a high PEEP alarm with a default value of 10 cm H_2O. High pressure and low inspiratory pressure alarms have default settings of 40 and 0 cm H_2O. There are high and low expiratory minute volume alarms as well as messages for leak, disconnection, and obstruction.

Calibration

The sensor needs to be calibrated at least every 6 months (27). One indication that calibration needs to be performed is an open or overshoot pressure- and flow-volume loop (Figs. 23.61 and 23.62). The operation manual should be consulted for the complete procedure. It should be performed with the equipment in the configuration that will be used with the next patient. Accessories, such as heat and moisture exchangers, placed proximal to the sensor will not affect calibration. However, if the clinician wishes to place an accessory on the distal end of the sensor, then the unit should be calibrated with this in place. A different size of tracheal tube or the omission of the connector could affect the calibration value and result in incorrect volume measurements.

Evaluation

The D-Lite is used to measure flows in ranges common for adults and children down to 3 kg. Resistance to flow is 0.5 cm H_2O at 30 L/minute. Its volume is 9.5 mL. Tidal volumes of 150 to 2000 mL and minute volumes of 2.5 to 30 L/minute can be measured. The pedi-lite sensor can measure tidal volumes in the range from 15 to 300 mL. The range of measurement for airway pressure is -20 to +80 cm H_2O. The range of flow rates is -100 to +100 L/minute. It over-reads when xenon is used (8).

Regular visual inspection and water removal is required for

troublefree performance. If used for extended periods with heavy humidification, condensed water may occlude the pressure sensing or gas sampling tubes. The pressure and sample line tubings should be on the upper side of the sensor.

The D-Lite sensor has a simple and robust construction, light weight, low dead space, and no moving parts. It is not position dependent and allows bidirectional gas flow measurement. Small amounts of mucus and water droplets do not affect the measurements. Only one adaptor is needed for respirometry and gas sampling. It can be used with both circle and Mapleson breathing systems. Another important advantage is the ability to monitor flow-volume and pressure-volume loops.

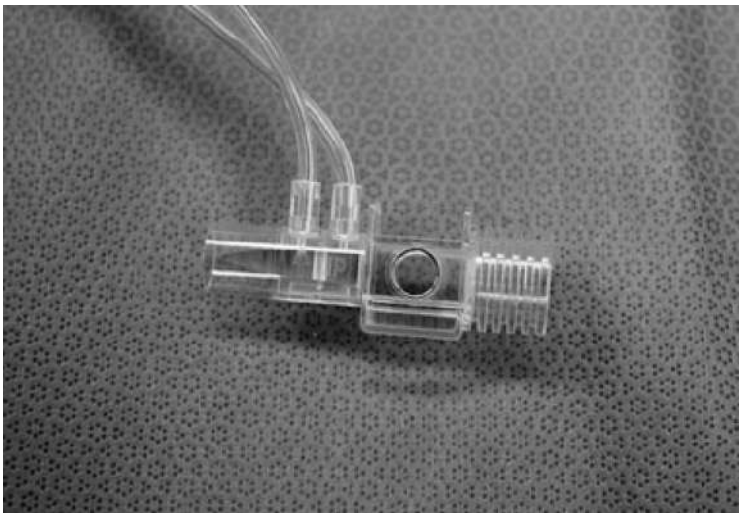

Figure 23.10 Novometrics sidestream sensor.

Novometrics Sidestream Sensor

The Novometrics sidestream sensor (Fig. 23.10) combines measurement of flow, pressure, and carbon dioxide. Flow is determined from a differential pressure measurement across a fixed orifice with a split obstruction to one side of the optical window used for mainstream carbon dioxide measurement. The sensor has a dead space of less than 0.8 mL, making it useful for the neonate (28).

Heated Wire Anemometer

In the heated-wire anemometer (thermal dissipation device) (Figs. 23.11, 23.12), gas flows around a thin wire (usually platinum or a platinum alloy) that is heated to a constant temperature (10). Heat is dissipated when gas flows past this wire. The greater the volume of gas flowing past per unit time, the more heat will be dissipated. The current level is usually low so that the outside of the sensor does not become heated.

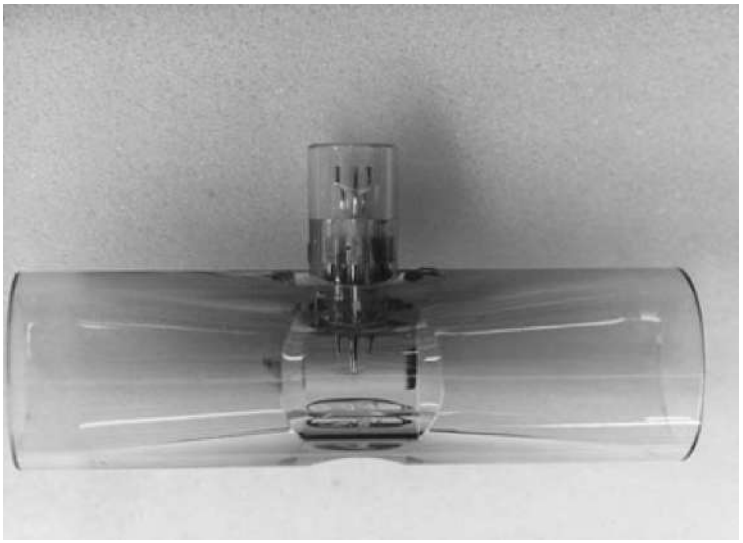

Figure 23.11 Heated wire anemometer.

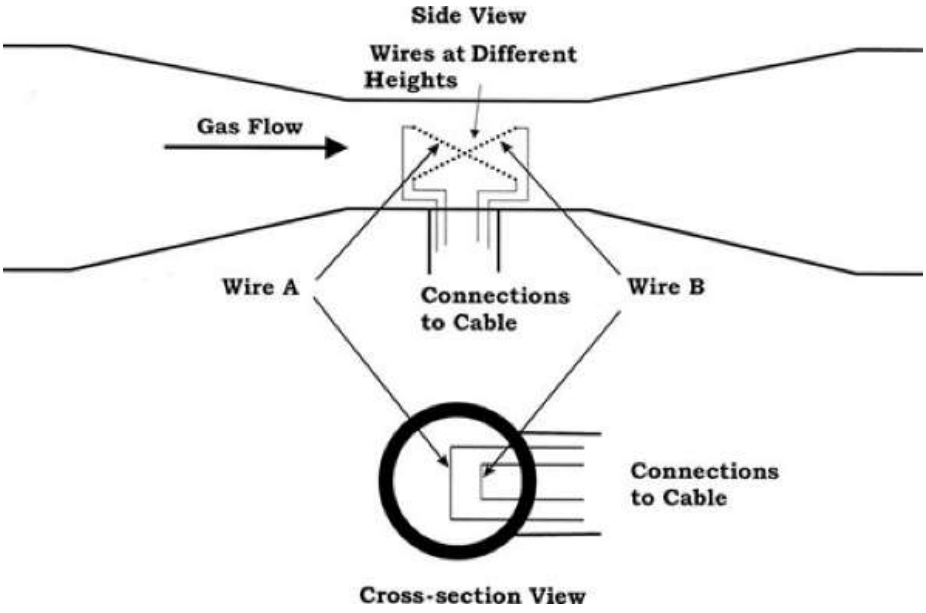

Figure 23.12 Heated wire anemometer. One wire is for measuring flow, and one is for reference.

The hot-wire sensor tends to be more accurate at low flow rates. Since it is insensitive to flow direction, two heated wires are needed to determine the flow direction. The heat dissipated by the second wire is determined when there is no gas flow (e.g., during inhalation in the exhalation side of the breathing system). It under-reads in the presence of xenon and slightly over-reads with nitrous oxide (8).

Ultrasonic Flow Sensor

An ultrasound sensor (Figs. 23.13, 23.14, 23.15) measures the influence of gas flow on the transmission times of pulses between two crystals. Sending and receiving transducers are used to transmit signals through the flow. The signal travels faster when moving with the flow stream rather than against the flow stream. The difference between the two transmission times is used to calculate the flow rate.

The flow sensor has no moving parts, is easy to clean, is autoclavable, and its accuracy is independent of gas composition. The flow measurement range is 0 to 120 L/minute. The accuracy is specified as ยท10% or 15 mL, whichever is

greater. Resistance is less than 2 cm H_2O at a flow of 60 L/minute.

Variable Orifice Flow Sensor

The variable orifice flow sensor is used with the Ohmeda 7900 series ventilators (Chapter 12) and the circle system. Sensors at both connections to the carbon dioxide absorber are used to measure inspiratory and expiratory flows. These sensors can be used to generate pressure- and flow-volume loops. The 7900 ventilator utilizes the information from these sensors to allow it to deliver accurate tidal volumes.

Construction

Each sensor (Figs. 23.16, 23.17) uses the principle of pressure drop across an orifice. A plastic flap that opens with increasing flows is placed across the direction of gas flow. Two sensors and a transducer

inside the anesthesia machine measure pressure proximal and distal to the flap. Volume is calculated from these flows. The sensor on the inspiratory side is connected to a pressure sensor so that breathing system pressure is measured. The information is used by the ventilator to compensate for changes in fresh gas flow.

Figure 23.13 Ultrasonic flow sensor in breathing system.

Figure 23.14 Inside of ultrasonic flow sensor.

Use

Before use, the tubes should be checked to make certain that they are clear. The pressure lines should point up, and there should be no kinks, cracks, or other problems. The use of filters is recommended to protect the sensors from contamination. Calibration by using a menu on the ventilator is recommended on a weekly basis.

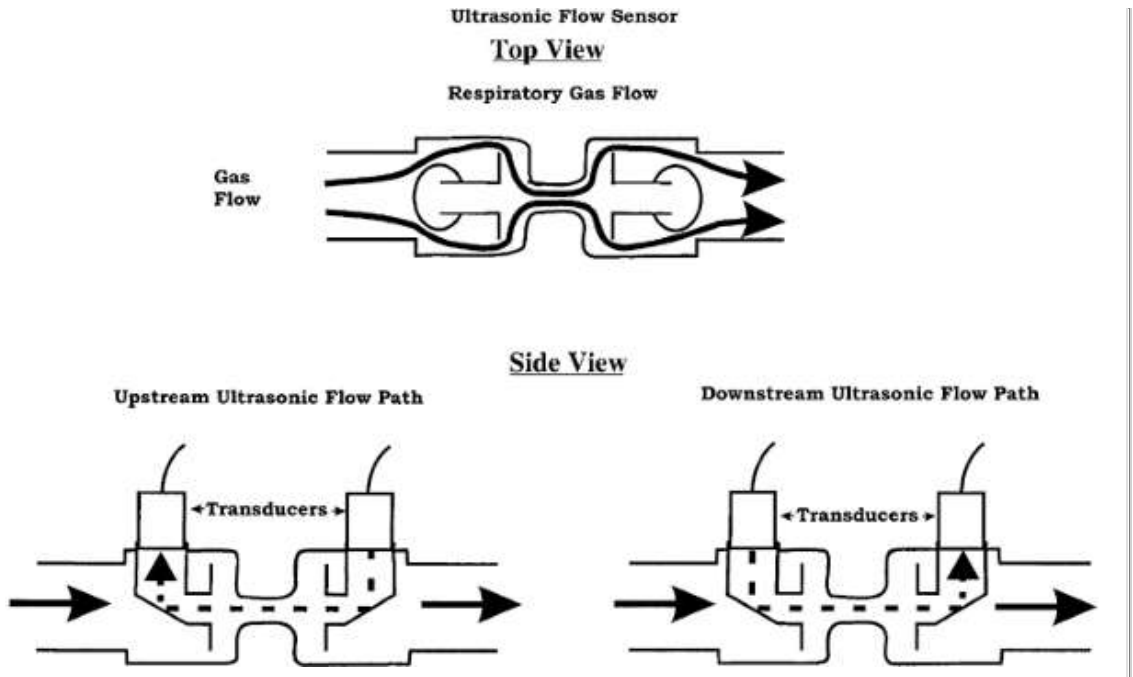

Figure 23.15 Diagram of ultrasonic flow sensor.

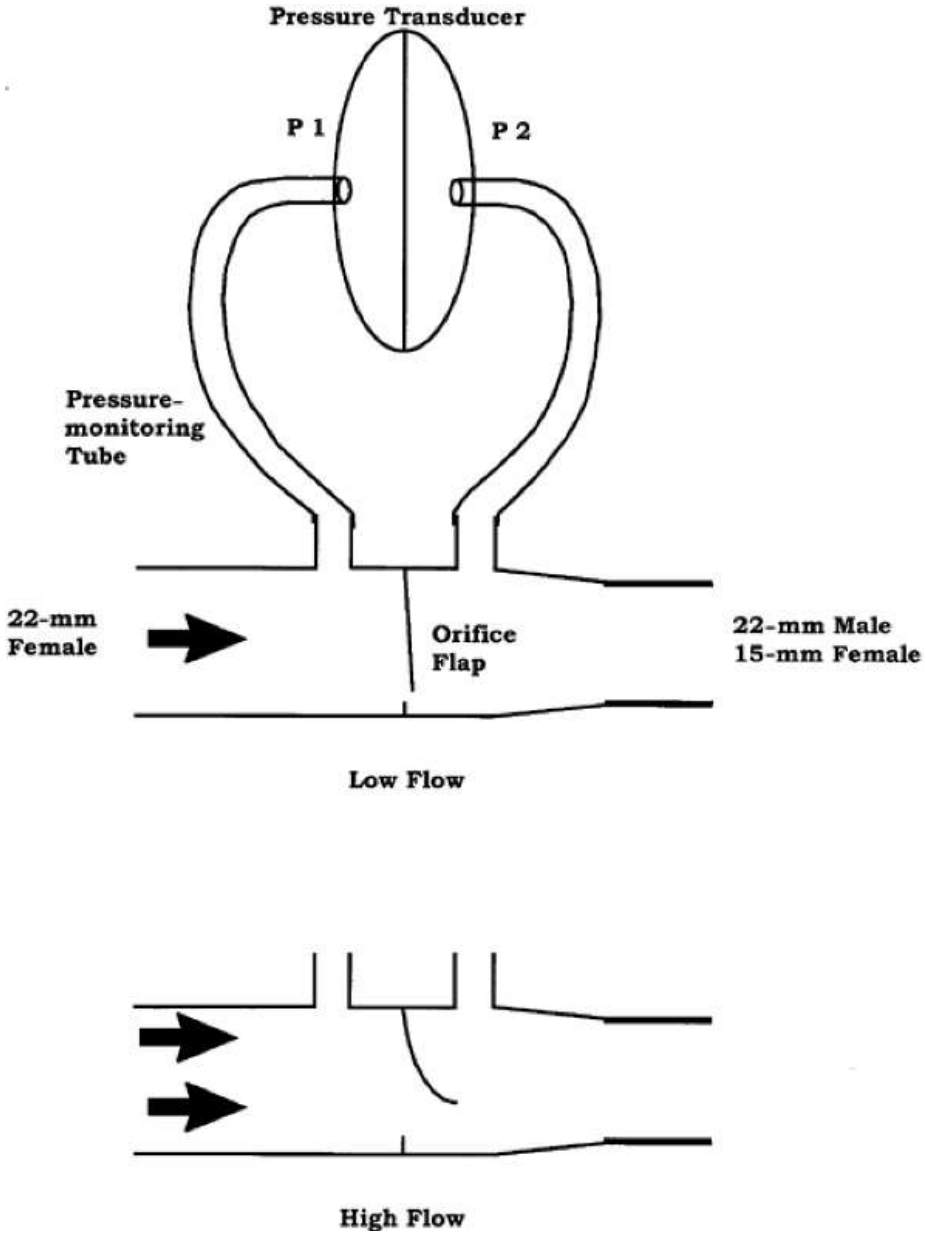

Figure 23.16 Variable orifice sensor. Gas flow causes the Milar flap to bend. There is a pressure drop across the flap. A transducer inside the ventilator converts the pressure drop into a flow.

Accuracy

The sensor can measure flows from 1 to 120 L/minute. There are

no respiratory rate limits. The instrument will read high with xenon and nitrous oxide (8).

Since both inspired and exhaled volumes are measured, the ventilator can make adjustments so that changes in fresh gas flow do not affect the delivered volumes. Since the sensors are located at the absorber, they cannot compensate for gas compression or expansion in the breathing system. This is a small error unless very compliant breathing tubes are used or the breathing system contains a large volume of gas.

Evaluation

The main advantage of this device is that it allows the ventilator to automatically compensate for changes in fresh gas flow. Disadvantages include the need for two sensors and filters. A break in one of the pressure lines can cause a leak in the breathing system

(29). The sensor itself may be the source of a leak (30,31,32,33). The sensors are sensitive to humidity (34,35).

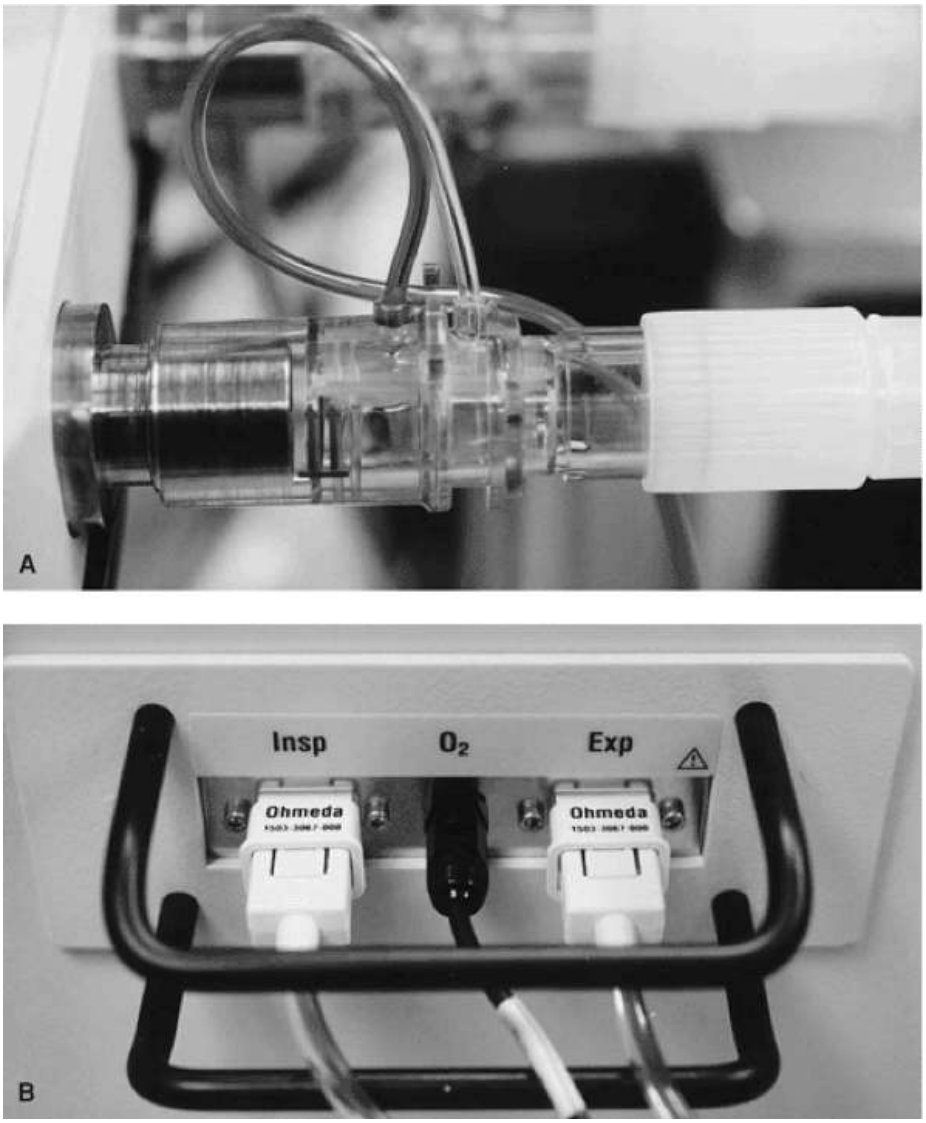

Figure 23.17 **A:** Variable orifice sensor. Tubings are attached on either side of the flap. **B:** Tubings from the sensors attached to the anesthesia machine. It is important that they are attached to the proper connection.

Fixed Orifice Flow Sensor

This device consists of a restrictor and two pressure sensors, one on either side of the restrictor. A zeroing valve compensates for pressure sensor drift.

Respirometer Position in the Breathing System

Figure 23.18 shows possible locations for a respirometer in the circle system. From the standpoint of accuracy, the most desirable location is between the breathing system and the patient (position C). In this location, readings are not affected by breathing system leaks, expansion of breathing system components, or gas compression. Both inspired and expired volumes can be measured. Placing the sensor at this site will increase the dead space, and water condensation may be a problem. This position may result in increased likelihood of damage, disconnection, or tracheal tube kinking.

A disadvantage of position C is that if a disconnection occurs between the sensor and the breathing system during spontaneous ventilation, the spirometry measurements will not be affected. If the sensor is located at position B, the disconnection will be detected by the change in volume.

A common practice is to locate the respirometer in the exhalation limb upstream or downstream of the unidirectional valve (positions A and B). An advantage of these positions is that if the respirometer can sense reverse flow, a malfunctioning unidirectional valve can be detected. If a disconnection that prevents exhaled gases from passing down the exhalation tubing occurs, the respirometer will not sense a gas flow, and an apnea message and alarm will be activated. A respirometer in this location will usually read accurately during spontaneous respiration, but during controlled respiration, it will usually give erroneously high readings

(36,37). This is due to expansion of components of the breathing system and gas compression. If a ventilator with a hanging bellows is used, a respirometer in this position may still indicate flow when a disconnection occurs (38).

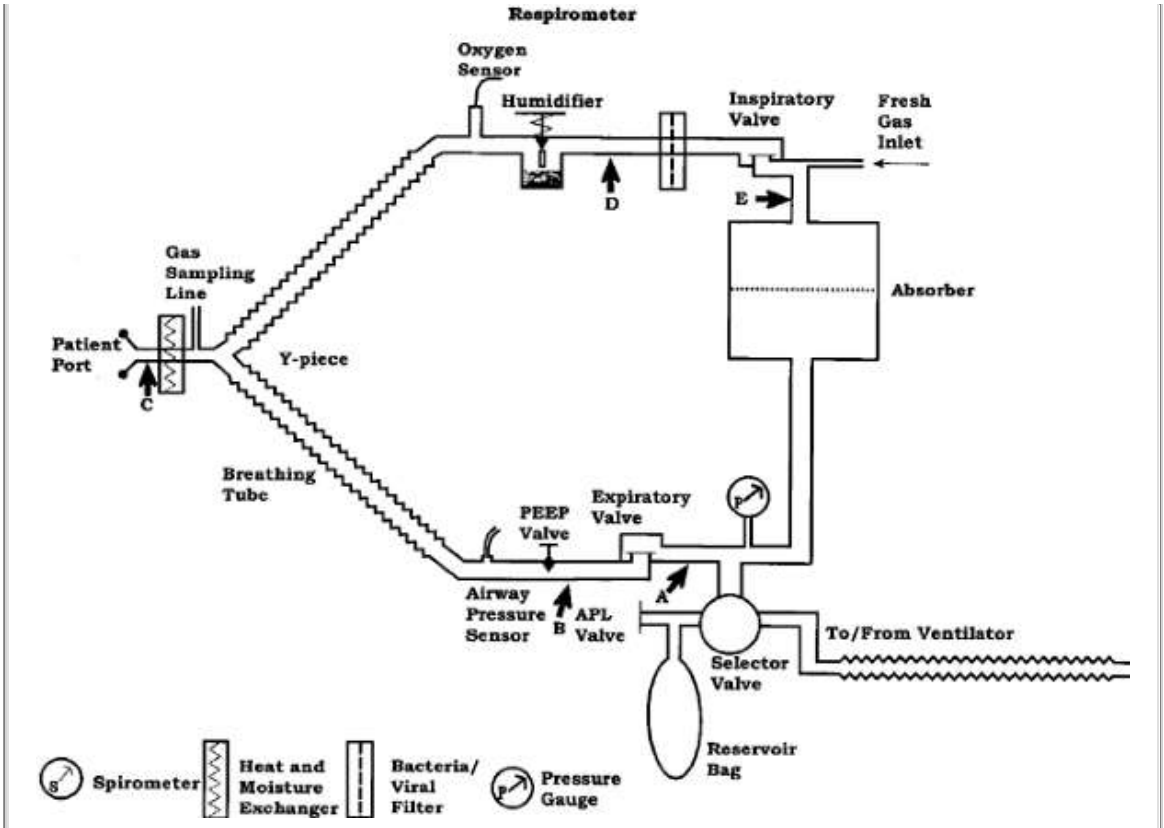

Figure 23.18 Possible sites for a respirometer in the circle system. (See text for details.) PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

If the respirometer is located downstream of the absorber (position E), the volume of gas measured will be decreased by the amount of carbon dioxide absorbed in the absorber.

Another possible location for the respirometer is on the inspiratory side of the system (position D). In this location, the respirometer will display erroneously high readings, as gas that does not inflate the patient's lungs will also pass through it. During controlled ventilation, a disconnection may not be detected.

It is common to locate pressure-flow sensors at both positions B and D. This allows both the inspiratory and exhalation volumes and pressures to be measured. This provides the information to produce a flow-volume or pressure-volume loop. Sensors in both these positions are used with the Datex-Ohmeda 7900 ventilator

to compensate for changes in tidal volume due to fresh gas flow or leaks.

When one of these devices is used in a Mapleson system with an adult patient, it should be placed between the patient connection port and the patient. In smaller patients, it should be placed in the expiratory limb to avoid an increase in dead space (11,15).

Airway Pressure Monitoring

Airway pressure monitors (ventilator or respiratory monitors or alarms; pressure alarms; pressure alarm systems; anesthesia, patient, or breathing circuit monitors; ventilator monitoring alarms; breathing gas interruption monitors; disconnect monitors; breathing pressure monitors) are used to warn of high- or low-pressure conditions in the breathing system (39,40).

High- or low-pressure conditions in the breathing system have been a major cause of anesthesia mortality and morbidity. A device that responds to pressure changes within the breathing system and provides warning of a problem is strongly recommended. Other parameters such as exhaled carbon dioxide and exhaled volumes may remain relatively normal in the presence of dangerously abnormal airway pressures.

Continuous airway pressure monitoring is now the norm in both the operating room and in critical care areas. It is a simple and noninvasive technique that helps in assessing the patient's mechanical and spontaneous ventilation and determining the presence of PEEP.

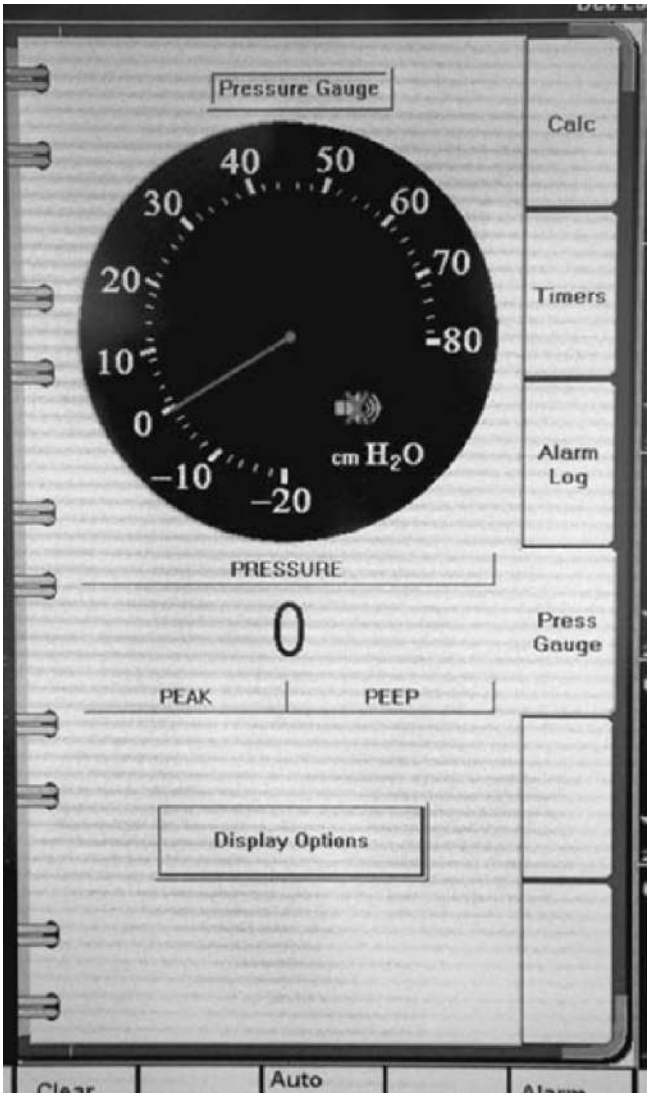

Figure 23.19 Virtual pressure gauge on anesthesia machine display. This can be displayed on demand.

Equipment

An airway pressure monitor may be freestanding or incorporated into a ventilator or an anesthesia machine. Most of these devices are inexpensive, robust, easy to use, and reliable. They may be powered either from the main electrical system with battery backup or by a battery with battery test capability.

Most new anesthesia machines have a built-in data screen where

information including airway pressure is available. Usually, there will be an airway pressure versus time waveform displayed on this screen. A virtual electronic pressure gauge may be displayed on the monitor screen (Fig. 23.19). Many machines in use are still equipped with a mechanical pressure gauge on the absorber. This does not allow electronic recording or the data to be integrated with other parameters to allow compliance calculations. Alarms were not associated with these manometers, so they had to be repeatedly scanned by the anesthesia provider.

Alarms

Most pressure alarms have an audio pause (delay, mute, silencing) control that will delay the audible signal for some or all functions. This pause should not prevent the visual signal from functioning. Some units' audible alarms can be completely turned OFF (41). Other features on some devices include automatic activation when a pressure is detected, the ability to detect impending battery failure, and protection from accidental inactivation or power failure (42,43). Some airway pressure monitors have the ability to display pressure waveforms.

Low Peak Inspiratory Pressure

A low peak inspiratory pressure (minimum airway pressure, low airway pressure, ventilation failure, apnea, cycling, pressure failure, disconnect, ventilator disconnect, minimum ventilatory, ventilation pressure, threshold pressure, low-pressure, peak airway, fail-to-cycle, low pressure, low circuit pressure) alarm is activated if the pressure detected does not exceed a preset minimum within a fixed time.

Basic monitoring standards adopted by the ASA and the American Association of Nurse Anesthetists (AANA) state that when ventilation is controlled by a mechanical ventilator, there shall be a means of detecting disconnection of breathing system components in continuous use. Such an alarm has been recommended by other responsible bodies around the world (44). The low peak inspiratory pressure alarm is one of the means to fulfill this requirement. However, the pressure monitor is not foolproof. Under certain circumstances, it may fail to detect anesthetic circuit disconnections. Pressure monitoring will fail to detect a disconnection that occurs during spontaneous

ventilation (45).

The airway pressure must exceed a threshold value (limit) to prevent an alarm. If this limit is not reached over a period of time, usually around 15 seconds, the alarm is activated. The threshold needs to be set at a value slightly below the peak airway pressure. This value varies, depending on the clinical situation. The limit may be set manually or automatically around a value slightly lower than the peak pressure determined by several successive breaths. When the peak airway pressure becomes higher or lower, the threshold may be automatically altered or there may be a means to move the threshold closer to the new peak pressure (Fig. 23.20). On some machines, there will be a visual informational signal that the limit is set too low.

The low peak pressure alarm is enabled when the ventilator is turned ON. It is inactive when the ventilator is not being used.

Conditions that can cause a low peak pressure alarm include a disconnection or major leak in the breathing system; an obstruction upstream of the pressure sensor; inadequate fresh gas flow (disconnection of the fresh gas line, an internal machine obstruction, or loss or reduction of pipeline pressure); the bag/ventilator selector

valve in the bag position; a leaking tracheal tube cuff; extubation; a faulty, poorly set, or unconnected ventilator; failure of the gas or power supply to the ventilator; a malfunctioning scavenging system; increased compliance; reduced resistance; and a suction device mistakenly placed within the gas flow pathway (46,47). Low pressure alarms are of little or no use during spontaneous breathing when the pressure in the system does not rise and fall appreciably (45).

Figure 23.20 The pressure (*top waveform*) exceeds the threshold (*dotted line*) by a small amount. At the bottom is a touch control marked ĩ€AUTO PRESSURE THRESHOLD.ĩ€ If the threshold is too high or too low, it can be altered by using the control or by touching the threshold on the screen and moving it to the desired location.

The alarm threshold should be set just below the minimum peak pressure expected during inspiration (41,42,48,49). This peak pressure will vary not only from patient to patient but also during a given case. Often, the threshold is set lower in an attempt to prevent false-positive alarms. If the alarm limit is set too low, a false negative may occur (50,51,52). It has been suggested that a pressure threshold of less than 8 to 10 cm H_2O is unacceptable (53). On most modern delivery systems, the circuit pressure waveform and the low-pressure alarm threshold can be displayed, making it easy for the operator to adjust the threshold properly (Fig. 23.2). On some monitors, an advisory signal will be activated if the threshold is set a certain amount below the peak pressure. Some units automatically set the threshold based on the pressure sensed during previous breaths. There may be a manual threshold reset control.

Problems with these monitors have been reported. A

disconnection or leak may not be detected if the alarm is not switched ON (54) or the threshold is set too low. A false-negative condition may occur if the end-expiratory pressure is above the threshold pressure. Other conditions that may produce a pressure high enough to exceed the threshold when a disconnection occurs include the breathing system connector's obstruction by a pillow, sheet, or surgical drape; a high-resistance component such as a heat and moisture exchanger, capnometer cuvette, or humidifier; air entrainment into the breathing system (especially with a ventilator bellows descending during expiration); partial extubation; compression of an empty ventilator bellows; and a Mapleson system with a high resistance (55,56,57,58,59). If a ventilator that uses a ram of oxygen to produce inspiration is used with a T-piece system, a disconnection at the common gas outlet may not be detected due to the high resistance of the fresh gas tubing (60). Those devices operating on batteries will not alarm if the batteries fail. It is essential that the alarm be checked before use by making a disconnection at the patient connector while the ventilator is cycling (Chapter 33) (50). Unfortunately, studies show that this test is not performed routinely or correctly (48). It is important that another means of detecting a disconnection (such as a capnograph or volume or flow monitor) be used.

Sustained Elevated Pressure

A sustained (continuous, continuing) pressure monitor activates an alarm if the pressure does not fall below a certain level during part of the respiratory cycle. Most are always enabled. Some incorporate a valve that opens to relieve the pressure after a certain time.

Several mechanisms can produce a sustained elevated pressure: accidental activation of the oxygen flush valve; occlusion or obstruction of the expiratory limb; an improperly adjusted adjustable pressure limiting (APL) valve; occlusion of the scavenging system; a malfunctioning ventilator; or a malfunctioning or incorrectly set PEEP valve (42,43,55).

High Pressure

A high-pressure alarm is activated if the pressure exceeds a certain limit. On some devices, the threshold

is fixed (usually 50 to 80 cm H_2O); on others, it is adjustable (41). Some instruments automatically set the alarm threshold at a set amount above the average peak pressure for several previous breaths. Most of these alarms are always enabled. There should be no delay on the high-pressure alarm. Some anesthesia delivery systems are fitted with pressure-limiting valves that vent gas from the breathing system when a high pressure is detected (41).

Possible causes of high pressure include airway obstruction, reduced compliance, increased resistance, oxygen flush activation during the inspiratory phase, a punctured ventilator bellows, occlusion or obstruction of the expiratory limb of the breathing system, scavenger malfunction, or the patient coughing or straining (42,61). Even in the presence of complete obstruction, this alarm will not be activated if the peak inspiratory pressure does not reach the set limit (49). High compliance, low resistance, leaks, low inspiratory flow rates, high respiratory rates, low I:E ratios, low tidal volumes, and low fresh gas flows can all decrease the peak inspiratory pressure so that there is no alarm condition (2,62). During pressure control ventilation, the inspiratory airway pressure is preset and thus cannot act as a warning of tracheal tube occlusion (63).

Subambient Pressure

A subambient (subatmospheric) pressure alarm is activated by a pressure that falls below atmospheric pressure by a predetermined amount. Subatmospheric pressure can be generated by a patient attempting to inhale against a collapsed reservoir bag or increased resistance; a blocked inspiratory limb (during the ventilator's expiratory phase); a malfunctioning active closed scavenging system; suction applied to a nasogastric tube placed in the tracheobronchial tree or to the working channel of an endoscope passed into the airway; a sidestream gas analyzer; or the refilling of a hanging bellows ventilator bellows (14,42,49,64,65,66).

Monitoring Site

The location where pressure is sensed will affect its usefulness. Figure 23.21 shows possible sites. Ideally, the site should be close to the patient's airway (position C). Many disposable

breathing systems have a small port at the Y-piece that can serve as the connection site for tubing that transmits the pressure to a monitoring device (57). Pressures during both inspiration and exhalation can be measured at this site. The D-Lite and Novometrics sensors discussed earlier in this chapter

are placed at this site. Pressure- and flow-volume loops can also be generated from pressures sensed at this site. While placement between the patient and the breathing system is best from this standpoint, in practice it may present problems with dead space, disconnections, tracheal tube kinking, and water buildup in the pilot line. The lines must be connected for every case.

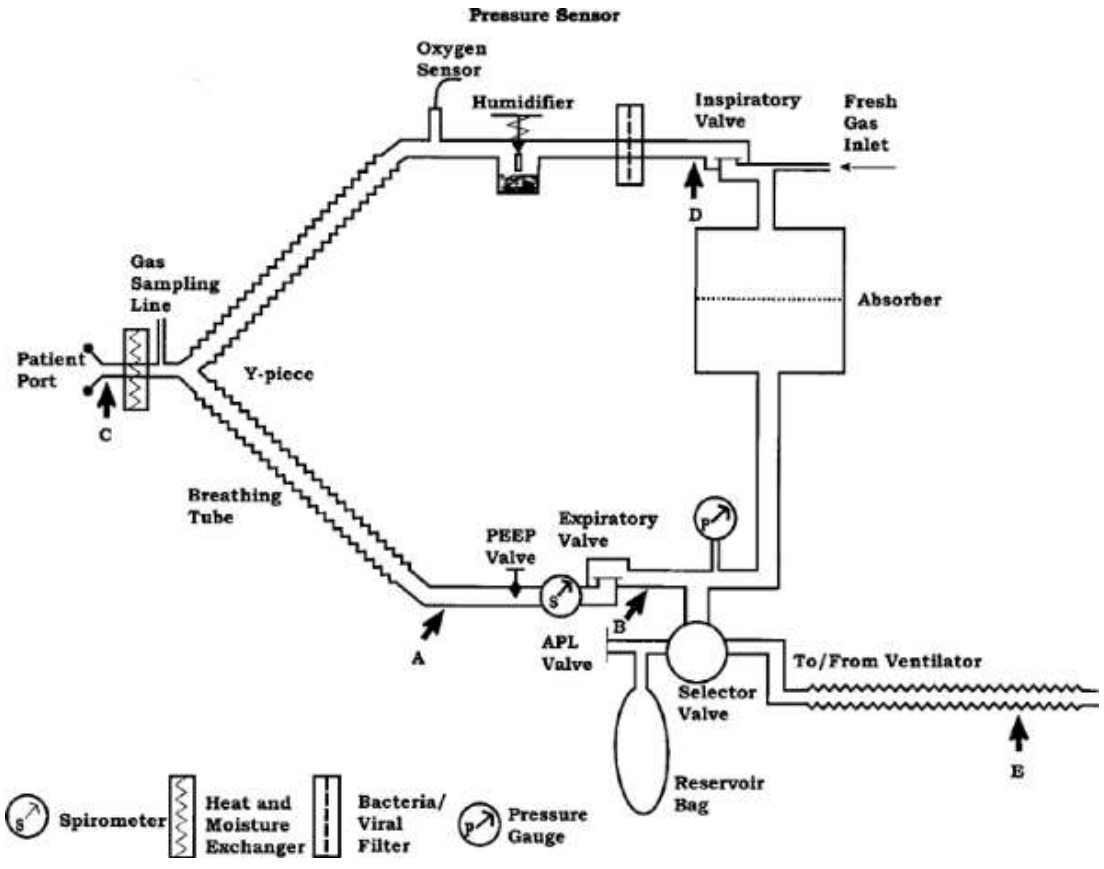

Figure 23.21 Possible sites for monitoring airway pressure in the circle system. (See text for details.) PEEP, positive end-expiratory pressure; APL, adjustable pressure limiting.

The more distant the measurement site is from the patient, the less useful it is as an estimate of airway pressure (2,67). Breathing system resistance and compliance, leaks, obstructions, and other mechanical factors may cause the measured pressure to be quite different from the pressure in the patient's airway (56).

Frequently, the monitoring site is in the breathing system (positions A, B, and D). An occlusion in the breathing system will cause a low-pressure state distal to the obstruction and a high-pressure state proximal to it, so certain types of problems may be missed (57). If PEEP is used, it will not be indicated on a pressure monitor located at position B. Positions A and D are frequently used to monitor pressure during inspiration and exhalation. These locations may be used to provide pressures for pressure-volume loops.

In the past, the sensor was sometimes located in the ventilator (position E). This is unsatisfactory because under certain circumstances, sufficient back pressure to inhibit the minimum pressure alarm may be generated at the bellows even when there is a disconnection (55,56). Placing the sensing point in the ventilator may also result in failure to detect an incorrectly set bag/ventilator selector valve.

Spirometry Loops

A loop is a graphic representation of the dynamic relationship between two variables (pressure and volume or flow and volume) during both inspiration and exhalation (6,23,68). The flow, volume, and pressure curves illustrated in Figure 23.1 are the bases of spirometry loops.

Pressure- and flow-volume loops are available on certain physiologic monitors as an option. Later-generation anesthesia machines and most physiologic monitors now offer these loops, usually as an option. The authors believe that the information provided justifies the extra cost.

Illustrative Loops

The Pressure-volume Loop

The pressure-volume (compliance) loop shows volume on the

vertical axis and airway pressure on the horizontal axis (Fig. 23.22). With controlled ventilation, the pressure in the breathing system increases during inspiration. At the same time, the inspired volume of gas increases. The tidal volume is the point on the vertical axis that corresponds to the highest point on the loop. The peak pressure is the highest value on the horizontal axis. The shape of the inspiratory phase is determined by the type of respiration being monitored.

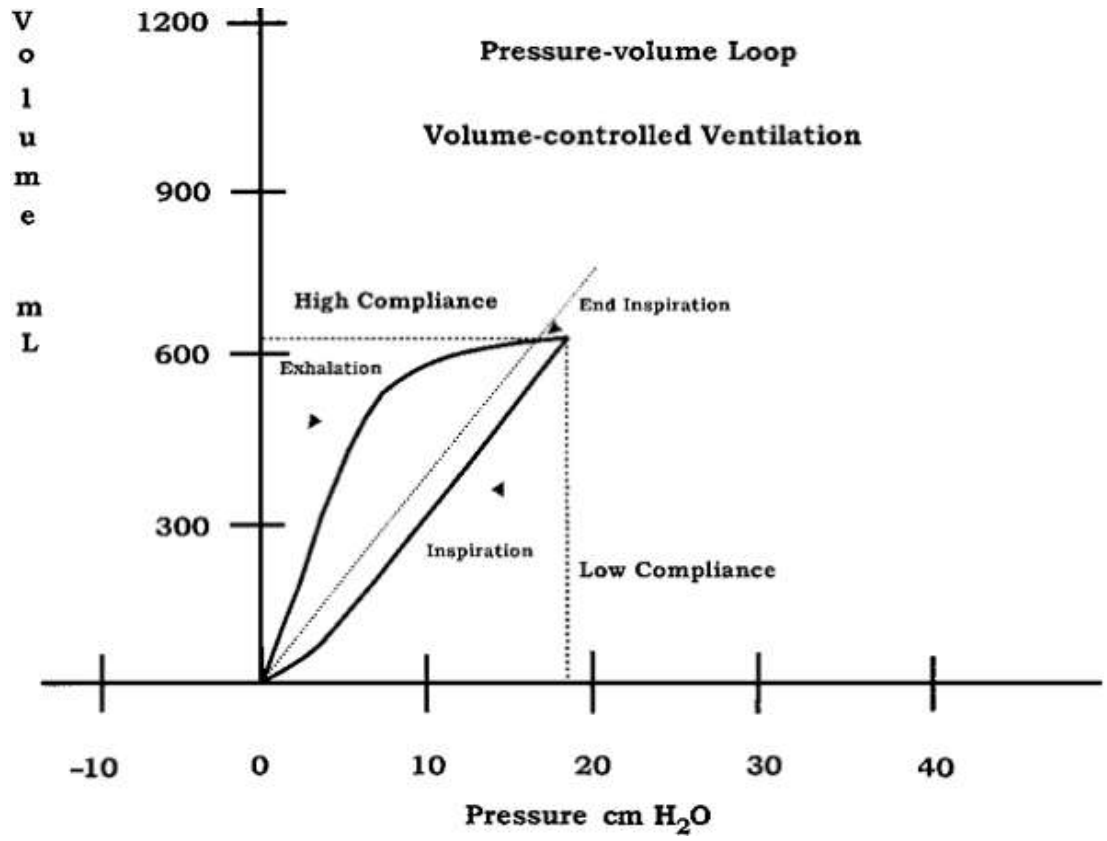

Figure 23.22 Pressure-volume loop. The pressure-volume relationship reflects pulmonary and tracheal tube mechanics. During controlled ventilation, a line drawn from the zero point through the point of end inspiration represents the compliance, which is determined by dividing the tidal volume by the pressure at end inspiration. With good compliance, that line forms an angle of 45 degrees or less with the volume scale. A loop that becomes more horizontal indicates a decrease in compliance.

A line drawn from the zero point through the point of end inspiration during controlled ventilation (Fig. 23.22) represents the compliance. With good compliance, that line forms an angle of 45 degrees or less with the volume scale. A loop that becomes more horizontal indicates a decrease in compliance.

The portion of the loop representing exhalation starts at the point of highest volume and moves downward toward zero. The area inside the loop is related to the work of breathing (1,69).

The Flow-volume Loop

The flow-volume (resistance) loop (Fig. 23.23) has volume on the horizontal axis and flow on the vertical axis. The zero point for volume is to the right on the horizontal axis, corresponding to functional residual capacity. During inspiration, flow rate increases (plotted downward). The inspiratory flow drops to zero as inspiration ends. The tidal volume is reached at the point where flow returns to zero and the loop crosses the horizontal axis. The shape of this part of the loop depends on the mechanism of respiration (e.g., volume controlled, pressure controlled, manual, or spontaneous).

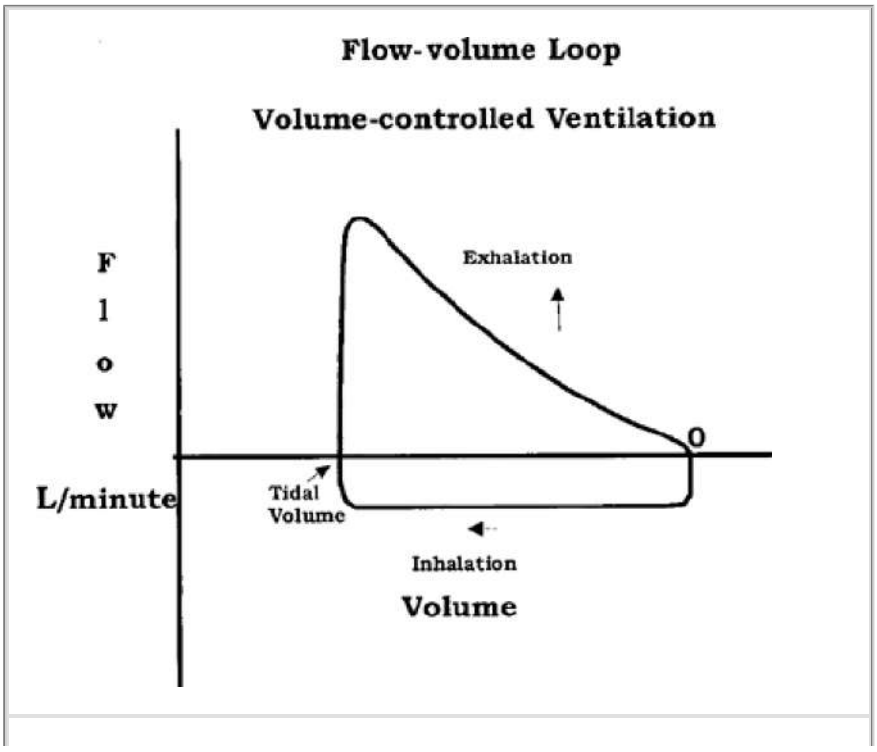

Figure 23.23 Flow-volume loops with controlled ventilation.

Exhalation is represented by the part of the loop above the horizontal axis. The shape of this portion of the loop is determined by the rate of passive lung deflation, which is in turn determined by elastic recoil of the lung and chest wall and by the total flow resistance offered by the bronchial tree, airway device tube, expiratory limb of the breathing system, and any additional equipment. With a normal loop, the flow rate during exhalation increases rapidly at the beginning, quickly reaches a peak, then slows and gradually returns to zero.

Figure 23.24 shows another way of illustrating a flow-volume loop that is used by some manufacturers. The zero point is at the junction of the horizontal with the vertical axis. Inhalation is above the horizontal axis, and exhalation is below. Flow-volume loops illustrated in this chapter employ the representation used by pulmonologists. This loop may be presented in other ways, but the basic loop is the same.

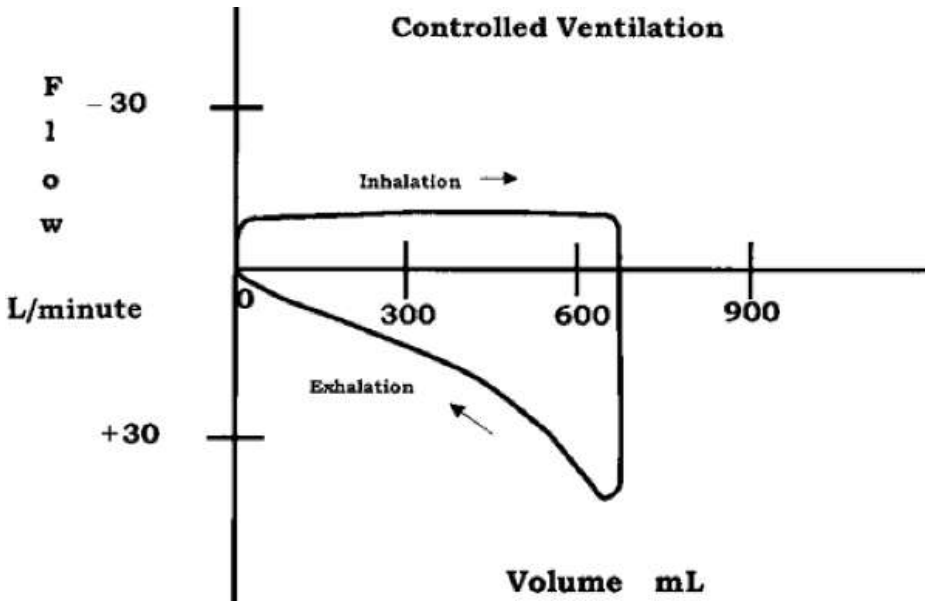

Figure 23.24 Alternative method of displaying flow-volume loops. (See text for details.)

Representative Normal Loops

Loops that are illustrated in this chapter do not come from actual patients but are stylized to illustrate certain aspects of respiratory mechanics. They are based on actual loops as much as possible. The reader should not expect to see an exact reproduction of these loops when monitoring a patient. Clinical conditions and ventilator function are rarely straightforward and usually include a number of factors. The loop represents a composite of mechanical and physiologic factors. As familiarity with the loops increases, the user can progress to the finer details of interpretation.

Volume-controlled Ventilation with No Inspiratory Pause

Pressure-volume Loop

The pressure-volume loop for volume-controlled ventilation with no inspiratory pause is shown in Figure 23.22. It begins at zero volume and near or at zero pressure. During inspiration, both pressure and volume increase, so the loop moves up and to the right. At the end of inspiration, both peak pressure and tidal volume are attained. The end of inspiration represents a fall in pressure that occurs before exhalation can begin. The loop returns downward and toward the left to its original starting position.

Flow-volume Loop

The flow-volume loop seen with volume-controlled ventilation with a constant flow generator is shown in Figure 23.23. The flow quickly rises to a level that is constant, producing a flat inspiratory portion. At the end of inspiration, the flow drops rapidly to zero. The tidal volume is reached as the loop crosses the volume line.

As exhalation begins, there is a rapid ascent to a peak. Flow then decreases, and the loop falls smoothly toward zero flow and volume. The angle at the top of the loop is narrow.

Controlled Ventilation with Positive End-

expiratory Pressure

Pressure-volume Loop

The addition of PEEP causes the starting point of the pressure-volume loop to shift to the right by the amount of PEEP that is applied (Fig. 23.25). PEEP may cause an increase in compliance and is represented by the loop becoming more vertical with a decrease in peak pressure. If the loop tends more to the right, PEEP may not be beneficial and may need to be withdrawn.

The loop display makes it easy to detect inadvertent PEEP. This may be due to the PEEP valve having been inadvertently turned ON, a partial obstruction in the breathing system, a malfunctioning exhalation unidirectional valve, failure of the positive-pressure relief in the scavenging interface, or an incorrectly set APL valve.

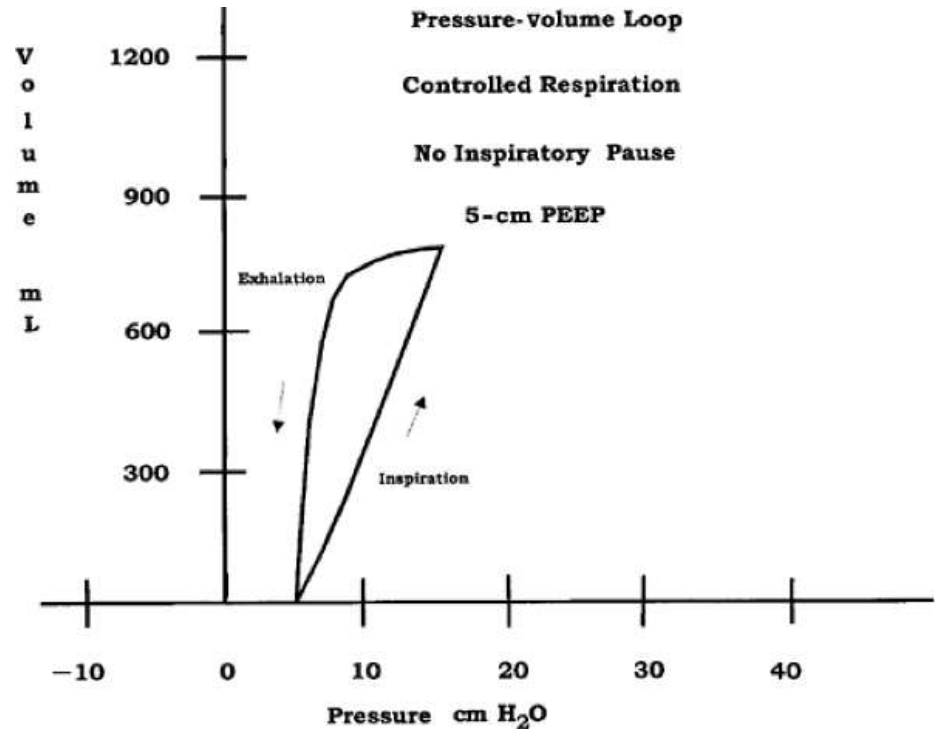

Figure 23.25 With PEEP, the loop is shifted to the right. PEEP, positive end-expiratory pressure.

Flow-volume Loop

The flow-volume loop with PEEP during controlled ventilation with a constant flow ventilator is shown in Figure 23.26. PEEP will decrease the expiratory driving pressure, producing lower flows during exhalation so that the loop appears flatter (4).

Controlled Ventilation with an Inspiratory Pause

Pressure-volume Loop

Figure 23.27 shows the pressure-volume loop during controlled ventilation with an inspiratory pause. After the peak pressure is reached, the ventilator pauses for a short time with the lungs inflated. During this pause, the pressure in the breathing system drops to a plateau level, usually 2 to 5 cm H_2O lower than peak pressure. Fresh gas entering the breathing system from the anesthesia machine without fresh gas decoupling (Chapter 12) will increase the inspired volume. During exhalation, the pressure and volume will drop in the expected manner.

Flow-volume Loop

The flow-volume loop seen with an inspiratory pause is shown in Figure 23.28. There is a drop in flow near the end of inspiration with a small increase in tidal volume during the pause resulting from fresh gas flowing into the breathing system if there is no fresh gas decoupling. This pattern should not be confused with a spontaneous breath during controlled ventilation (Fig. 23.60). The increase in volume due to fresh gas flow is straight, from right to left, and stays near the zero flow line. Exhalation is similar to the loop without an inspiratory pause.

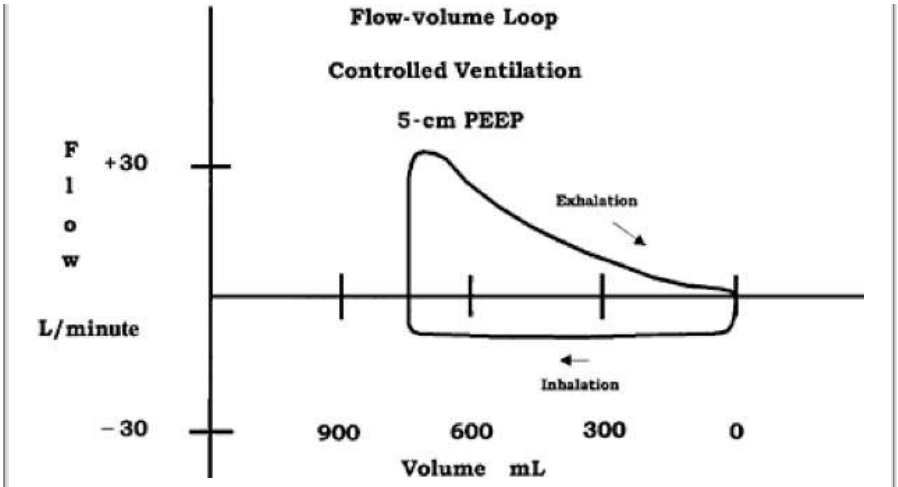

Figure 23.26 PEEP produces a decrease in expiratory flow. PEEP, positive end-expiratory pressure.

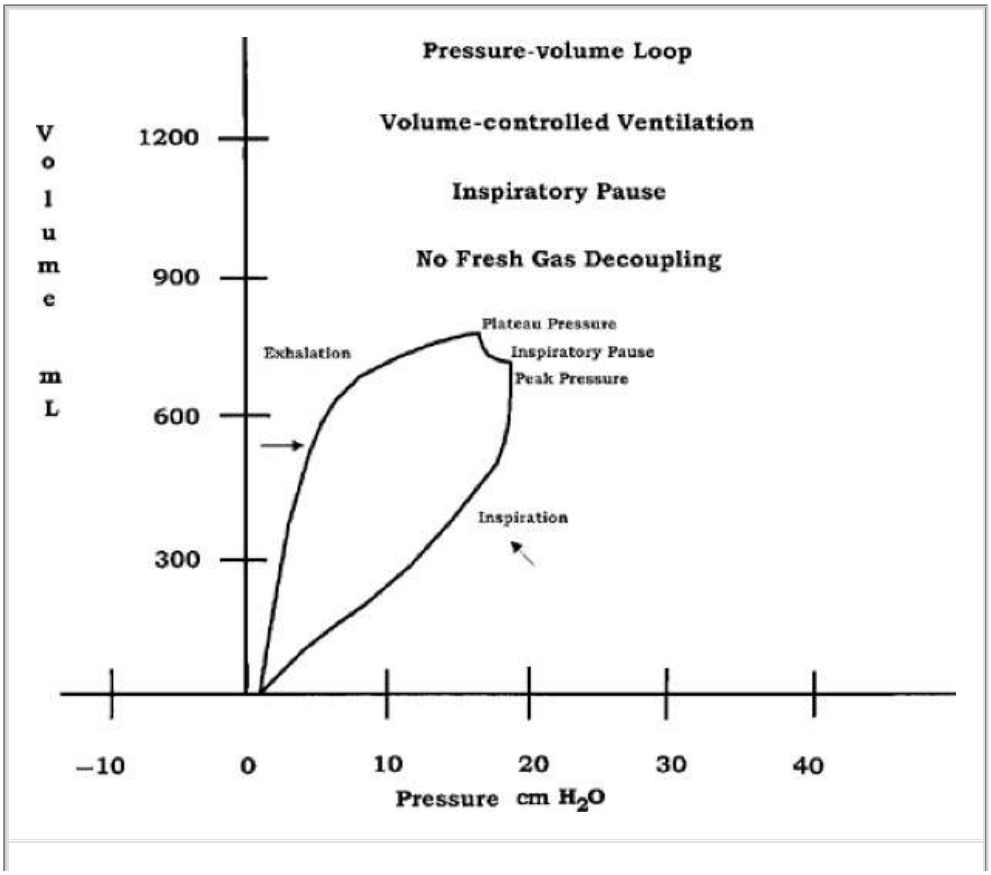

Figure 23.27 During an inspiratory pause, it is common for the airway pressure to decline 2 to 5 cm H_2O. The lower pressure is called the *plateau pressure*. If the ventilator does not block fresh gas flow during inspiration (fresh gas decoupling) there will be an increase in tidal volume during the inspiratory pause.

Pressure-controlled Ventilation

Pressure-controlled ventilation differs from volume-controlled respiration in that the inspiratory flow is not constant. Pressure-controlled ventilation is discussed in Chapter 12.

Pressure-volume Loop

The pressure-volume loop is shown in Figure 23.29. The loop is wider than that seen with volume-controlled ventilation and starts off with a greater pressure rise than volume increase. As inspiration proceeds, volume rises faster than with volume-controlled ventilation.

Flow-volume Loop

The pressure-controlled mode of ventilation has an accelerating-decelerating inspiratory flow profile in contrast to the constant inspiratory flow seen with volume-controlled ventilation (Fig. 23.30). The exhalation part of the loop is similar to that with volume-controlled ventilation.

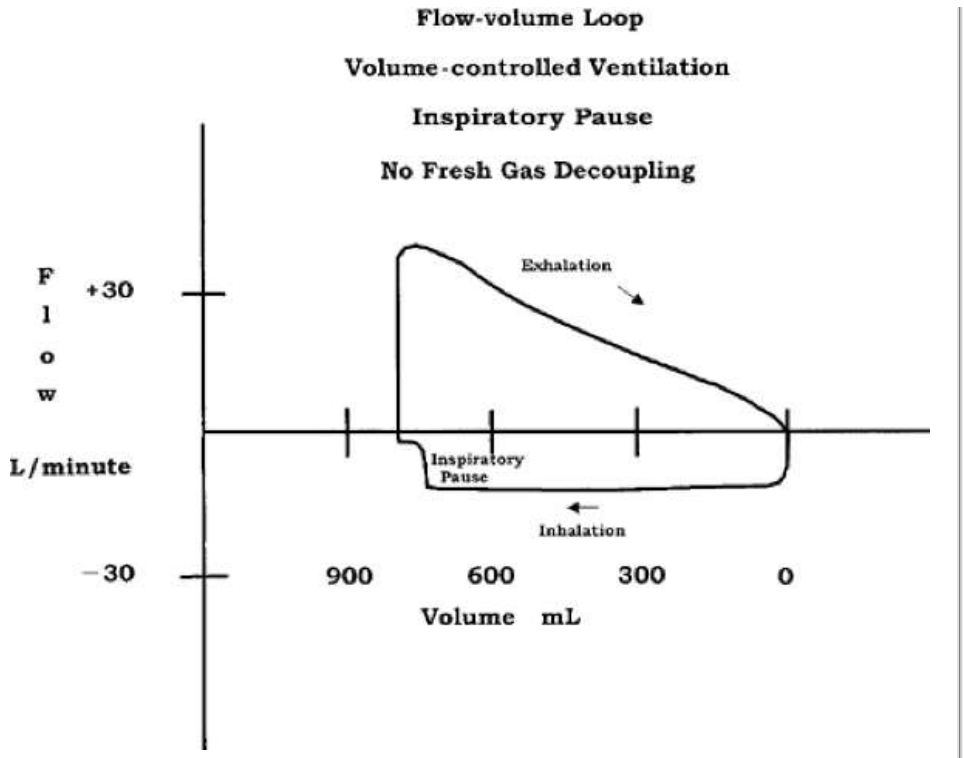

Figure 23.28 The blip near the end of inspiration represents the increase in tidal volume during the inspiratory pause due to fresh gas continuing to flow into the breathing system. This will not be seen if the ventilator has fresh gas decoupling.

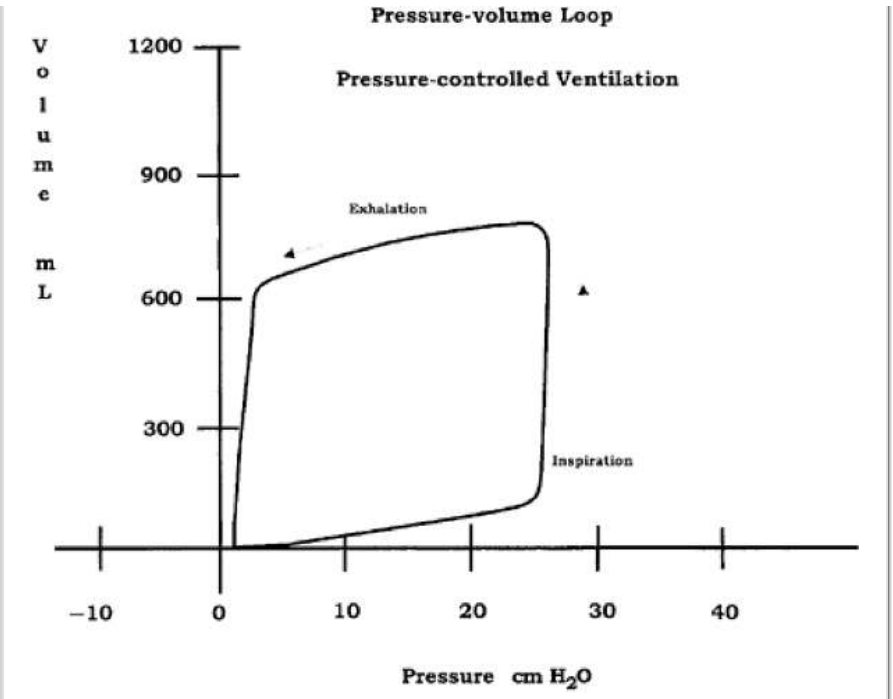

Figure 23.29 Pressure-volume loop with pressure-controlled ventilation. Pressure rises rapidly to the set pressure during inspiration.

Spontaneous Respiration without Positive End-expiratory Pressure

Pressure-volume Loop

With spontaneous respiration and no PEEP, the pressure-volume loop (Fig. 23.31) starts out at zero pressure and volume. During inspiration airway, pressure is negative, so the loop moves in a clockwise direction. At the end of inspiration, the pressure returns to zero. At this point, the loop crosses the tidal volume point on the ordinate. During exhalation, airway pressure becomes positive, and the loop moves to the right. At the same time, the volume drops. At the end of exhalation, the pressure and volume return to zero. The shape of the loop is still double convex, but its slope is different from that seen with controlled ventilation. Compliance cannot be calculated from this loop because the inspiratory pressure is negative. The area of the loop represents the work of breathing.

Flow-volume Loop

The flow-volume loop with spontaneous respiration is shown in Figure 23.32. The flow rate during inspiration varies more than with mechanical ventilation. Peak flow occurs near the middle of inspiration. At the end of inspiration, flow becomes zero, and the loop crosses the horizontal line at a volume corresponding to the tidal volume. The flow during exhalation is similar to that found in other forms of respiration.

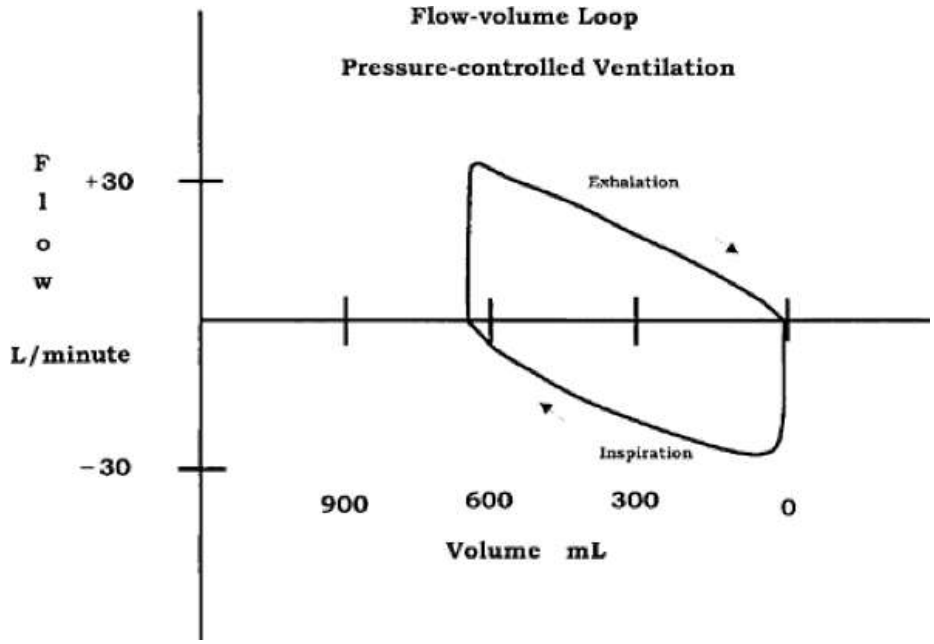

Figure 23.30 Flow-volume loop with pressure-controlled ventilation. Flow is rapid at the beginning of inspiration, then decreases.

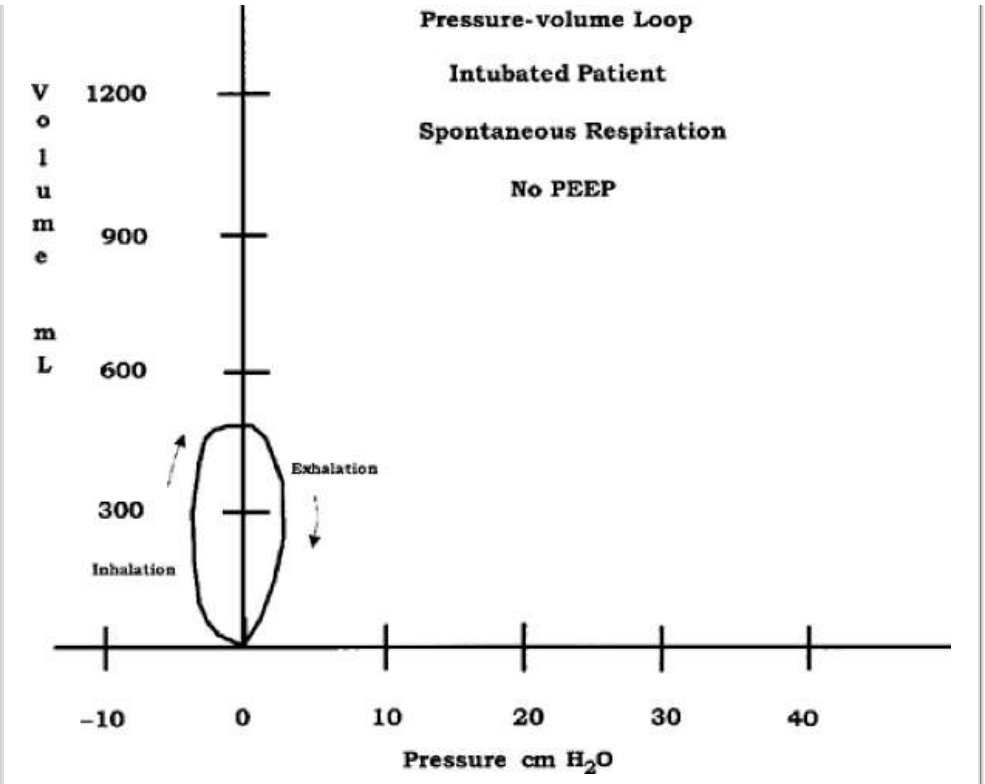

Figure 23.31 With spontaneous ventilation, the shape of the loop is double convex, but the slope is different from that seen with controlled ventilation. PEEP, positive end-expiratory pressure.

Spontaneous Respiration with Positive End-expiratory Pressure

Pressure-volume Loop

If PEEP is applied during spontaneous ventilation, the pressure-volume loop will start out at the PEEP value and move to the left (Fig. 23.33). Inspiration cannot begin until the pressure has become negative. At this point, the tidal volume increases rapidly. During exhalation, pressure increases rapidly, and the loop moves toward the right and downward to the point of origin. The loop has a rectangular shape. The larger internal area of the loop indicates the increased work of breathing.

Flow-volume Loop

The corresponding flow-volume loop during spontaneous respiration with PEEP is shown in Figure 23.34. Both the inspiratory and exhalation portions of the loop are flattened. The exhalation portion is more rounded than when PEEP is not present. This configuration is similar to the loop demonstrating a fixed inspiratory and expiratory obstruction (Fig. 23.52).

Face Mask Positive-pressure Ventilation

Pressure-volume Loop

The basic shape of the pressure-volume loop is still double convex (Fig. 23.35). The inspiratory portion of the loop is more rounded. If there is a significant leak around the mask, an open loop may be seen.

Flow-volume Loop

The flow-volume loop with mask ventilation (Fig. 23.36) is more rounded during both inspiration and exhalation than that seen with intubation. This can vary with the way in which the anesthesia provider squeezes the bag.

Intermittent Mandatory Ventilation

Intermittent mandatory ventilation produces a combination of loops representing both spontaneous and controlled breaths.

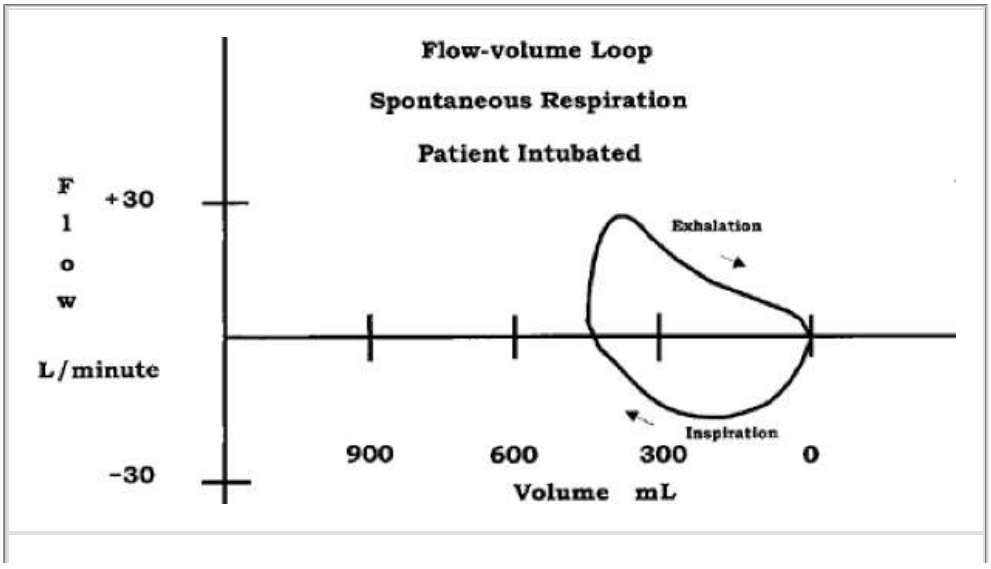

Figure 23.32 With spontaneous ventilation, the flow rate during inspiration varies more than with mechanical ventilation. Inspiration and exhalation tend to mirror each other. Tidal volume during spontaneous ventilation is usually lower than with controlled ventilation.

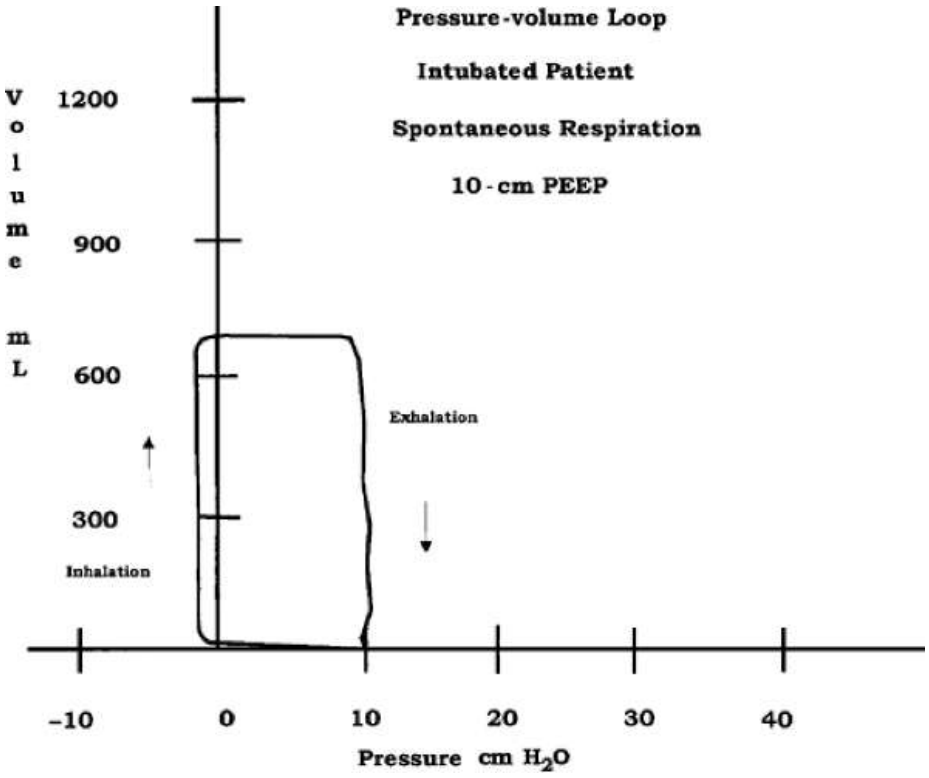

Figure 23.33 With spontaneous ventilation and positive end-expiratory pressure, the loop is shifted leftward and becomes rectangular. PEEP, positive end-expiratory pressure.

Pressure-volume Loop

The pressure-volume loop (Fig. 23.37) shows both a spontaneous breath (solid line) and a controlled breath (dashed line). Most monitors will display these loops consecutively and not on the same screen as illustrated unless one of the loops has been previously saved.

Flow-volume Loop

The flow-volume loop (Fig. 23.38) shows a spontaneous breath (solid line) and a controlled breath (dashed line). Each has the characteristics of the normal loop for this type of respiration.

Patient-triggered Ventilation

If the ventilator is in a triggering mode (pressure support ventilation), a spontaneous breath will be necessary to initiate a positive-pressure respiration. The pressure-volume loop will start out negatively, but as the ventilator is engaged, the loop becomes rapidly positive for

the duration of inspiration (Fig. 23.39). The exhalation portion of the loop will be similar to that found in controlled ventilation. The flow-volume loop associated with pressure support ventilation is shown in Figure 23.40.

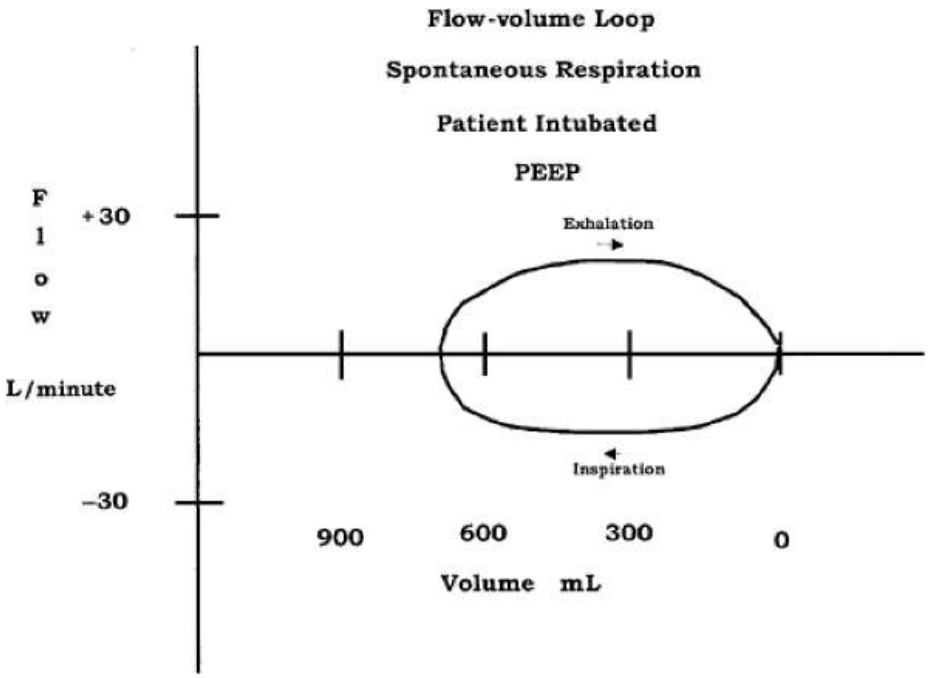

Figure 23.34 PEEP during spontaneous respiration results in lower flows during both inspiration and exhalation. PEEP, positive end-expiratory pressure.

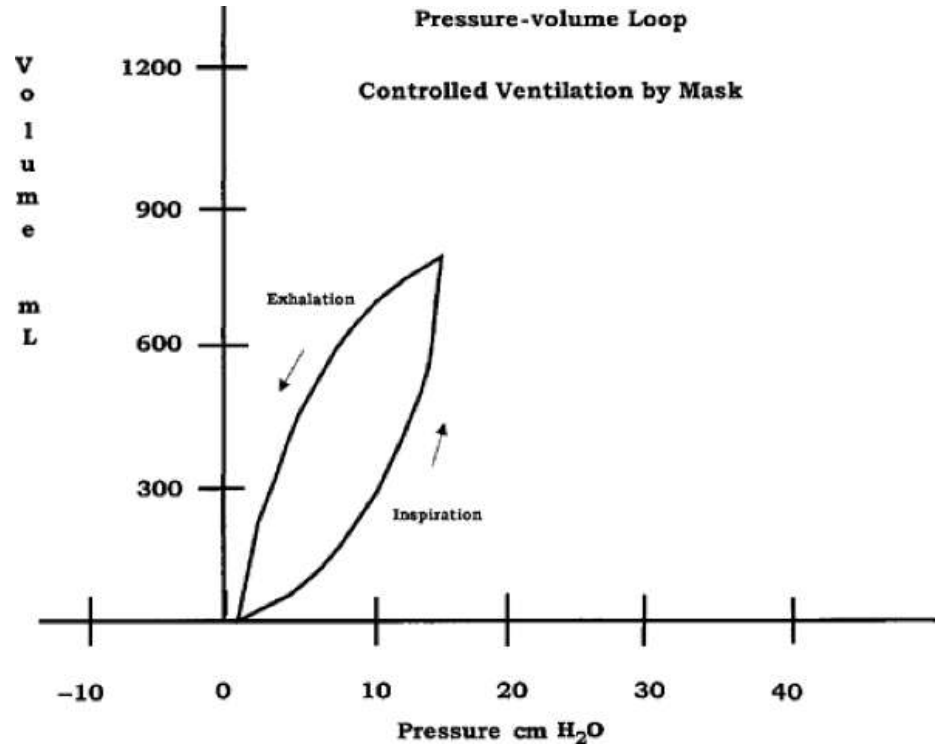

Figure 23.35 With mask ventilation, the pressure rises more slowly during inspiration. During expiration, the absence of the tracheal tube decreases resistance to flow and volume and pressure drops rapidly. The shape of the upstroke will vary.

Spontaneous-assisted Ventilation

If the spontaneously breathing patient is not producing a satisfactory tidal volume, respiration is often manually assisted. Figure 23.41 shows one of the configurations of the pressure-volume loop that may be seen. As the patient initiates the ventilation, there will first be a negative pressure. As the bag is squeezed, pressure and tidal volume increase.

Loops Representative of Patient Factors

Variations from a normal loop can be caused by anything that affects the way gas moves past the sensor during inspiration or

expiration. This may be a patient factor, a circuit variable, or a ventilator variable.

Changes in Compliance

Pressure-volume Loop

A major advantage of pressure-volume loops is their ability to detect changes in compliance. If the lungs or chest wall become stiffer, increased pressure will be necessary to deliver the same tidal volume. This causes the pressure-volume loop to be

displaced clockwise (Fig. 23.42). If PEEP is introduced, there may or may not be an increase in compliance (Fig. 23.43). If PEEP does not increase compliance or makes the situation worse, this can be determined by subsequent loops.

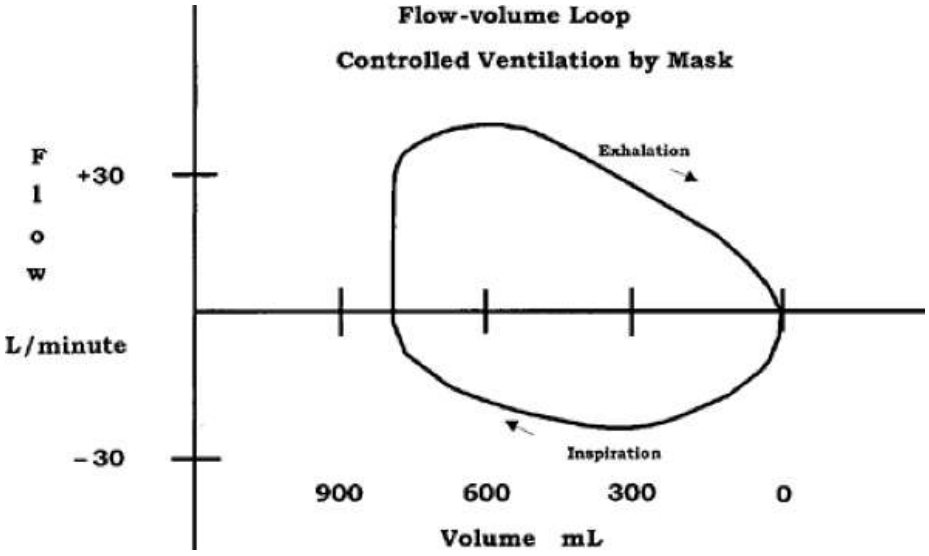

Figure 23.36 Mask ventilation. The inspiratory flow is more variable when ventilation is manually controlled than when a ventilator is used. During exhalation, the lower resistance due to the absence of a tracheal tube results in higher flow.

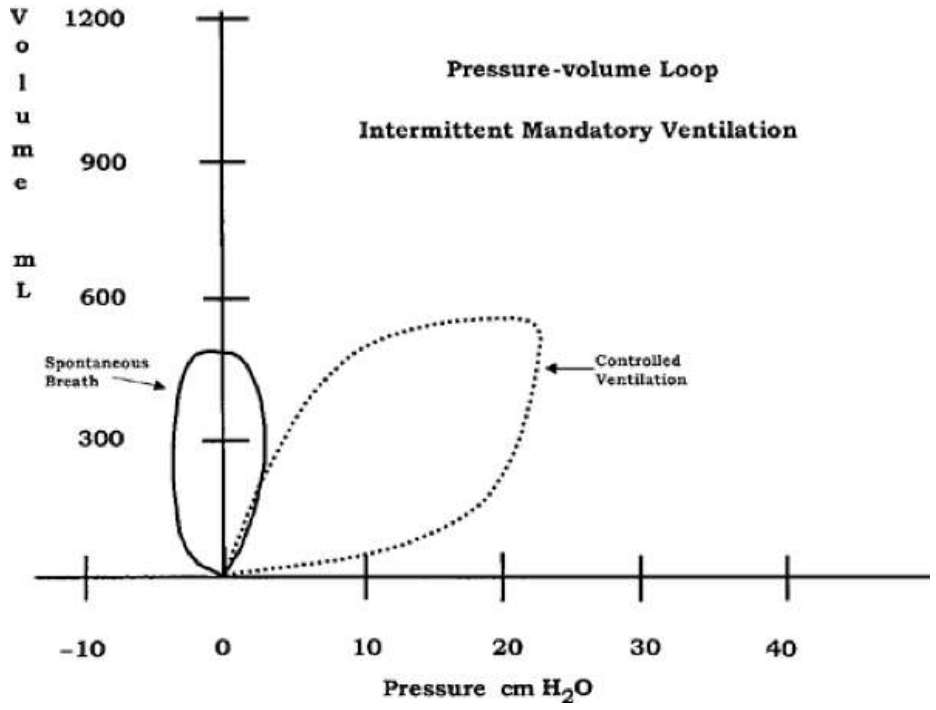

Figure 23.37 Pressure-volume loop with intermittent mandatory ventilation.

Flow-volume Loop

Decreases in compliance will affect the flow-volume loop (Fig. 23.44). Flow will be increased during exhalation, with a higher peak and a steeper slope.

Decreases in compliance can result from inadequate muscle relaxation; air embolism; diseases and tumors that invade large areas of the lung or alter its distensibility; narcotics; bronchial intubation; bronchoconstriction; pneumothorax; reduction pneumoplasty; lateral decubitus, lithotomy, or Trendelenburg positions; external pressure on the chest or abdomen; abdominal retractors or packing; abdominal enlargement; curvature of the spine; obesity; prone position; pressurization in the peritoneal cavity during laparoscopic surgery; or adult respiratory distress syndrome (ARDS) (6,68,70,71,72,73,74,75,76,77,78,79,80). Decreases in compliance can be found during partial coronary bypass. The loop returns to the prebypass state after the bypass is discontinued. Compliance is lower in children than in adults

(Fig. 23.45) (80).

Factors that increase compliance include PEEP, emphysema, and resolution of the factors that decrease compliance. Since changes in compliance often occur gradually, they may not be recognized unless the change is large. It is useful, therefore, to store a loop from the beginning of a case for comparison.

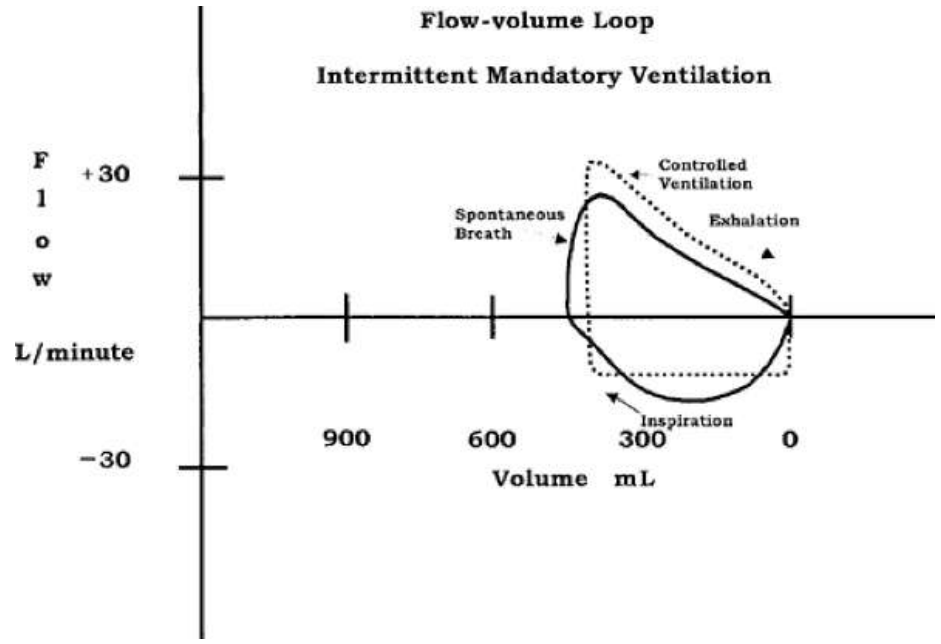

Figure 23.38 Flow-volume loop with intermittent mandatory ventilation.

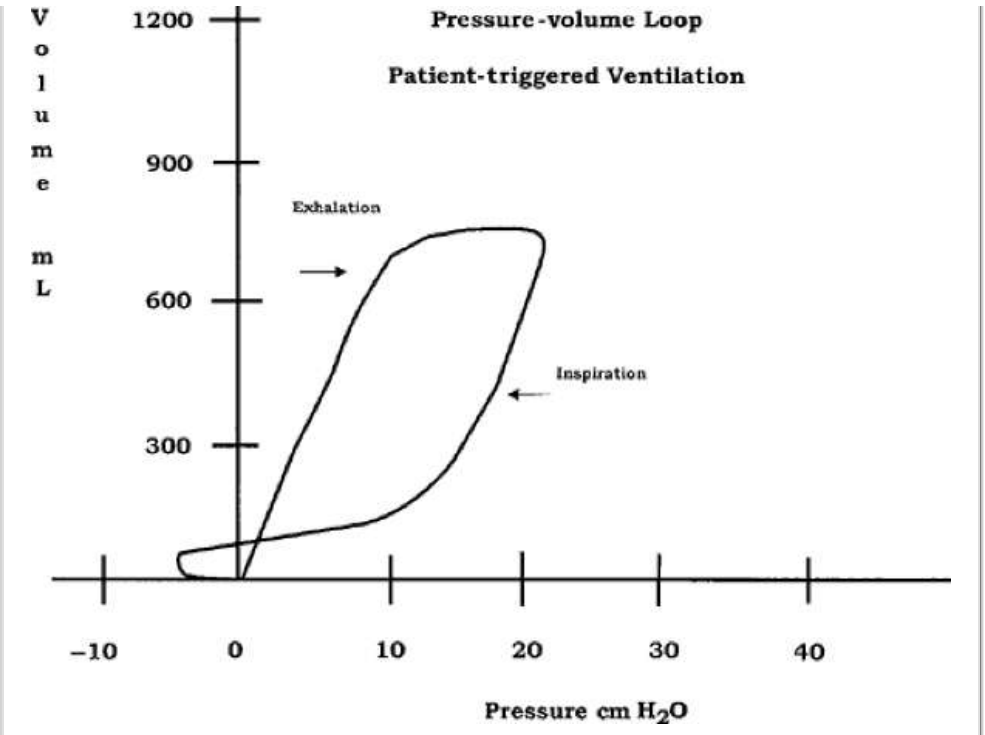

Figure 23.39 Patient-triggered ventilation. As the patient takes a spontaneous breath, the loop becomes positive for the duration of inspiration.

Changes in Resistance

An increase in resistance may be caused by tracheal tube obstruction (kinking, dislodgment, or secretions), bronchoconstriction, airway collapse from loss of elastic recoil or by obstruction in a large airway caused by secretions, blood, foreign body, neoplasm, inflammation, or using a tracheal tube that is too small. While mild bronchospasm causes only slight changes in the flow-volume loop, as it increases there will be changes in both the inspiratory and exhalation portions. With severe expiratory resistance, expiratory flow may stop abruptly before the next mechanical inflation. The effects of treatment for bronchospasm can be assessed by observing the loop after treatment.

Pressure-volume Loop

During controlled ventilation, increased resistance means that

higher inspiratory pressures will be required to deliver a given flow. Tidal volume may be reduced. As shown in Figure 23.46 (solid line), the pressure-volume loop is shifted to the right and downward with a large internal area. The pressure falls rapidly after inspiration is complete. The loop may be open if there is air trapping. With spontaneous ventilation, the inspiratory limb is displaced leftward (Fig. 23.47).

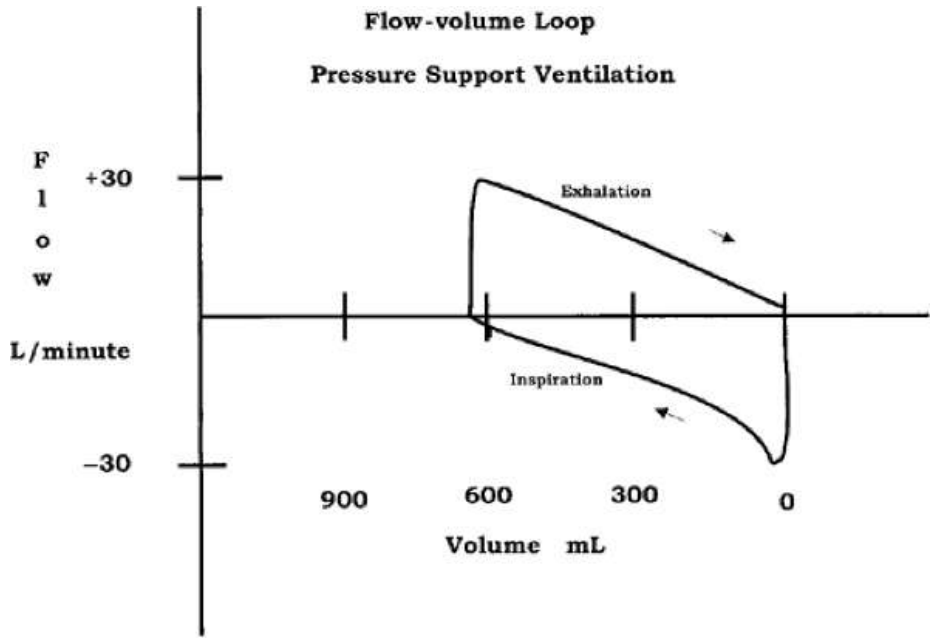

Figure 23.40 Pressure support ventilation.

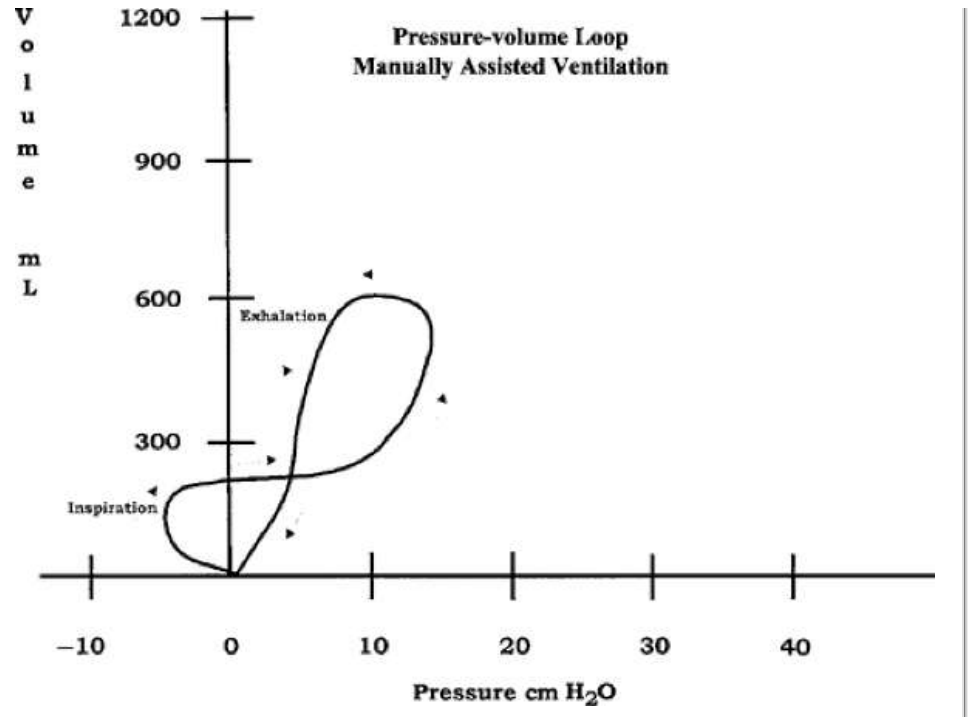

Figure 23.41 Spontaneous-assisted ventilation. As the patient begins to inspire, a negative pressure is seen. Then the bag is squeezed and the pressure becomes positive. The shape of the inspiratory portion will depend on how the bag is squeezed.

Flow-volume Loop

If resistance is increased, the flow-volume loop will show decreased flow throughout exhalation (4,21) (Fig. 23.48). As resistance increases further (Fig. 23.49), there will be changes in both the inspiratory and exhalation portions, and the tidal volume may be decreased. With severe expiratory resistance, expiratory flow may stop abruptly before the next mechanical inflation.

Chronic Obstructive Lung Disease

Emphysema is characterized by a progressive loss of elastic tissue in the lung. These patients have no problem with inflating the lungs but must work to exhale. During mechanical ventilation, patients with airflow obstruction may develop inadvertent PEEP (auto-PEEP, occult or intrinsic PEEP, dynamic hyperinflation, air

trapping) if there is not enough time for complete

exhalation (81,82,83,84,85). The exhaled volume will be less than the inspired volume.

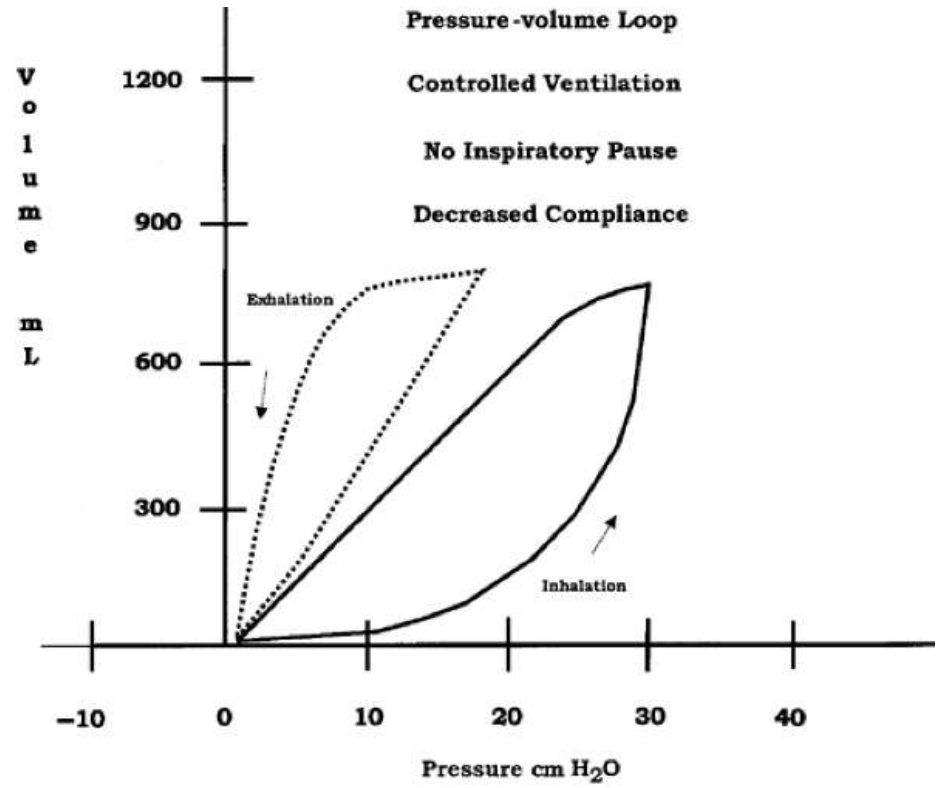

Figure 23.42 Low compliance causes the loop to be moved closer to the horizontal axis. High compliance causes the loop to move closer to the vertical axis. The dotted line shows normal compliance. The solid line shows decreased compliance.

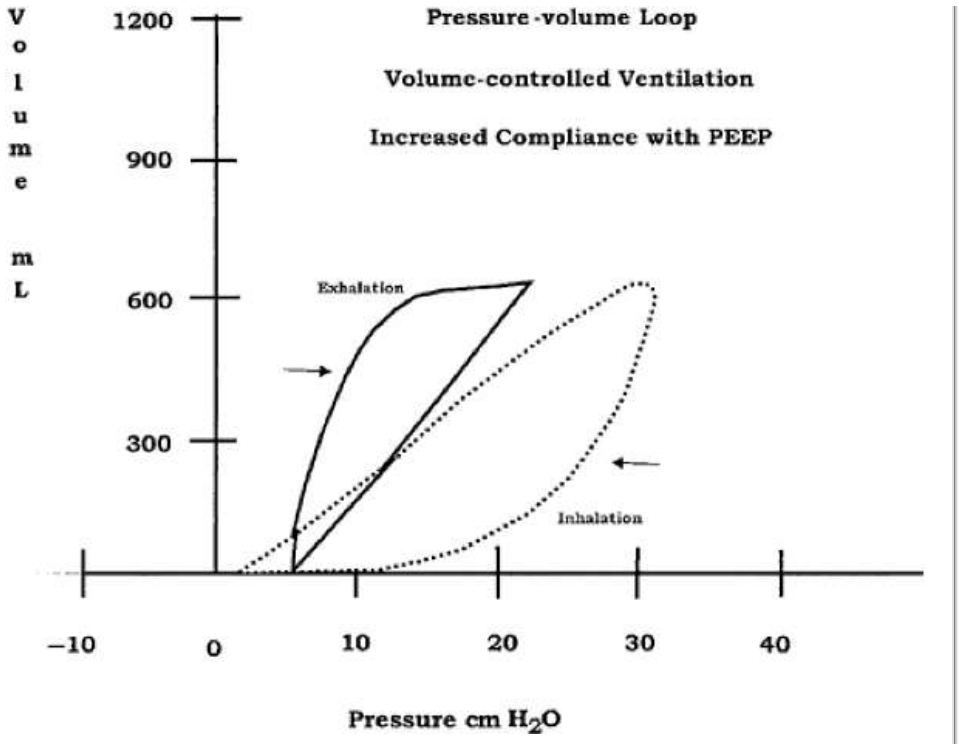

Figure 23.43 The *dotted line* represents decreased compliance. With the addition of PEEP, the loop is moved to the left, and the increased compliance results in a more normal-looking loop. If the loop does not improve with PEEP, the PEEP may not be beneficial and may need to be removed. PEEP, positive end-expiratory pressure.

Pressure-volume Loop

The pressure-volume loop seen with this condition is shown in Figure 23.50. At the beginning of inspiration, the pressure rises slowly.

During exhalation, the pressure drops with little change in volume until the end of exhalation. An open loop may be seen.

Flow-volume Loop

The corresponding flow-volume loop is shown in Figure 23.51. During expiration, there is a severe reduction in flow. The loop may be open if the patient does not have sufficient time to exhale completely. Interrupted expiratory flow may suggest the

presence of intrinsic PEEP (auto-PEEP).

Patients with obstructive airway disease may not complete a full exhalation prior to the start of the next inhalation, resulting in persistent positive pressure. This will be indicated by the absence of a period of zero flow before the next inhalation (Fig. 23.63).

Airway Obstruction

Flow-volume loops may be helpful in identifying airway obstructions (86,87,88). The inspiratory limb of the loop

is useful in diagnosing extrathoracic airway obstruction, and the expiratory limb is sensitive to intrathoracic obstruction (87,89). When the cross-sectional area of the airway is decreased to a critical level, characteristic patterns of flow occur with spontaneous ventilation. Typically, the flow rate will plateau. The value of the flow rate at this plateau will depend on the cross-sectional area of the flow-limiting segment in the airway.

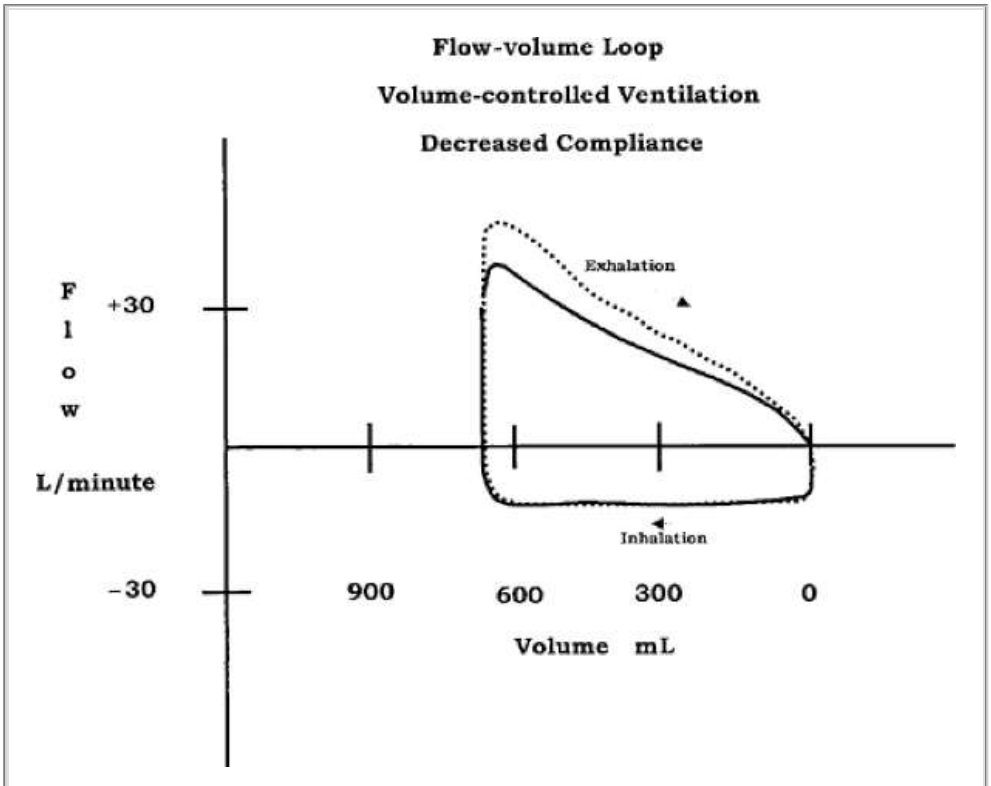

Figure 23.44 The *dotted line* represents decreased

compliance. Flow is greater at the beginning of exhalation due to the increased pressure.

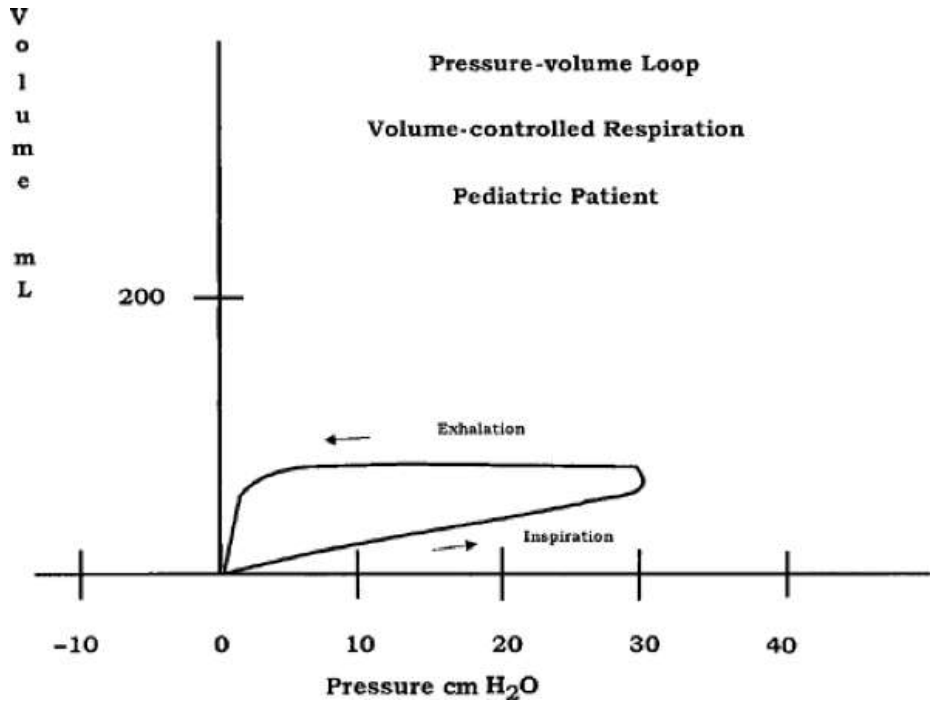

Figure 23.45 Pressure-volume loop in pediatric patient.

With a fixed intrathoracic or thoracic obstruction and spontaneous ventilation (Fig. 23.52), both the inspiratory and expiratory limbs of the flow-volume curve are flattened (86,87,90).

A variable extrathoracic obstruction (Fig. 23.53) will affect inspiration as the negative pressure causes the obstruction to increase. During exhalation, positive pressure in the airway will keep the trachea open at the site of the lesion, leaving the expiratory curve unaffected (87).

A variable intrathoracic obstruction (Fig. 23.54) will show a normal inspiratory curve as the negative intrathoracic pressure will keep the airway open. During expiration, the intrathoracic pressure becomes positive

and thus decreases the airway diameter so that the expiratory flow is reduced.

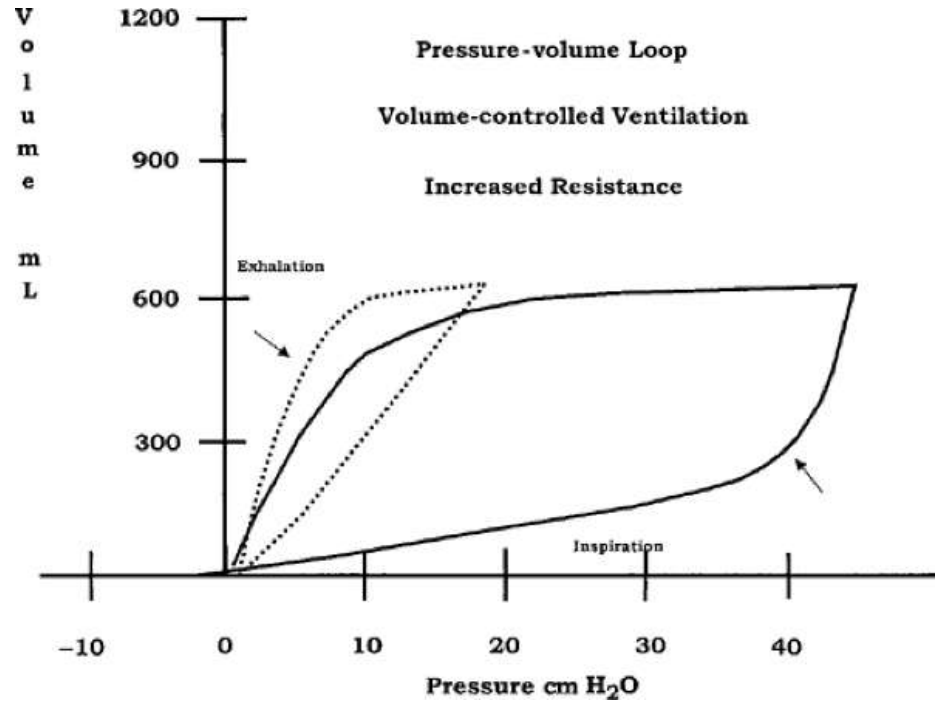

Figure 23.46 With an increase in resistance, a higher pressure is needed to deliver the same volume (*solid curve*). Tidal volume may be reduced.

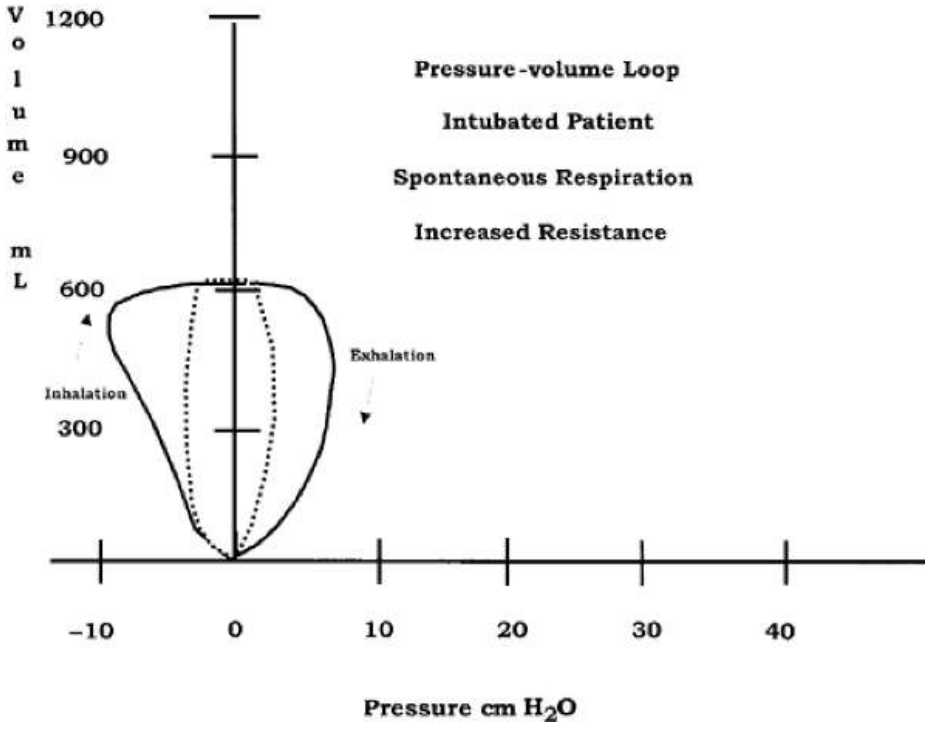

Figure 23.47 Spontaneous respiration with increased resistance. The normal loop is shown with *dotted lines*. With increased resistance, greater pressure (more negative during inspiration, more positive during exhalation) will be needed to move the same volume of gas.

Restrictive Disease

The increase in elastic recoil with restrictive defects increases the force driving expiratory flow. Thus, the flow-volume loop usually shows a high expiratory flow associated with a steep descending limb (Fig. 23.55).

Secretions

Secretions in the tracheal tube will cause a sawtooth pattern in the pressure- and flow-volume loops (83,91) (Figs. 23.56, 23.57).

Pediatric Patients

Pediatric patients require a different scale for pressure- and

flow-volume loops. Small patients require relatively high airway pressures because of the small diameter of the tracheal tube. An example is found in Figure 23.45.

Spontaneous Breathing during Controlled Ventilation

It is possible for a nonparalyzed patient to breathe spontaneously during controlled ventilation. This can occur at any time during the respiratory cycle. The spontaneous breath usually has a lower inspiratory flow than the mechanical breath.

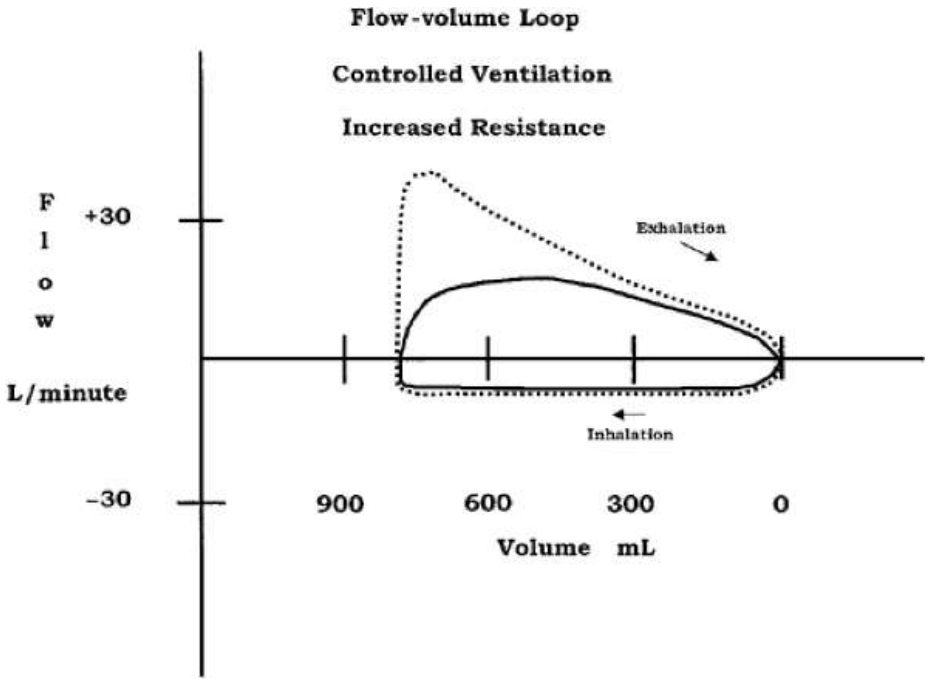

Figure 23.48 Flow-volume loop with increased resistance. The *dotted line* represents the curve with normal resistance. With increased resistance, there is diminished expiratory flow. The convex configuration of the expiratory limb reflects uneven lung emptying.

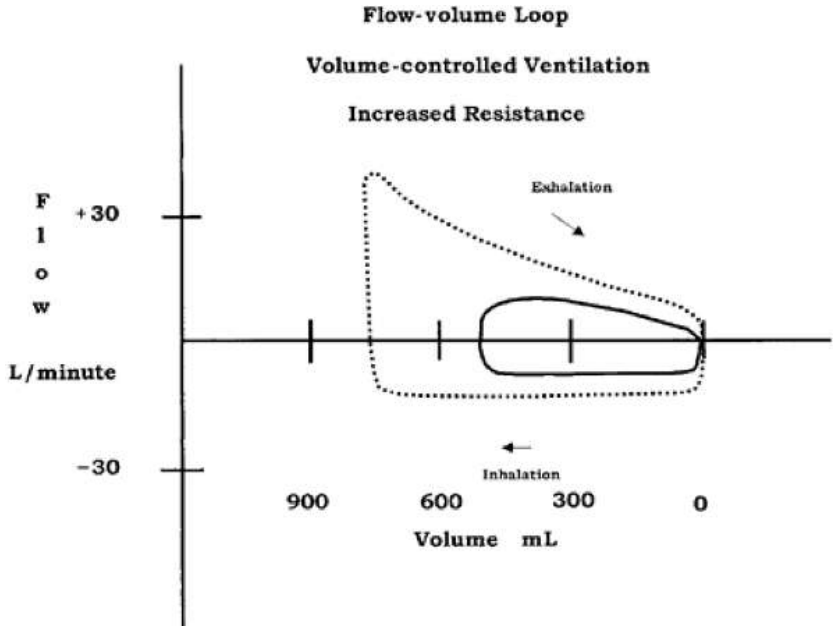

Figure 23.49 With a severe increase in resistance, the ventilator cannot fully compensate, and inspiratory flow will be diminished. Tidal volume may be decreased. Expiratory flow is also severely decreased. The *dotted line* represents the normal curve.

Pressure-volume Loop

Figure 23.58 shows a pressure-volume loop with a spontaneous breath during exhalation. As the spontaneous breath occurs, the pressure drops below the expected level while the volume rises above the usual curve. As the spontaneous breath is exhaled, the pressure increases briefly and the volume drops rapidly. The remainder of the loop follows the expected shape.

Figure 23.59 shows a series of pressure-volume loops with the solid line (loop 1) representing a normal loop produced with mechanical ventilation. Loops 2 and 3 show the patient breathing against the ventilator. The loop moves toward the negative side of the pressure axis and then changes to positive. The pressures generated are quite high and the tidal volume is decreased since the patient is exhaling during inspiration.

Flow-volume Loop

Figure 23.60 depicts a flow-volume loop with a spontaneous breath near the end of inspiration. There is a sudden increase in inspiratory flow and volume. As the breath is exhaled, the flow and volume move toward zero.

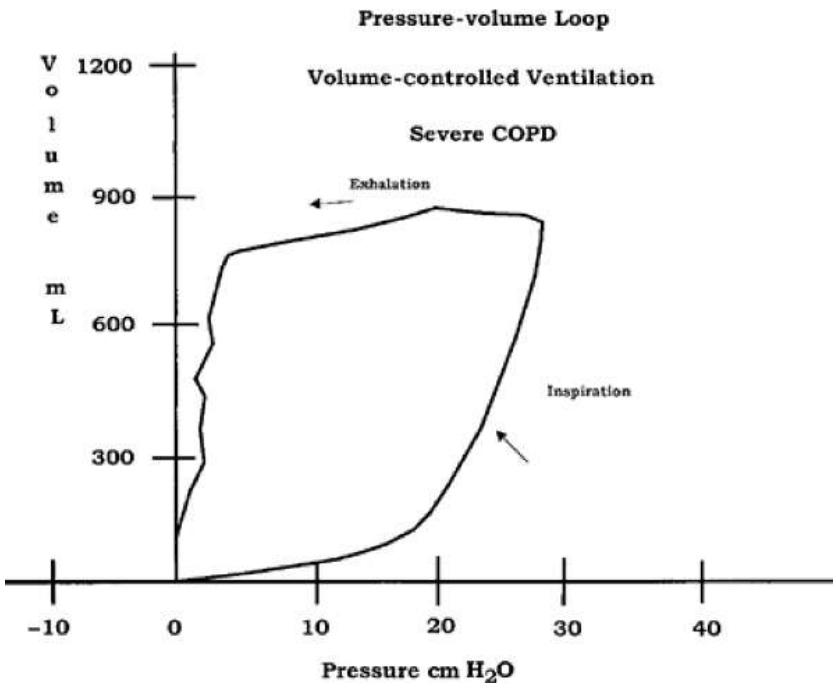

Figure 23.50 With severe COPD, resistance during expiration is greatly increased. The patient may have difficulty exhaling completely before the next inspiration, producing an open loop. COPD, chronic obstructive pulmonary disease.

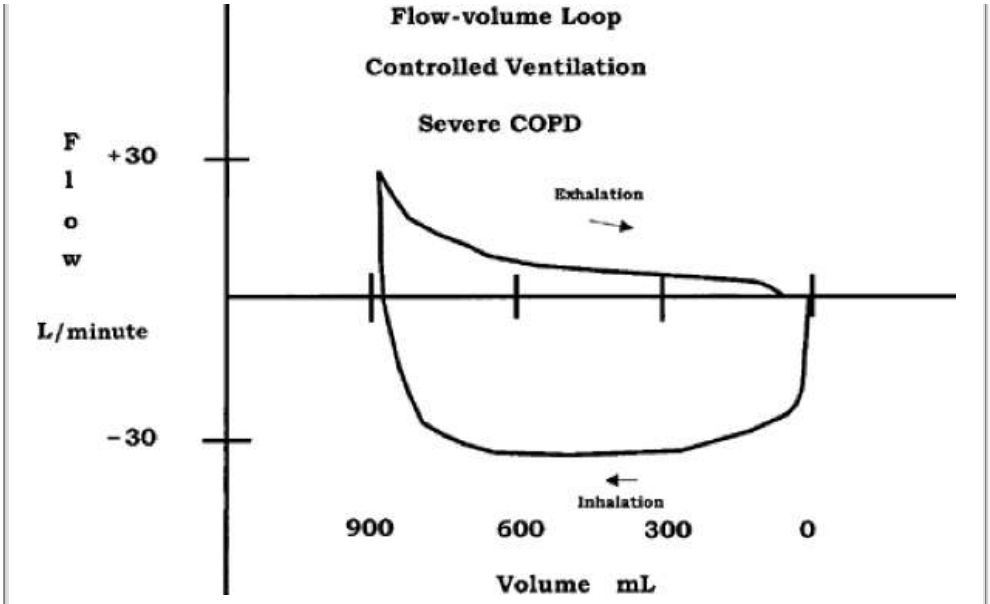

Figure 23.51 With severe COPD, expiratory flow is severely reduced. COPD, chronic obstructive pulmonary disease.

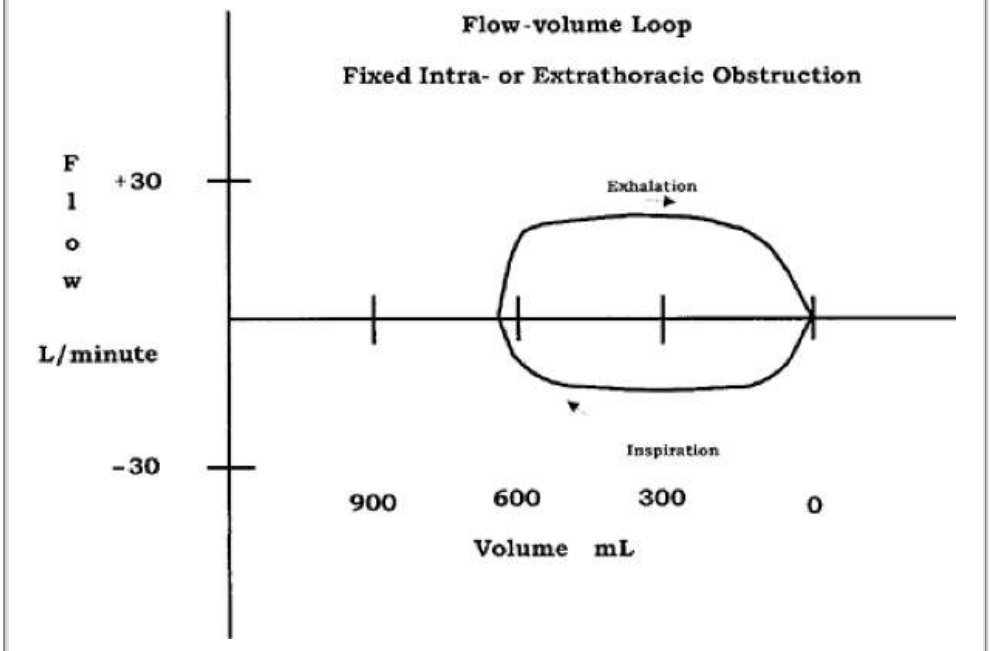

Figure 23.52 Flow-volume loop with fixed intra- or extrathoracic obstruction.

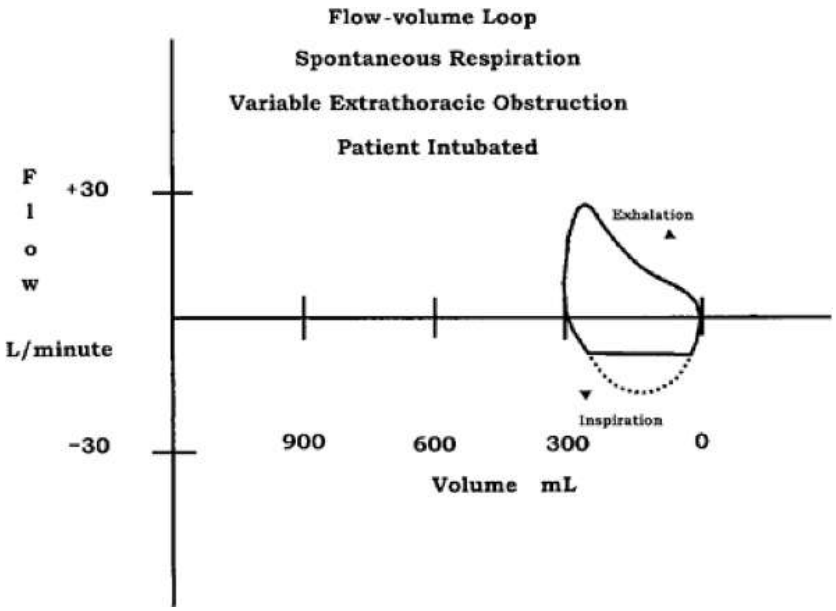

Figure 23.53 A variable obstruction located outside the thorax will cause a plateau during inspiration. The expiratory portion of the curve is close to normal. The dotted line shows a normal loop.

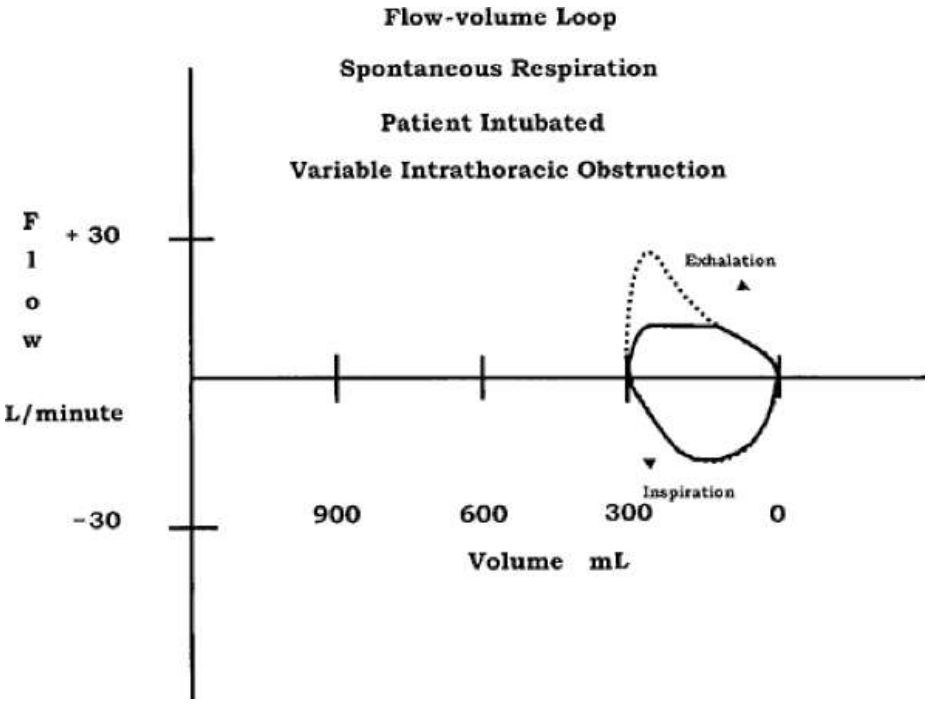

Figure 23.54 With a variable intrathoracic obstruction (such as a tumor in the trachea or a mediastinal mass), inspiratory flow may be relatively normal, but during expiration, flow rises to a plateau instead of the usual rise to and descent from peak flow. The dotted line shows a normal loop.

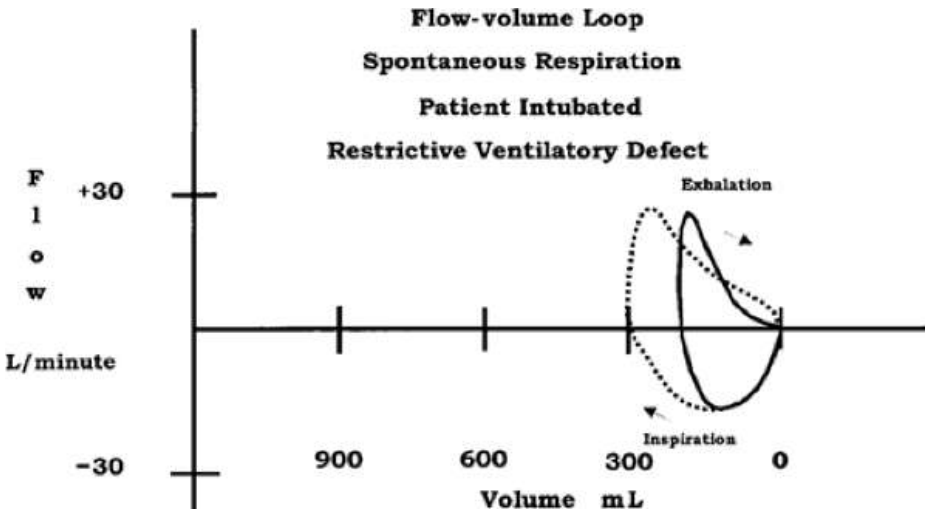

Figure 23.55 With a restrictive defect, the increase in elastic recoil is associated with higher expiratory flows. As the process becomes more severe and lung volumes are decreased, the flow-volume curve becomes tall and narrow. The dotted line shows a normal loop.

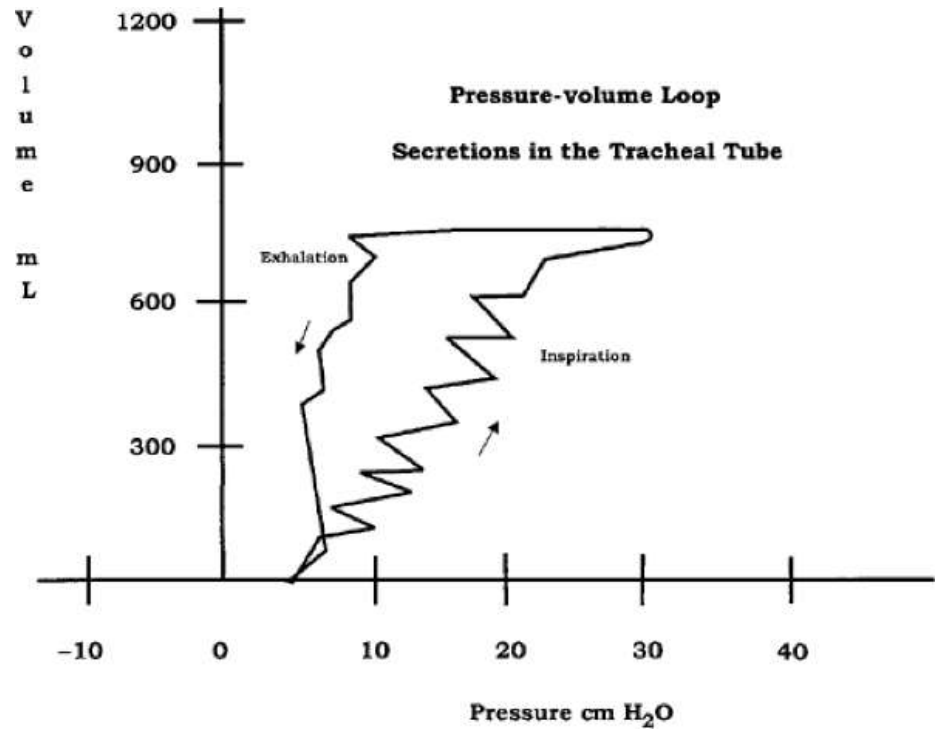

Figure 23.56 Pressure-volume loop with secretions in the tracheal tube.

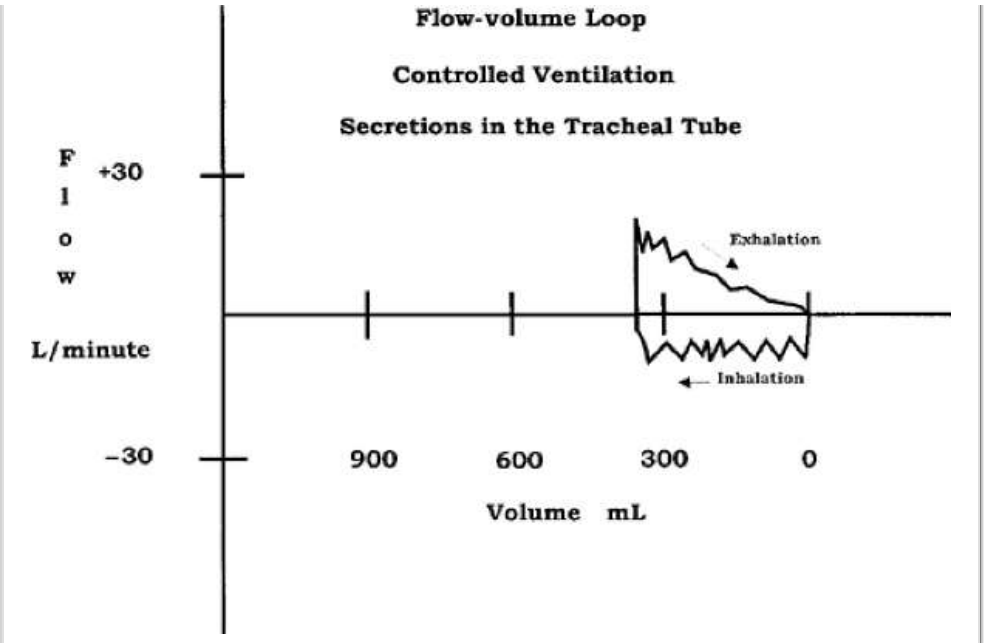

Figure 23.57 Flow-volume loop with secretions in the tracheal tube.

Open Loop

A loop should return to its starting point at the end of the respiratory cycle. An open loop (Fig. 23.61) has a gap between the end and starting points, indicating that the exhaled volume is less than the inhaled volume. While the pressure-volume loop appears to close, it actually returns to zero pressure along the vertical axis rather than at the starting point. The amount of gas loss can be read between zero and the return point of the loop.

An open loop means that more gas has passed the sensor during inspiration than returns during exhalation. Most often, this is because of a leak distal to the sensor. Incorrect calibration should also be considered. An open loop is often seen with mask anesthesia, an uncuffed tracheal tube, or a supraglottic airway device. A double-lumen tube may impose sufficient resistance to result in the lungs not completely emptying, even in patients with normal airways (22,92).

Leaks often occur after lung reduction or other thoracic surgery (93). The extent of the leak and changes in the volume of gas

lost can be tracked with the flow-volume loop.

An open loop may be due to incomplete exhalation caused by chronic obstructive pulmonary disease (COPD), increased resistance caused by apparatus, a tension pneumothorax, lung retraction, or a flap-valve obstruction in a large airway or a double-lumen tube (94).

Overshoot Loop

An overshoot loop indicates that the exhaled volume is greater than the inspired volume. This usually indicates

that the monitor needs to be recalibrated. It can also result if pressure on the thorax causes some of the functional residual volume to be added to the tidal volume.

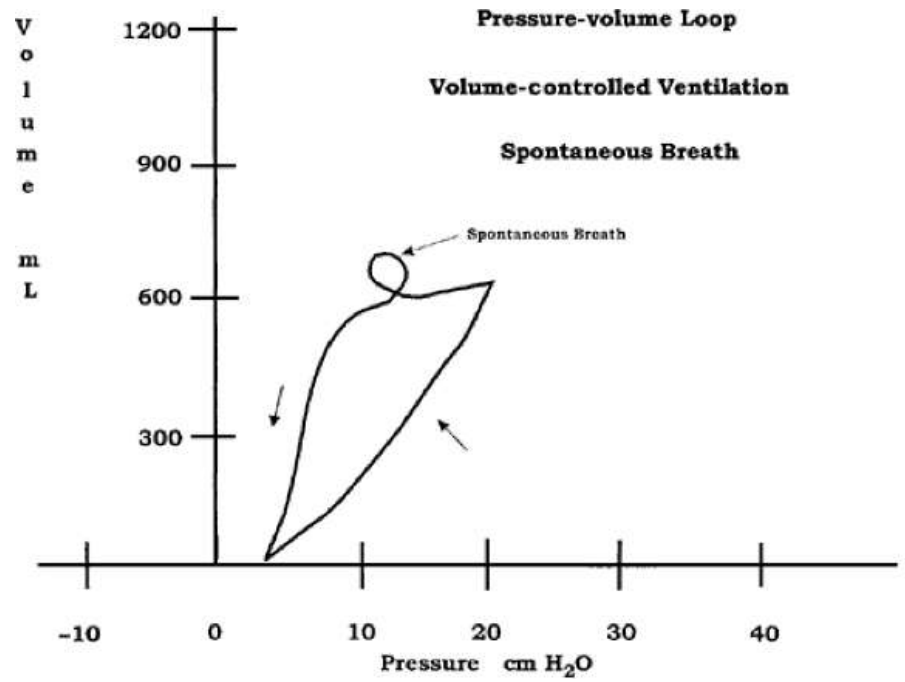

Figure 23.58 This spontaneous breath occurs during expiration.

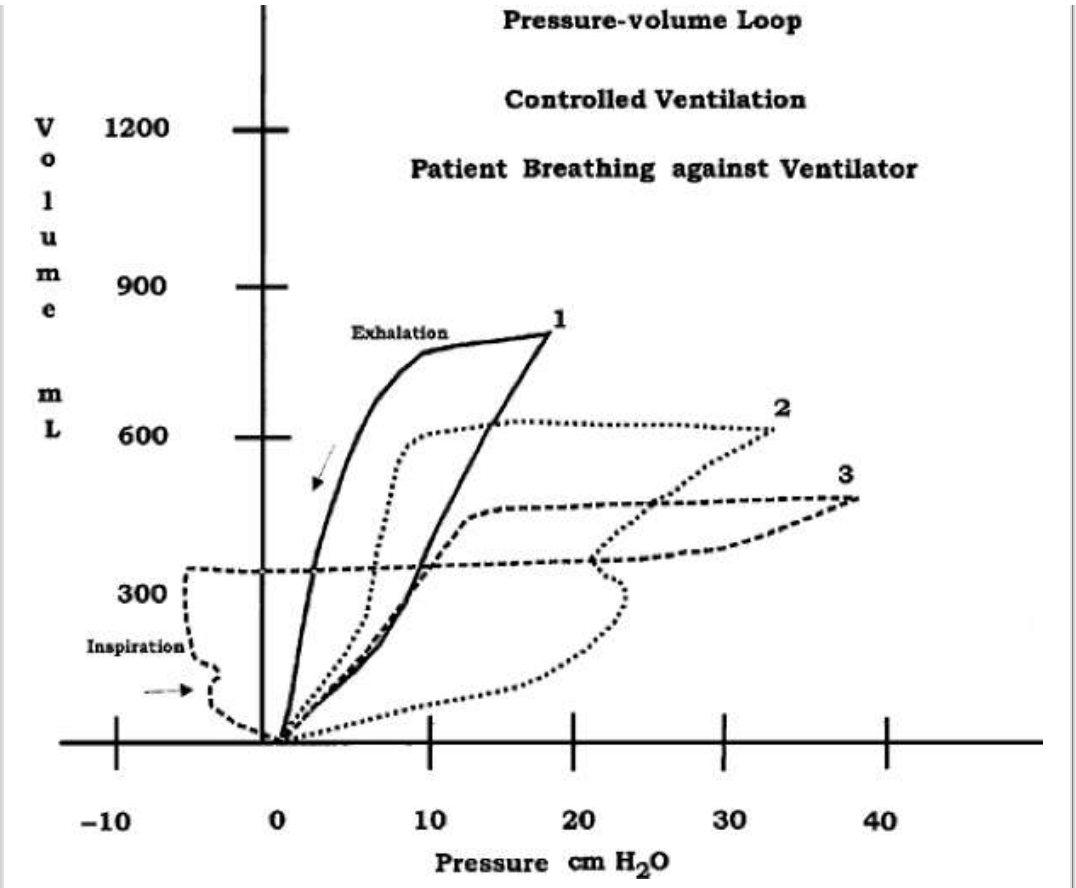

Figure 23.59 Loop 1 represents the normal loop. Loop 2 shows a spontaneous breath during inspiration. The pressure drops, and the volume increases briefly. There is a decrease in compliance caused by an increase in tension in the chest wall muscles. In loop 3, the patient inhales at the beginning of the respiratory cycle, so the loop moves to the left of the vertical axis. There is a further decrease in compliance.

Pressure-volume Loop

The pressure-volume overshoot loop (Fig. 23.62) can appear as a normal loop, but the beginning point is to the right of the endpoint. The difference between the beginning and endpoint is the amount of excess gas that is exhaled.

Flow-volume Loop

On the overshoot flow-volume loop (Fig. 23.63), the endpoint is

to the right of the zero volume point. The distance to the right represents the excess gas that has been exhaled.

Intrinsic Positive End-expiratory Pressure and Air Trapping

Intrinsic (auto, occult) PEEP (PEEPi) results from a difference between the actual expiratory time and the

expiratory time required for complete exhalation of the tidal volume so that some air is trapped in the lungs (Fig. 23.63). It may be generated by a very short expiratory time and/or slow expiration due to high resistance or abnormally high compliance. Air trapping is likely to occur in patients with airflow limitation, inverse ratio ventilation, or when using a high respiratory rate.

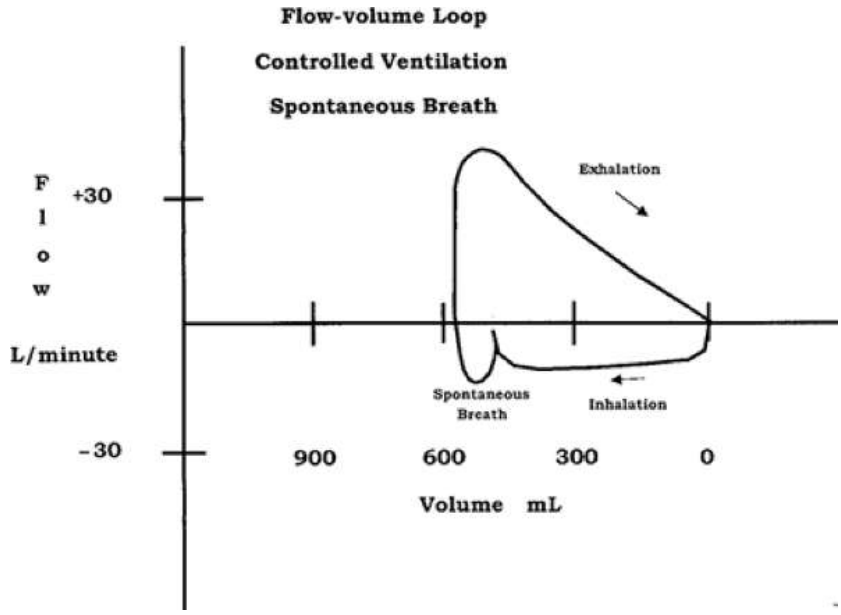

Figure 23.60 The spontaneous breath occurs near the end of inspiration. The *thin, dotted line* represents the normal loop. Instead of returning to zero at the end of inspiration, the flow increases. There is a small increase in volume as well.

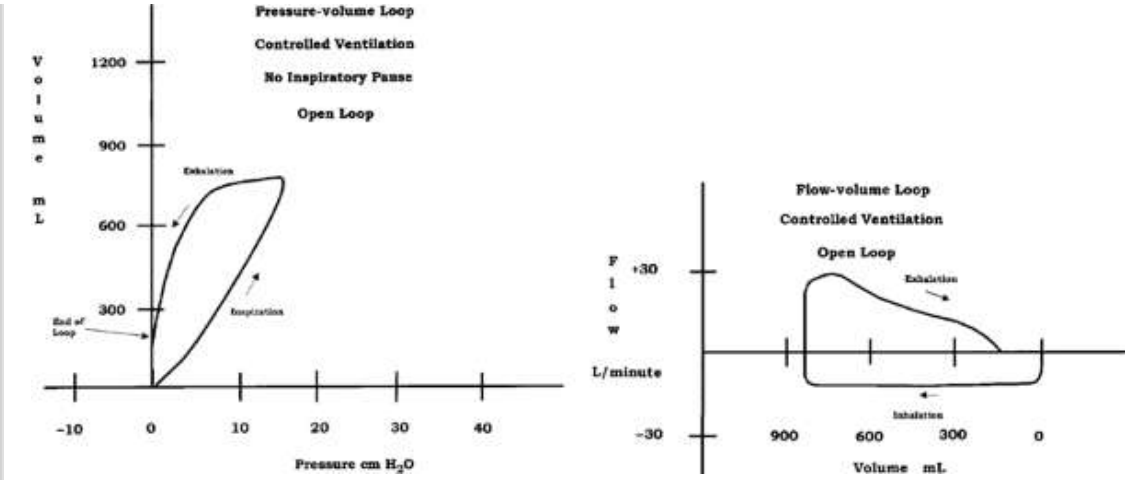

Figure 23.61 There is a leak, so exhaled volume is approximately 150 mL less than the inhaled volume. This produces open pressure-volume and flow-volume loops.

Loops Representing Equipment Problems

Tubing Misconnection

Some older sensors had a long and a short nipple designed to connect to the short and long lumens of the pressure tubing, respectively. It was possible to connect the tubings long to long and short to short. If this were done, the monitor would sense exhalation as inhalation and vice versa. The loops would be drawn backward and upside down (Fig. 23.64). It would take two respiratory cycles to produce a full loop, and the monitor would be unable to compute the compliance. Extremely high PEEP values would be recorded. Newer sensors with male and female connections make tubing misconnections less likely (Fig. 23.8).

Disconnection between the Sensor and the Breathing System

If there is a disconnection between the spirometry sensor and the breathing system, there will be no flow

through the sensor during mechanical ventilation and a loop will not be generated (Fig. 23.65).

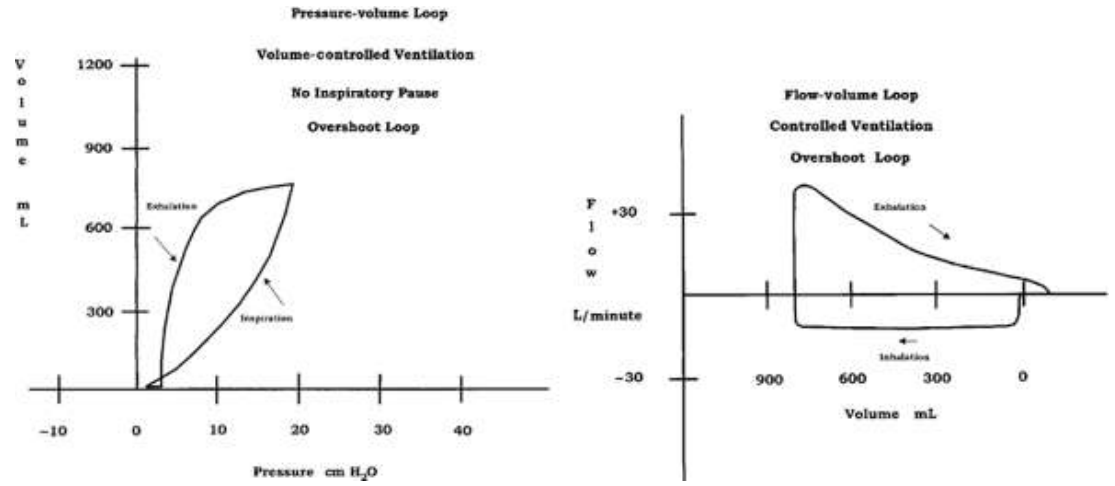

Figure 23.62 The exhaled volume exceeds the inhaled volume, producing an overshoot loop.

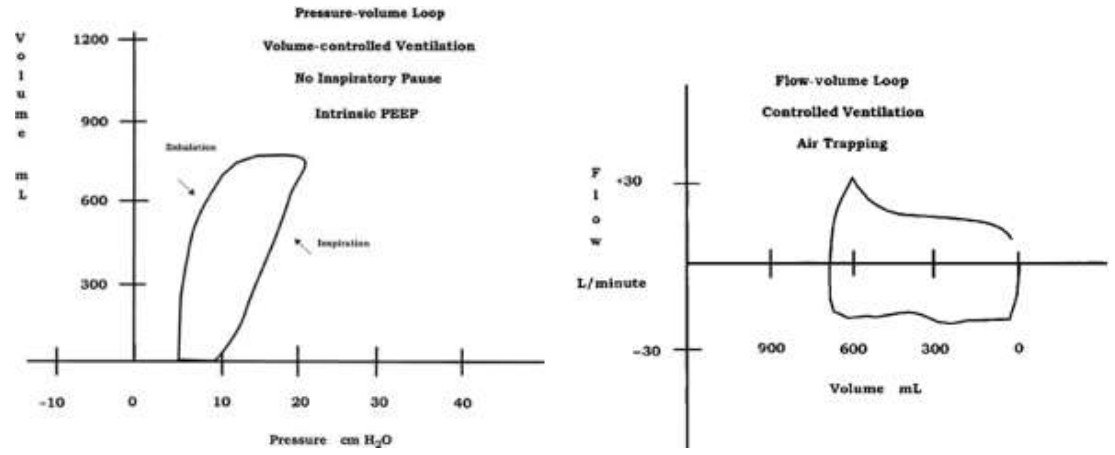

Figure 23.63 Intrinsic positive end-expiratory pressure and air trapping. The gap in the flow-volume loop indicates that there was still expiratory flow when the next inspiration commenced. PEEP, positive end-expiratory pressure.

If the patient breathes spontaneously with a disconnection between the sensor and the breathing system, loops seen with spontaneous respiration will be generated. If a circle breathing system also contains a flow sensor mounted on the exhalation

side near the absorber, this sensor will not indicate flow during spontaneous ventilation and will help to localize the disconnection.

Leak between the Sensor and the Breathing System

Pressure-volume Loop

If there is a leak or partial disconnection between the sensor and the breathing system, some gas will be lost. The pressure-volume loop (Fig. 23.66) will be normal in shape but will show a decrease in tidal volume and a decrease in peak airway pressure. This differs from the leak associated with the open loop in that the inhaled volume is decreased as a result of the leak, but the amount of gas exhaled is equal to the amount of gas inhaled.

Flow-volume Loop

The flow-volume loop during a partial disconnection (Fig. 23.66) will show a decreased tidal volume and a decrease in peak expiratory flow. The loop will not be open because both inspired and exhaled tidal volumes will be the same.

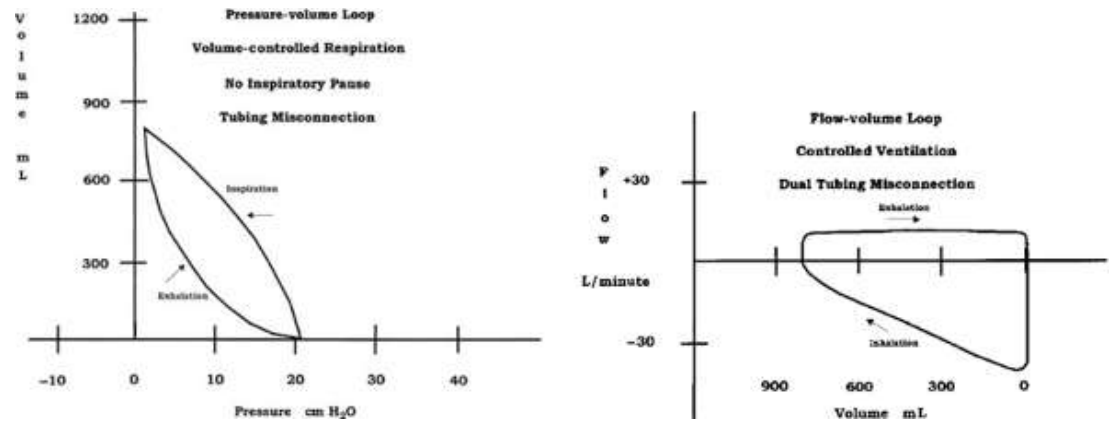

Figure 23.64 Misconnection of the tubings will cause the loop to be drawn backward and upside down.

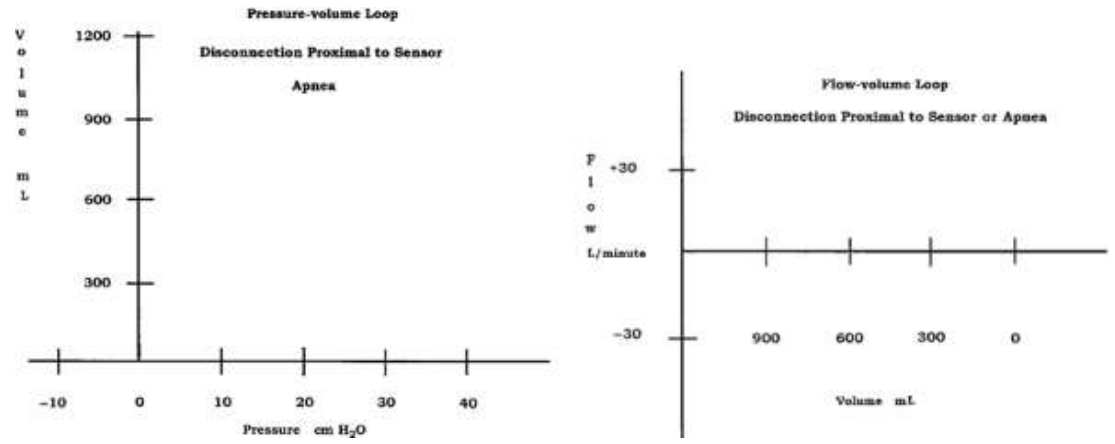

Figure 23.65 A disconnection between the sensor and the breathing system will result in no flow through the sensor.

Disconnection between the Sensor and the Patient

With a disconnection between the sensor and the patient, during controlled ventilation there will be flow during inspiration but not exhalation (Fig. 23.67). The pressure-volume loop will show a high tidal volume but almost no pressure. Since there will be no return gas flow, there will be only half of a pressure- or flow-volume loop.

Bronchial Intubation

Bronchial intubation can occur anytime a tracheal tube is in place. It is the most frequently occurring problem leading to hypoxia (95). If this happens, the compliance decreases and the pressure needed to deliver a set tidal volume rises (21,96,97). Bronchial intubation is discussed in Chapter 19. It is most likely to occur with a change in the patient's position. If a sudden change occurs in the pressure-volume loop at this time, bronchial intubation should be suspected. Withdrawing the tracheal tube slightly will remedy the problem and will be demonstrated with the next loop. Pressure-volume loops may be among the best ways of detecting this problem.

Pressure-volume Loop

The pressure-volume loop will show a decrease in compliance with a rightward and downward shift and a high peak pressure (Fig. 23.68, solid line).

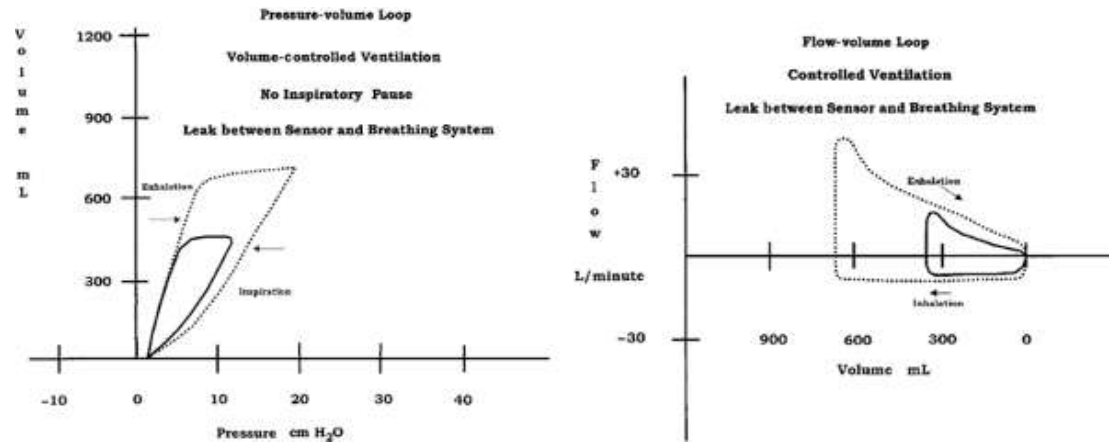

Figure 23.66 With a leak between the sensor and the breathing system, the loop will have a normal shape but the tidal volume, peak pressure, and expiratory flows will be decreased. The *dotted line* represents the normal loop, and the *solid line* represents the loop with a leak.

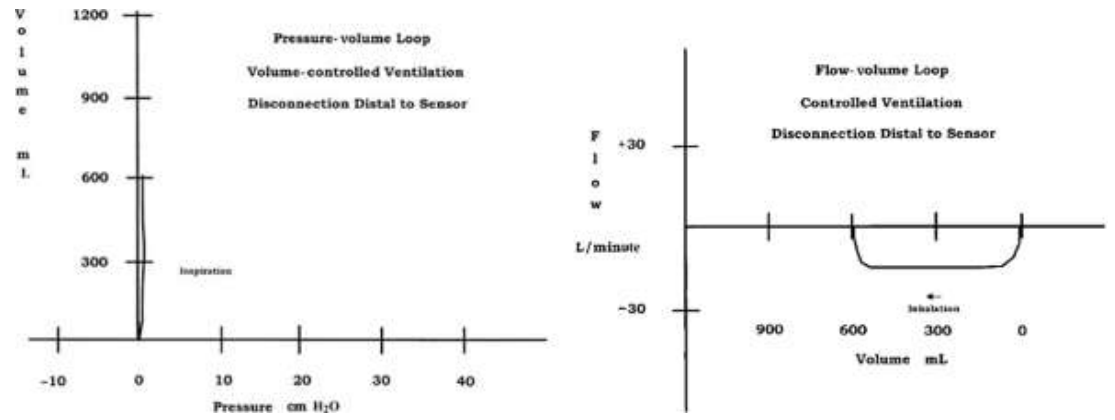

Figure 23.67 A disconnection distal to the sensor will result in flow during inspiration but none during exhalation.

Flow-volume Loop

The flow-volume loop associated with bronchial intubation is shown in Figure 23.69 (solid line). The increase in peak pressure will increase the peak flow during exhalation.

Double-lumen Bronchial Tube Problem

Double-lumen bronchial tubes are often placed incorrectly or may be displaced during patient positioning or surgery (6,21,22,98,99,100). Continuous spirometric monitoring can help to detect the problem. Baseline flow-volume and pressure-volume loops should be established and recorded for each patient while in the supine position during two-lung ventilation to allow comparison with later loops.

Pressure-volume Loop

When one-lung ventilation is begun, the pressure-volume loop should show a slight shift of the slope to the right, reflecting decreased compliance (98,99,100). With surgical handling of the nondependent lung, compliance may decrease further (100).

If a double-lumen tube is placed too deeply, there will appear to be a decrease in compliance (Fig. 23.70). Tidal volume may be decreased. Incomplete lung emptying will result in an open loop (22).

The loops shown in Figure 23.71 resulted from the tip of the bronchial lumen impinging on the wall of the bronchus. Loop 1 (solid line) is the normal loop. In loop 3 (dotted line), the tube tip has impinged on the wall of the bronchus. Pressure rises rapidly with little increase in volume until sufficient pressure has been

exerted to move the tip away from the wall. At this point, the volume rises rapidly. There will be an increase in peak pressure and/or a decrease in compliance. If there is a ball-valve action, during exhalation the pressure will decrease rapidly with little change in volume until the pressure in the bronchial tube has fallen sufficiently to allow exhalation.

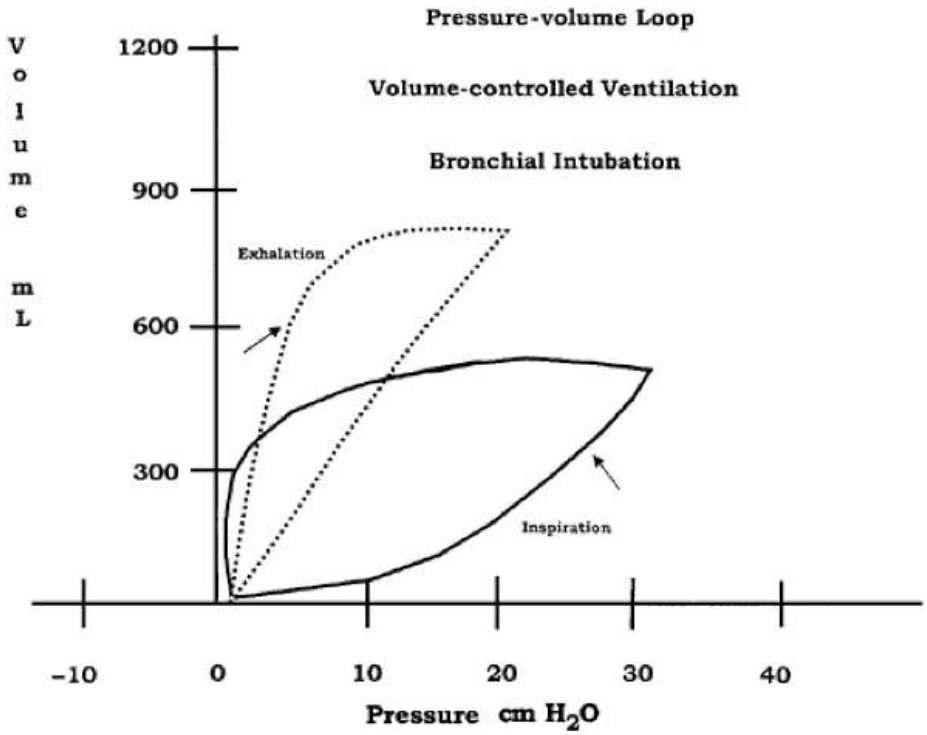

Figure 23.68 Bronchial intubation (*solid loop*) will result in a decrease in compliance.

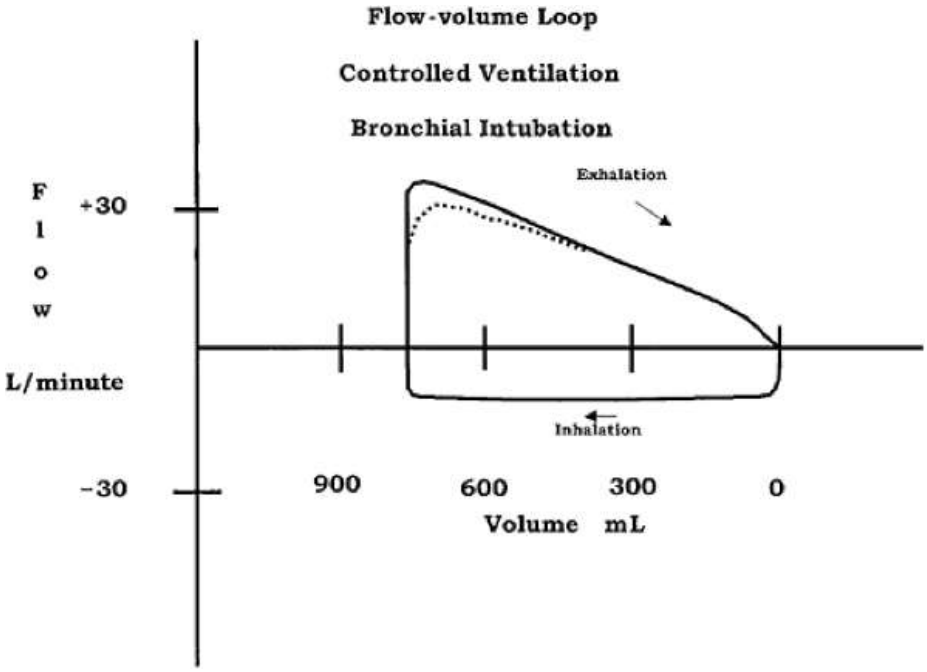

Figure 23.69 Bronchial intubation. The *solid loop* shows an increase in expiratory flow, especially during the early part of expiration.

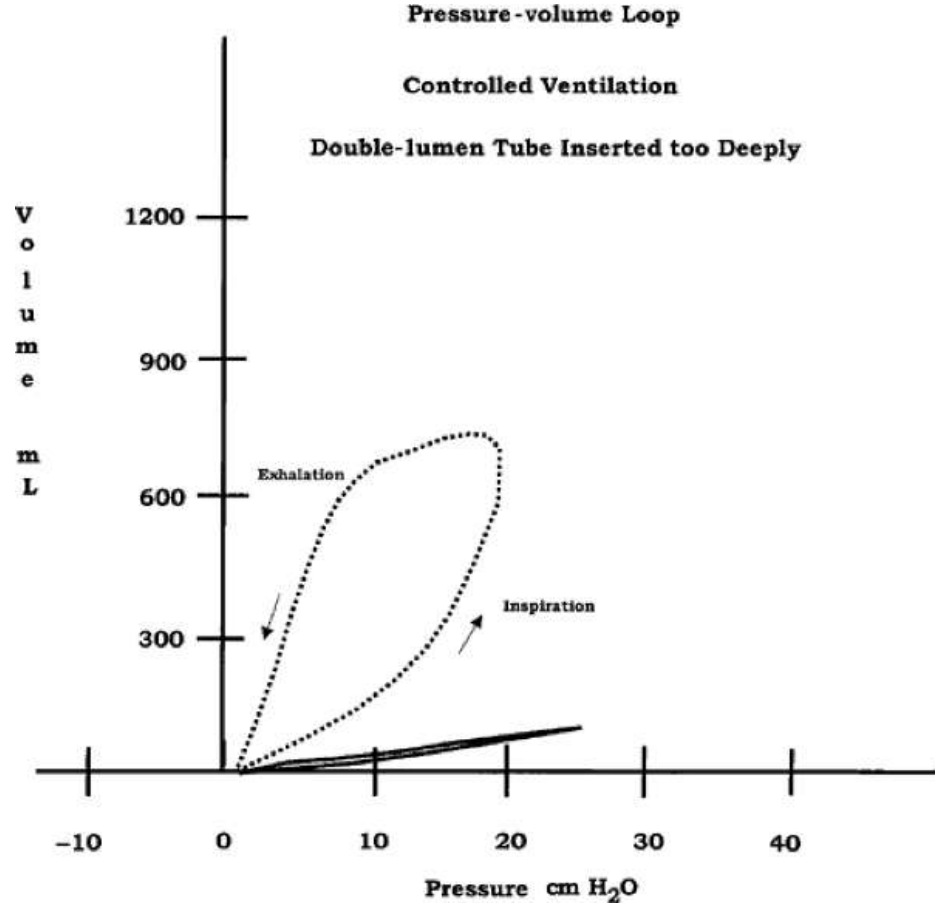

Figure 23.70 The *dotted line* represents the loop when the double-lumen tube is correctly positioned. If the bronchial lumen is inserted too deeply, a severe reduction in compliance and tidal volume will be seen.

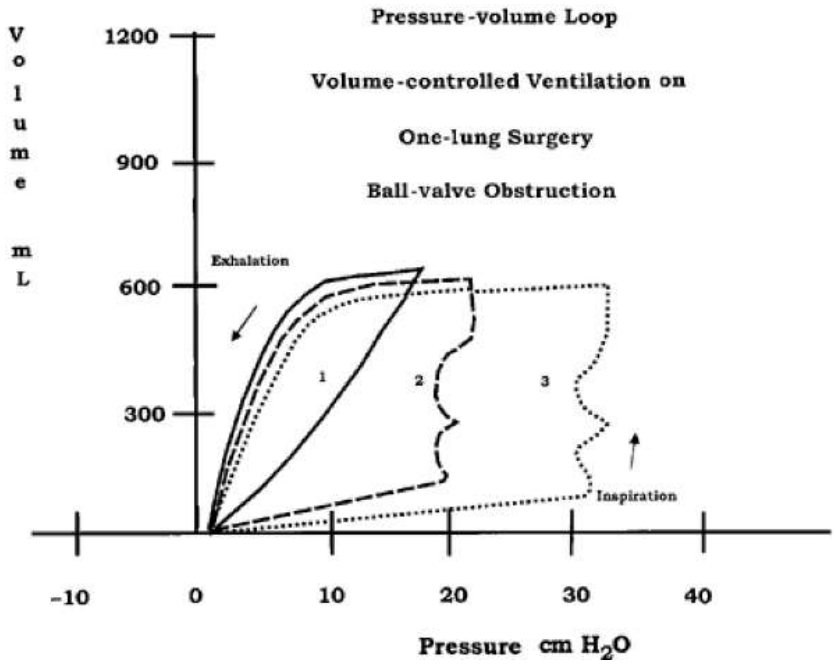

Figure 23.71 Impingement of the end of the tube on the bronchial wall has created a ball-valve obstruction. The pressure rises rapidly with little increase in volume until the pressure is sufficient to overcome the obstruction. The volume then increases, and the pressure drops. If the pressure drops low enough, there will again be obstruction to flow, creating another notch on the upswing of the loop.

Flow-volume Loop

The flow-volume loop during proper double-lumen tube placement will show a slightly decreased expiratory flow rate. If the tube is placed too deeply into the bronchus, the loop will show diminished inspiratory and expiratory flows. If there is a ball-valve obstruction to the tip of the double-lumen tube, the flow-volume loop will be irregular (Fig. 23.72).

The flow-volume loop that would be generated if there were a disconnection of one limb of a double-lumen tube or a leaking bronchial cuff is shown in Figure 23.73 (solid line). The inspiratory portion is normal. Because much of the inspired tidal volume is lost through the leak, the loop is open. In addition, there will be decreased flow during exhalation.

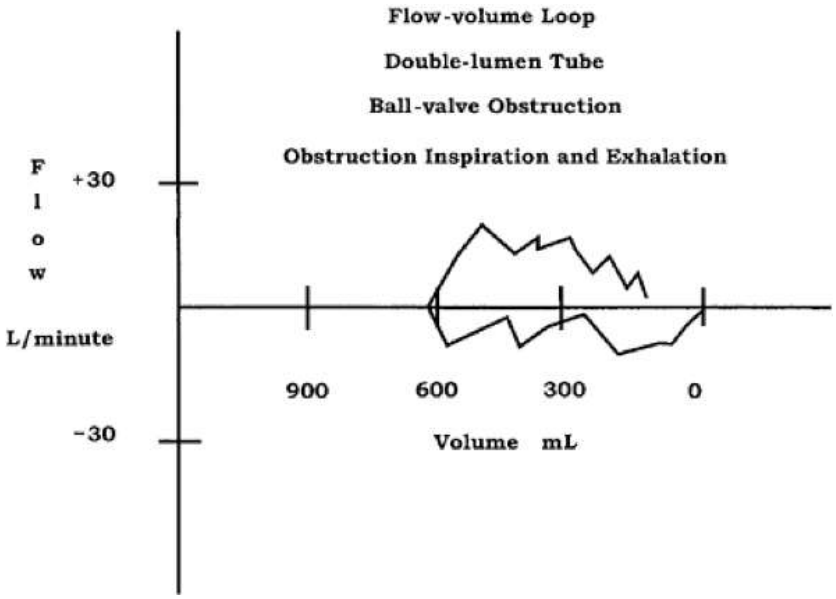

Figure 23.72 The loop represents repeated ball-valve obstruction to flow during both inspiration and expiration.

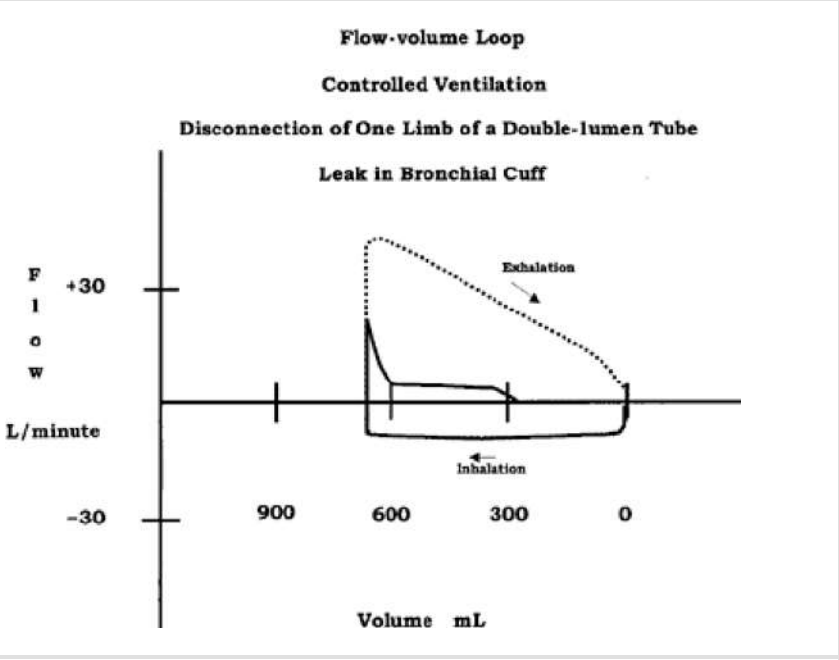

Figure 23.73 With a leak in the bronchial cuff or a disconnection of one limb (*solid loop*), there will be an open loop, with the inhaled volume exceeding the exhaled volume. Exhaled flows will be decreased.

Esophageal Intubation

With esophageal intubation, the pressure-volume loop will usually show a decrease in compliance (Fig. 23.74, solid line), although compliance may be increased or normal (21). Gas that enters the stomach and is not returned will create an open loop. The flow-volume loop will be distorted and show small inspiratory and expiratory volumes, often with an open loop.

Obstructed Tube

A nearly completely obstructed tracheal tube or an incorrectly placed supraglottic airway device will result in a pressure-volume loop that shows a high pressure with little or no tidal volume (Fig. 23.75). This is usually a signal that the device should be removed and reinserted.

Advantages of Loop Technology

Pressure- and flow-volume loops provide the clinician with real-time information. There are many problems that can occur unexpectedly during a case (e.g., kinked tracheal tube, disconnection, migration of a tracheal tube into a bronchus). Without loops, these problems might not be recognized promptly and corrective action may be delayed. While many of the problems that occur during respiration could be determined by watching

pressure, tidal volume, and flow monitors, loop technology offers a graphic representation that integrates that information, making changes more obvious.

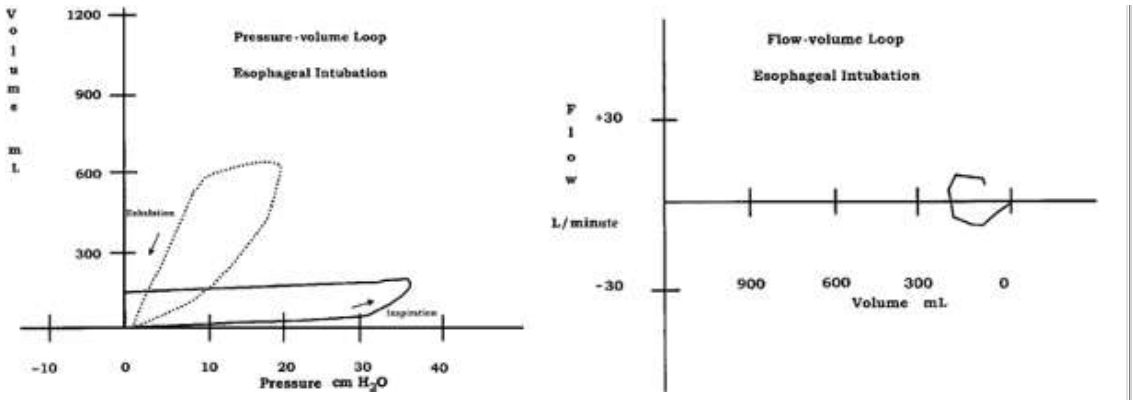

Figure 23.74 The loops associated with esophageal intubation may vary greatly. Compliance may be increased, decreased, or normal.

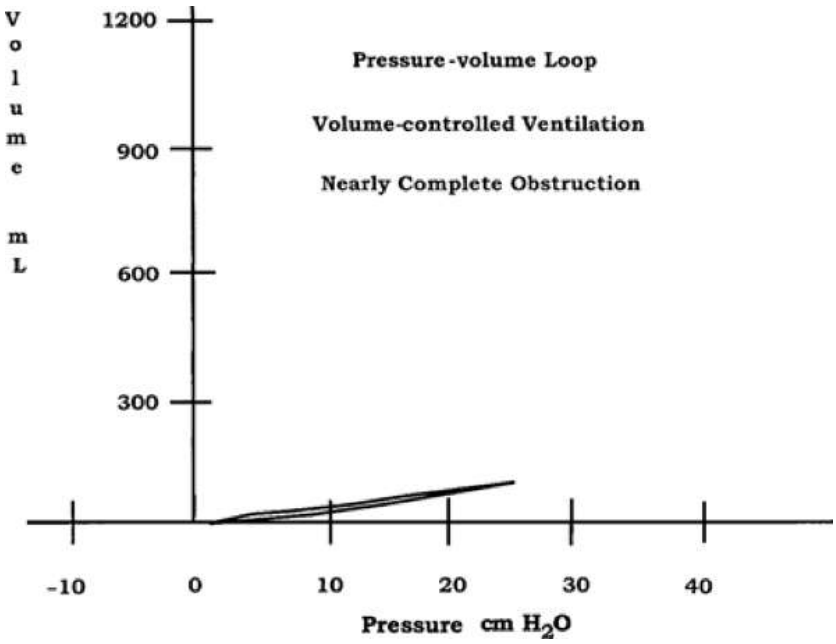

Figure 23.75 With a nearly obstructed tube, there will be a high pressure with little volume.

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Questions

For the following questions, select the correct answer

1. Normal static compliance in an adult is

A. 15 mL/cm H_2O

B. 35 to 100 mL/cm H_2O

C. 20 to 35 mL/cm H_2O

D. 35 to 50 mL/cm H_2O

E. 75 to 125 mL/cm H_2O

View Answer

2. For greatest accuracy, the gas flow sensor should be placed

A. In the inspiratory limb at the absorber

B. Between the inspiratory limb and the Y-piece

C. Between the Y-piece and the patient

D. Between the Y-piece and the expiratory limb

E. On the absorber on the exhalation side

View Answer

3. The preferred site for monitoring airway pressure is

A. At the ventilator

B. In the inspiratory limb at the canister

C. At the connection between the patient and the breathing system

D. On the expiratory limb at the canister

E. At the bag mount connection

View Answer

For the following questions, answer

if A, B, and C are correct

if A and C are correct

if B and D are correct

is D is correct

if A, B, C, and D are correct.

4. What does the difference between the peak and plateau pressure measure?

A. Plateau pressure

B. Total airway resistance

C. Compliance

D. Inspiratory flow

E. Resistance in the breathing system

View Answer

5. Use of muscle relaxants

A. May cause the compliance of the lungs to increase

B. May cause the compliance of the chest wall to increase

C. May cause a decrease in resistance

D. May result in a decrease in plateau pressure

View Answer

6. A rise in peak airway pressure may occur as a result of

A. An increase in tidal volume

B. An increase in inspiratory flow rate

C. An increase in resistance

D. An increase in compliance

View Answer

7. With inadvertent bronchial intubation,

A. There will be a decrease in compliance

B. The pressure-volume loop will be shifted to the right and downward

C. The peak pressure will be increased

D. The flow-volume loop will show an increase in peak expiratory flow

View Answer

8. Increased resistance to breathing during controlled respiration can be overcome by

A. Adding or increasing PEEP

B. Increasing the driving pressure

C. Increasing the inspired oxygen

D. Decreasing inspiratory flow

View Answer

9. Total resistance during inspiration and expiration is influenced by

A. The patient's airway

B. The exhalation portion of the breathing system

C. The size and characteristics of the tracheal tube

D. The amount of PEEP added to the breathing system

View Answer

10. Means to detect a leak around a tracheal tube include

A. Airway pressure monitors

B. Respiratory breath sound monitoring

C. Respiratory volume measurement

D. Capnography

View Answer

11. Respiratory volume monitoring may fail to detect

A. Occlusion of the airway

B. A disconnection during spontaneous breathing

C. Esophageal intubation

D. Apnea

View Answer

12. Which factors are components of total compliance?

A. Elastic properties of the lungs

B. Elastic properties of the thorax

C. Elastic properties of the abdomen

D. Elastic properties of the breathing system

View Answer

13. Conditions that can be detected by using a minimum pressure alarm include

A. An unconnected ventilator

B. A major leak in the breathing system

C. A malfunctioning scavenging system

D. An increase in resistance

View Answer

14. The minimum airway pressure alarm should be set

A. At the lowest setting

B. At different settings during a case

C. Greater than 6 cm H_2O

D. Slightly less than the peak pressure during inspiration

View Answer

15. Conditions that may prevent activation of the minimum pressure alarm with a disconnection include

A. Obstruction of a breathing system connector

B. Partial extubation

C. High resistance of components of the breathing system

D. Air entrained into the breathing system

View Answer

16. A sustained pressure may be caused by

A. Occlusion of the scavenging system

B. Activation of the oxygen flush valve

C. Improper adjustment of the APL valve

D. Occlusion of the inspiratory limb of the breathing system

View Answer

17. An excessively high pressure in the breathing system may be caused by

A. The patient coughing or straining

B. Use of the oxygen flush during the inspiratory phase of the ventilator cycle

C. A punctured ventilator bellows

D. Increased compliance

View Answer

18. Subambient pressure in the breathing system may be caused by

A. A nasogastric tube placed in the trachea and attached to suction

B. A blocked expiratory limb

C. Inspiration with an empty reservoir bag

D. Refilling of a ventilator with a standing bellows with low fresh gas flows

View Answer

19. On a pressure-volume loop,

A. The farthest point to the right on the horizontal axis represents the tidal volume

B. The slope of the inspiratory portion is determined by the resistance

C. The highest point on the curve represents the peak pressure

D. The curve can slope to the right or left during inspiration

View Answer

20. Concerning a flow-volume loop,

A. The portion below the horizontal line represents inspiration using the representation used by pulmonologists

B. The portion above the horizontal line represents the passive deflation as determined by the elastic recoil of the lungs and chest wall in the representation used by pulmonologists

C. The tidal volume is that point where the loop crosses the horizontal line

D. This loop is known as a compliance loop

View Answer

21. If a double-lumen tube is placed too deeply,

A. The pressure-volume loop will be shifted to the right and downward

B. There will be a decrease in compliance

C. An overshoot loop may result

D. Resistance will increase

View Answer

22. Possible causes of inadvertent PEEP include

A. Partial obstruction of the breathing system

B. Malfunctioning scavenging device

C. Obstructive airway disease

D. Airflow obstruction

View Answer

23. Possible causes of an open loop include

A. Improper calibration of the monitor

B. An uncuffed tracheal tube

C. A leak distal to the sensor

D. Tension pneumothorax

View Answer

24. Decreases in compliance may be caused by

A. Inadequate muscle relaxation

B. Bronchial intubation

C. Obesity

D. Reverse Trendelenburg position

View Answer

25. With restrictive lung disease,

A. Peak expiratory flow will be increased

B. The flow-volume loop may become tall and narrow

C. The flow-volume loop may have a relatively normal shape but may appear smaller in all dimensions

D. Resistance is increased

View Answer

Chapter 24
Pulse Oximetry

Introduction

Pulse oximetry, sometimes called the *fifth vital sign*, is a noninvasive method of measuring hemoglobin saturation (SpO_2) by using a light signal transmitted through tissue. A low SpO_2 can provide warning of hypoxemia before other signs such as cyanosis or a change in heart rate are observed.

Until the 1980s, noninvasive oximeters, known as ear oximeters, were large, expensive, and cumbersome. They required ‘€arterialization‘€ by heat or chemical treatment, and their utility was limited by difficulties in differentiating light absorbance of arterial blood from that of venous blood and tissues.

Technical advances, including light-emitting diodes (LEDs), miniaturized photodetectors, and microprocessors, allowed the creation of a new generation of oximeters, which were smaller, less expensive, and easier to use. These differentiate the absorption of light by the pulsatile arterial component from the static components, so they are called *pulse oximeters*.

A pulse oximeter may be a stand-alone device or incorporated into another device such as a multiparameter monitoring system. A relatively new development is a combined pulse oximetry and transcutaneous carbon dioxide tension ear sensor (1,2,3,4).

The American Society of Anesthesiologists (ASA) and American Association of Nurse Anesthetists have made assessment of oxygenation a standard for intraoperative and postoperative monitoring. In 2005, an audible alarm for the pulse oximeter was added to the ASA monitoring standard (5). International standards for safe practice endorsed by the World Federation of Societies of Anesthesiologists highly recommend continuous use of a quantitative monitor of oxygenation such as pulse oximetry (6). In some states, the use of pulse oximetry is mandatory. A study of closed claims of anesthetic-related malpractice cases determined that a combination of pulse oximetry and capnography could have prevented 93% of avoidable mishaps (7). One study determined that pulse oximetry provided the first warning of an incident in 27% of situations (8). The number of unanticipated intensive care unit admissions decreased after the introduction of the pulse oximetry (9).

Operating Principles

The pulse oximeter estimates SpO_2 from the differential absorption of red and infrared light in tissue (10,11,12,13,14,15,16). The two wavelengths allow differentiation of reduced hemoglobin and oxyhemoglobin. Reduced hemoglobin absorbs more light in the red band than

oxyhemoglobin (Fig. 24.1). Oxyhemoglobin absorbs more light in the infrared band. The pulse oximeter computes the ratio between these two signals and relates this ratio to the arterial oxygen saturation, using an empirical algorithm.

Pulse oximeters discriminate between arterial blood and other components by determining the change in transmitted light caused by the flow of arterial blood. The oximeter pulses the red and infrared LEDs ON and OFF several hundred times per second. The rapid sampling rate allows recognition of the peak and trough of each pulse wave. At the trough, the light is transmitted through a vascular bed that contains mainly capillary and venous blood as well as intervening tissue. At the peak, it shines through all this plus arterial blood. A photodiode collects the transmitted light and converts it into electrical signals. The emitted signals are then amplified, processed, and displayed on the monitor. Oximeters have a phase with both LEDs OFF to allow detection of and compensation for extraneous light. Light readings during the OFF period are subtracted from the next sequence.

Fractional oxygen saturation (% HbO_2) is the ratio of oxyhemoglobin to the sum of all hemoglobin species present, whether available for reversible binding to oxygen or not (17). Functional oxygen saturation (SaO_2) is defined as the ratio of oxyhemoglobin to all functional hemoglobins. These must be determined by using an

in vitro oximeter. For patients with low dyshemoglobin levels, the difference between fractional and functional saturation is very small. However, when dyshemoglobin levels are elevated, the two values can vary greatly, and pulse oximeter readings may not agree with either the true fractional or functional saturation values (18).

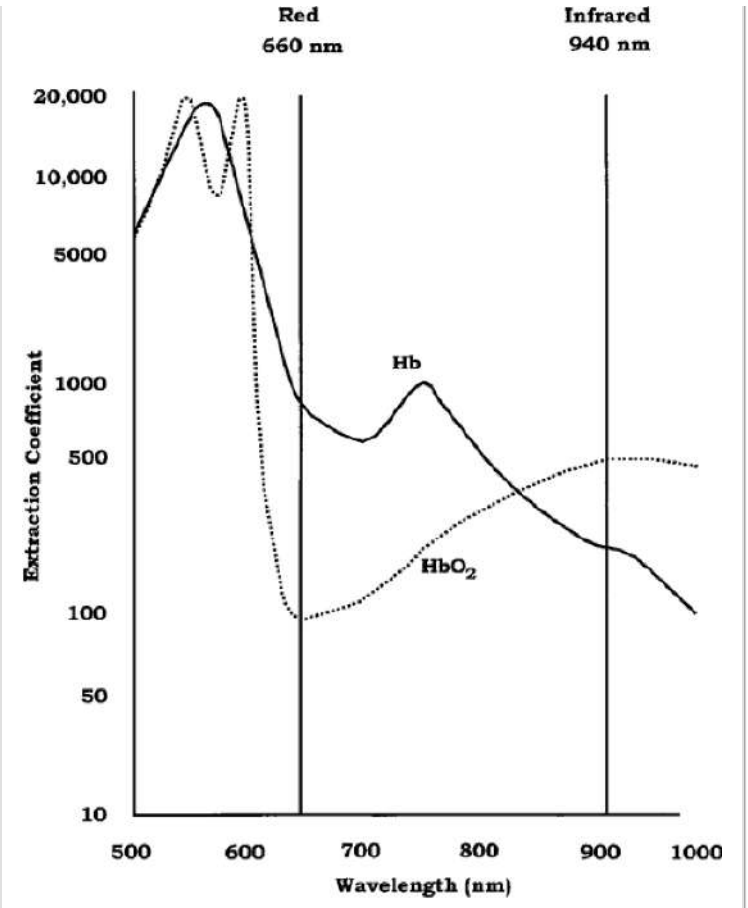

Figure 24.1 Absorbance of light as a function of wavelength. The extinction coefficient is a measure of the tendency of a substance to absorb light. At the red wavelengths (650 to 750 nm), reduced hemoglobin absorbs more light than does oxyhemoglobin. In the infrared region (900 to 1000 nm), the reverse is true.

Transmission Pulse Oximetry

The most common type of pulse oximeter is the transmission oximeter. With this technology, a light beam is transmitted through a vascular bed and is detected on the opposite side of that bed.

Reflectance Pulse Oximetry

Reflectance oximetry relies on light that is reflected (backscattered) to determine oxygen saturation. The probe has both an LED and a photodiode (Fig. 24.16). Transmission pulse oximetry probes are not accurate when used in the manner of reflectance oximetry (19). Reflection originates from nonhomogeneity in the optical path, that is, at the interfaces between materials with different reflective indices. The tissue must be well perfused to obtain a strong signal. Heating the

measurement site and applying pressure may be helpful (20,21).

There are a number of limitations of reflectance oximetry. The probe design must eliminate light that is passed directly to the probe or is scattered in the outer surface of the skin. The signals are weaker than those found in transmission oximetry, so the photodiode area needs to be as large as possible. If the probe is located over an artery or a vein, the reading may be artifactually low (22,23). Vasoconstriction can cause overestimation of the oxygen saturation (23).

Physiology

Efficient oxygen transport relies on the ability of hemoglobin to reversibly load and unload oxygen. The relationship between oxygen tension and oxygen binding is seen in the oxyhemoglobin dissociation curve (Fig. 24.2), which plots the hemoglobin oxygen saturation against the oxygen tension. The sigmoid shape of the curve is essential for physiologic transport. As oxygen is taken up in the lungs, the blood is nearly fully saturated over a large range of tensions. During passage through the

systemic capillaries, a large amount of oxygen is released with a relatively small drop in tension. This allows oxygen to be released at sufficiently high concentrations to provide an adequate gradient for diffusion into the cells.

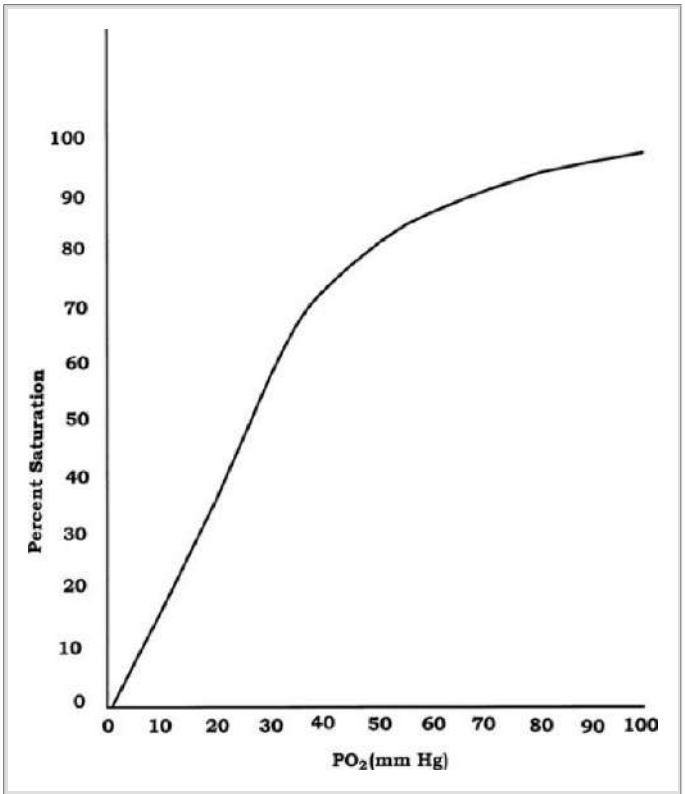

Figure 24.2 The oxyhemoglobin dissociation curve.

Hemoglobin saturation is plotted as a function of oxygen tension.

The shape of the oxyhemoglobin dissociation curve limits the degree of desaturation that can be tolerated. Between 90% and 100% saturation, the partial pressure of oxygen in arterial blood (PaO_2) will be 60 torr or above. Below 90% saturation, the curve becomes steeper, and small drops in saturation correspond to large drops in oxygen partial pressure. If a problem develops, there may not be much warning before the oxygen level becomes dangerously low. Normal saturation will decrease as altitude above sea level increases (24).

Equipment

Probes

The probe (sensor, transducer) is the part that comes in contact with the patient. It contains one or more LEDs (photodiodes) that emit light at specific wavelengths and a photodetector (photocell, transducer). The LEDs provide monochromatic light. This means that they emit a constant wavelength throughout their life, so they never need recalibration. LEDs cause relatively little heating and are so inexpensive that they may be used in a disposable probe. The light, partially absorbed and modulated as it passes through the tissue, is converted into an electronic signal by the photodetector.

Figures 24.3 to 24.11 show several types of probes. Probes may be reusable or disposable. They have the same accuracy (25,26,27,28). A disposable probe is usually attached by using adhesive. Reusable probes either clip on or are attached by using adhesive or Velcro. Disposable probes may be easier to use, but reusable probes are more economical as long as personnel are careful not to damage the reusable probe (26,29,30,31). Self-adhesive (band, wrap) probes are less susceptible to motion artifact and are less likely to come off if the patient moves than those that clip on. However, they are usually not as well shielded from ambient light as clip-on probes. Attaching reusable probes by using an adhesive or Velco wrap may improve their stability. Probes lined with soft material may be associated with fewer motion artifacts (32).

Some probes are available in different sizes. If a probe is too large for the patient, some of the light output from the LED can reach the photocell without passing through tissue, and falsely high SpO_2 readings will be produced (33,34). The photocell may not align with the probe, and readings will not be possible.

Loss of reusable probes can be reduced by making it difficult to separate the probe from the cable (31). Attaching the probe to the oximeter case when not in use will reduce damage and make it easy to find (35).

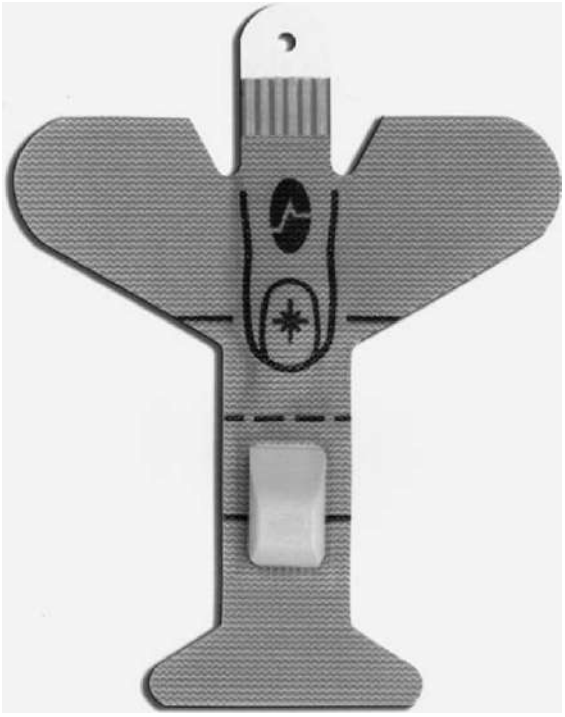

Figure 24.3 Disposable flexible probe. This can be placed on a variety of sites, including the finger, ear, cheek, tongue, toe, penis, hypothenar or thenar eminence, palm, foot, and wrist. (Picture courtesy of Masimo Corporation, Irvine, CA.)

To reduce contamination, a glove, the finger of a glove, or other covering may be used either over the application site or over the probe (36,37,38). Mitts are available to shield ambient light (Fig. 24.12).

Cable

The probe is connected to the oximeter by an electrical cable. Cables from different manufacturers are not interchangeable.

Console

Many different consoles are available (Figs. 24.13,24.14,24.15). Most oximeters that are used in the operating room are part of a physiologic monitor. Most stand-alone units are line operated but will work on batteries, making them useful during transport. Some oximeters are hand-held (Figs. 24.14, 24.15).

A microcomputer monitors and controls signal levels, performs the calculations, implements signal validity schemes, activates alarms and messages, and monitors its own circuitry to warn of malfunctions. A variety of messages may be provided to inform the operator of its

functional status (13). The panel usually displays percent

saturation, pulse rate, and alarm limits. Most units have a bright display, allowing them to be seen in a well-lighted room.

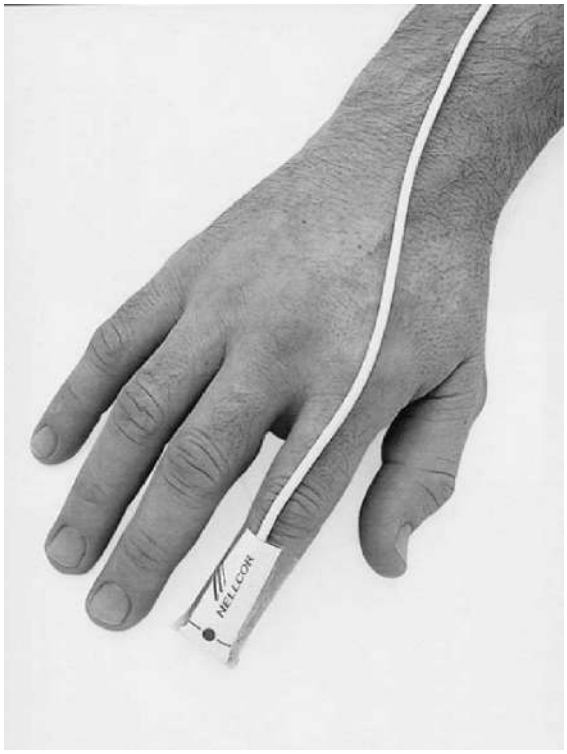

Figure 24.4 Disposable flexible probe in place on a finger. (Reprinted by permission of Nellcor Puritan Bennett Inc., Pleasanton, CA.)

Figure 24.5 Reusable probe. This is most commonly used on a finger or toe. In infants, this type of probe can be placed on part of the hand or foot. These probes offer good shielding from ambient light. (Picture courtesy of Masimo Corporation, Irvine, CA.)

Figure 24.6 Reusable finger probe in place.

(Reprinted by permission of Nellcor Puritan Bennett Inc., Pleasanton, CA.)

The displayed values for SpO_2 and pulse rate are usually weighted averages. Some oximeters allow the averaging period to be adjusted. A mode that averages over a longer period of time may work better if there is much probe motion (39). Changes in pulse rate or saturation will be reflected more rapidly if the averaging is done over a shorter period of time.

Pulse amplitude may be represented by a signal indicator. Other units use a graphic that indicates pulse amplitude and may provide a plethysmographic waveform.

Most instruments provide an audible tone whose pitch changes with the saturation. In this way, the operator can be made aware of changes in SpO_2 without looking at the oximeter. By using a variable tone pulse oximeter, anesthesia providers recognized an episode of oxygen desaturation more quickly than those using one with a fixed tone (40). There is usually a means to control the volume of the audible signal.

Alarms are commonly provided for low and high pulse rates and low and high saturation. Many units

generate an alarm when the probe is not properly applied to the patient or if for some other reason the signal is inadequate. ASA standards for Basic Anesthetic Monitoring require that the variable pitch pulse tone and low threshold alarm be audible (41).

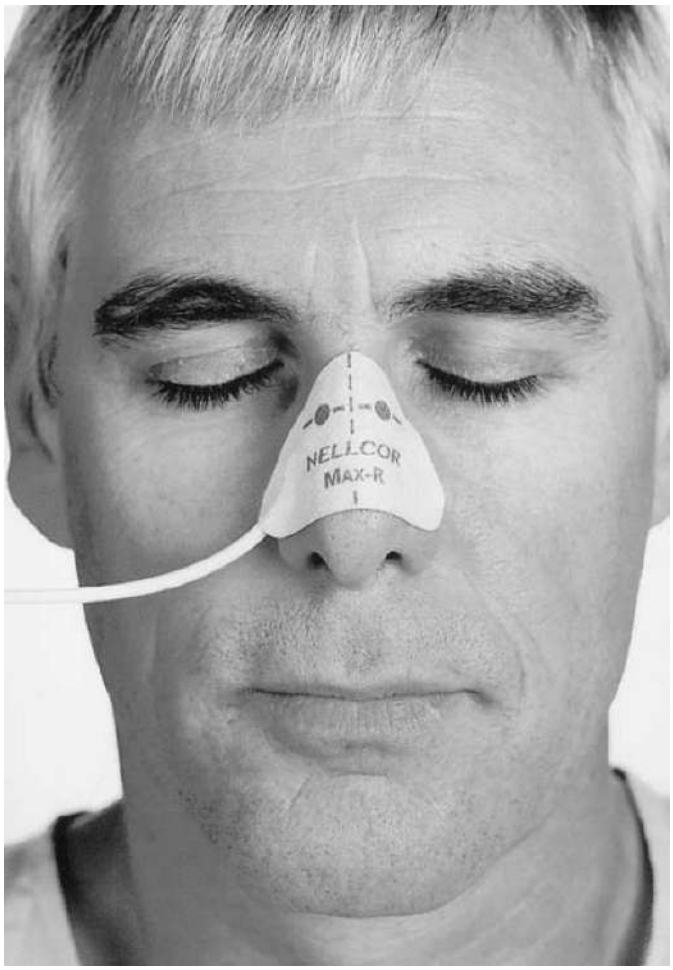

Figure 24.7 Disposable nasal probe in place. The clip from a disposable oxygen mask may be used to improve contact and to hold the probe in place. (Reprinted by permission of Nellcor Puritan Bennett, Inc., Pleasanton, CA.)

Figure 24.8 Reusable probe designed for use on the ear. This may be used on other locations, including the cheek. (Picture courtesy of Masimo Corporation, Irvine, CA.)

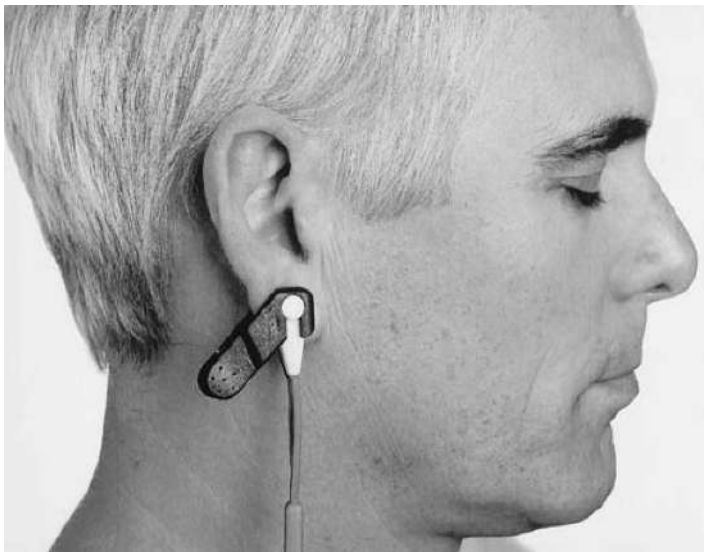

Figure 24.9 Reusable probe on the ear. (Reprinted by permission of Nellcor Puritan Bennett, Inc., Pleasanton, CA.)

Most pulse oximeters offer trend data. Interfaces for hard copy recording and data management systems are usually available.

Figure 24.10 Disposable wraparound probe on the foot. (Reprinted by permission of Nellcor Puritan Bennett, Inc., Pleasanton, CA.)

Figure 24.11 Disposable wraparound probe on the toe. (Reprinted by permission of Nellcor Puritan Bennett, Inc., Pleasanton, CA.)

Oximeter Standards

The international and U.S. standards are quite similar (42,43). Among the provisions are the following:

1. There must be a means to limit the duration of continuous operation at temperatures above 41ยฐC.
2. The accuracy must be stated over the range of 70% to 100% SpO_2. If the manufacturer claims accuracy below 65%, the accuracy must be stated over the additional range.
3. If the manufacturer claims accuracy during motion, this and the test methods used to establish it must be disclosed in the instructions for use.
4. If the manufacturer claims accuracy during conditions of low perfusion, this and the test methods used to establish it must be disclosed in the instructions for use.
5. There must be an indication when the SpO_2 or pulse rate data is not current.
6. If the pulse oximeter is provided with any physiologic alarm, it must be provided with an alarm system that monitors for equipment faults, and there must be an alarm for low SpO_2 that is not less than 85% SpO_2 in the manufacturer-configured alarm preset. An alarm for high SpO_2 is optional.
7. An indication of signal inadequacy must be provided if the SpO_2 or pulse rate value displayed is potentially incorrect.

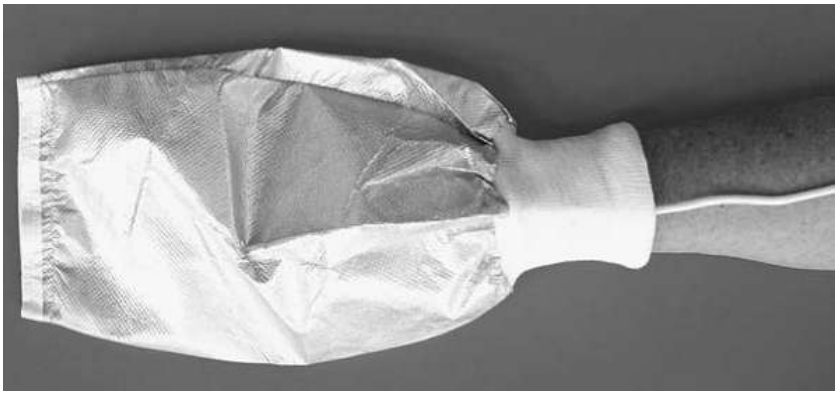

Figure 24.12 Special mitts are available to shield pulse oximeter probes from ambient light.

8. If a variable pitch auditory signal is provided to indicate the pulse signal, the pitch change shall follow the SpO_2 reading (i.e., as the SpO_2 reading lowers, the pitch shall also be lowered).

Use

Sites

Finger

The probe is most commonly attached over the fingertip (Figs. 24.4, 24.6). The failure rate is less, and accuracy is better when the probe is placed on the finger than on the earlobe (44,45,46).

The finger is relatively sensitive to sympathetic system vasoconstriction (47,48). If there is poor circulation, a finger block, digital pulp space infiltration, or a vasodilator may improve performance (48,49,50,51,52,53,54). Vigorously rubbing the fingertip may temporarily improve circulation to the area (50).

If there is dark fingernail polish or synthetic fingernails, the probe should be oriented so that it transmits light from one side of the finger to the other (55). Some clear acrylic nails do not affect pulse oximeter readings (56).

A disadvantage of placing a probe on an extremity is that detection of desaturation and resaturation is slower than when probes are placed more centrally (48,57,58,59,60,61,62,63,64). Response time may be quicker when the probe is placed on the thumb (62).

Motion artifacts are less frequent when the probe is placed on one of the larger fingers (32). The little finger may be useful if the patient is particularly large (65). The probe may be placed over a finger that has a burn (66).

The probe should not be on the index finger during recovery. As a patient awakens, the patient often will want to rub his or her eye, usually with the index finger. If the oximeter probe is on that finger, the cornea can be scratched.

In general, the arm opposite from that on which the blood pressure cuff is applied or in which an arterial catheter has been inserted should be used. The pulse oximeter is sometimes integrated with the noninvasive blood pressure monitor so that the pulse oximeter will not alarm during the inflation cycle if placed on the same arm as the blood pressure cuff. Insertion of a radial artery catheter is commonly followed by a transient

decrease in blood flow and loss of an adequate signal for a pulse oximeter if the probe is on a finger of that hand (67). However, performance is unaffected if pulse oximeter readings are made on the arm in which an arterial cannula is present (68).

Occasionally, poor function may occur with probe attachment to the same extremity as the intravenous infusion, due to local hypothermia and vasoconstriction.

Figure 24.13 The console may be a freestanding unit. (Reprinted by permission of Nellcor Puritan Bennett, Inc., Pleasanton, CA.)

Figure 24.14 Small handheld, battery-operated pulse oximeters are often used, especially during patient transport. This unit is in its recharger. (Picture courtesy of Masimo Corporation, Irvine, CA.)

The position of the arm may affect the reading. In most patients, the SpO_2 falls after the monitored arm is raised (69). It may also fall when the arm is lowered (70).

Toe

The toe is an alternate site when the finger is not available or the signal from the finger is unsatisfactory. Detection of desaturation or resaturation will not be as rapid as with more centrally placed probes (63). The delay in detection of hypoxemia may be up to 1 to 2 minutes (64,71). The toe may provide a more reliable signal in patients who have had an epidural block (72). An increase in pulse amplitude from the toe may be a sign of a successful block (73).

Figure 24.15 Combined pulse oximeter and carbon dioxide monitor. (Reprinted by permission of Nellcor Puritan Bennett, Inc., Pleasanton, CA.)

Nose

The nose is usually a convenient location. Nasal probes respond more rapidly to changes in saturation than probes placed on extremities. The bridge (Fig. 24.7), the wings of the nostrils, and the nasal septum have been used (74,75,76). The nose clip from a disposable oxygen face mask can be attached to the outer surface of a flexible probe to make it fit snugly over the bridge (77).

Accuracy at this site is controversial. It has been recommended under conditions such as hypothermia, hypotension, and infusion of vasoconstrictor drugs. In hypothermic patients, the nasal septum was a more reliable site than the finger (74,76). However, some studies have found that nasal probes often give grossly erroneous results and have a higher failure rate than other sites under conditions of poor perfusion (78,79).

If the patient is placed in the Trendelenberg position, venous

congestion may occur around the nose, causing the pulse oximeter to display artificially low saturations (80,81).

Ear

An ear probe (Figs. 24.8, 24.9) may be held in place by a plastic semicircular device hung around the ear.

Stabilizing devices such as headbands or around-the-ear loops may be useful. Using a clip may improve the quality of the signal (82). The earlobe should be massaged for 30 to 45 seconds with alcohol or vasodilator or EMLA cream can be applied for 30 minutes prior to probe application to increase perfusion (83).

An ear probe can be particularly useful when there is finger motion. Response time is faster with an ear probe than with a finger probe (48,58,62,64,84,85). Under conditions of poor perfusion, some ear probes perform better than finger probes (78). The ear is relatively immune to vasoconstrictive effects of the sympathetic system (47). The amplitude of ear plethysmography will respond mainly to changes in pulse pressure. Ear probes may give more erroneous readings than finger probes in patients with tricuspid incompetence (86). A steep head down position may result in erroneous readings (87). An ear oximeter may be combined with a transcutaneous carbon dioxide sensor (4,88).

Tongue

A tongue probe can be made by placing a malleable aluminum strip behind the probe to allow it to bend around the tongue (89,90). A disposable probe wrapped around the tip of the tongue in the sagittal plane may also be used (91). Reflectance pulse oximetry has been used on the superior surface of the tongue. The mouth should be closed.

Glossal pulse oximetry has been shown to be accurate (91). This site may be especially useful in patients who have burns over a large percentage of their body surface (90,91). Desaturation and resaturation is detected by a probe at the tongue quicker than one on the finger or toe (63).

A lingual probe is more resistant to signal interference from electrosurgery than probes placed on peripheral sites but may be difficult to maintain in place during emergence (89,90). Tongue quivering may mimic tachycardia. Other problems are venous congestion from a head down position and excess oral secretions. The probe must be positioned after tracheal intubation or insertion of a supraglottic airway. It can be easily dislodged.

Cheek

A probe with a metal strip backing can be used to hold a disposable probe around the cheek or lips (92,93). A clip-on probe with a cover over the part of the probe on the buccal surface can also be used (94,95,96,97). This method of use is not recommended by the manufacturer (98,99). Probes specially designed for this site are commercially available.

Buccal pulse oximetry is more accurate than finger pulse oximetry (93,100). Probes at this location detect increases and decreases in saturation more quickly than finger or toe probes (63). Buccal oximetry has been found to be effective during hypothermia, decreased cardiac output, increased systemic vascular resistance, and other low pulse pressure states. This site is useful in patients who have burns (101). Disadvantages include difficult placement, poor acceptance by awake patients, and artifacts during airway maneuvers.

Esophagus

This probe uses reflectance oximetry. The esophagus, a core organ, is better perfused than the extremities during states of poor peripheral perfusion and may therefore provide a more consistent, reliable source for pulse oximetry with hemodynamic instability (102,103,104,105,106,107,108). It reflects changes in arterial saturation more quickly than peripheral sites such as the finger. This site may be useful for patients who have extensive burns, on whom conventional probes would be difficult to place (109,110).

Accurate placement of the esophageal probe requires practice by the user (107). Achievement of a reliable signal may be a problem (104).

Forehead

A flat reflectance pulse oximeter sensor can be used on the forehead (82,111,112) (Figs. 24.16, 24.17). It should be placed just above the eyebrow so that it is centered slightly lateral of the iris (113). The sensor site should be cleaned with alcohol before applying the sensor to help secure the adhesive. Pressure on the probe from a headband or pressure dressing may improve the signal (21,82).

This site is usually easily accessible. The forehead is less affected by vasoconstriction from cold or poor

perfusion than the ear or finger (114,115). Changes in saturation can be detected more rapidly at the forehead than at the finger (48,116). However, pooling of venous blood due to compromised return to the heart may cause low saturation readings in supine patients (81). It should not be used if the patient is in the Trendelenburg position. There are usually few motion artifacts when the forehead is used (117,118).

Figure 24.16 Reflectance pulse oximeter probe. The light source and sensor are situated next to each other. (Picture courtesy of Masimo Corporation, Irvine, CA.)

Figure 24.17 Reflectance pulse oximeter on the forehead. Note the headband securing it in place. (Picture courtesy of Masimo Corporation, Irvine, CA.)

Other

Pharyngeal pulse oximetry by using a pulse oximeter attached to a laryngeal mask may be useful in patients with poor peripheral perfusion (119,120).

Flexible probes (Fig. 24.3) may work through the palm, foot, penis, ankle, lower calf, or even the arm in infants (27,121,122) (Fig. 24.10).

Pulse oximetry may be used to monitor fetal oxygenation during labor by attaching a reflectance pulse oximetry probe to the presenting part (20,23,123,124). A disadvantage is that the probe has to be placed blindly and may be positioned over a subcutaneous vein or artery, which will affect the reliability of the readings (23).

Fixation

Proper probe placement is crucial for good performance. A malpositioned probe can result in false-positive and false-negative alarms. Probes can be totally or partially dislodged without this being noticed.

Adhesive probes may stay on better than clip-on probes. It may be beneficial to tape probes in place when they will be inaccessible during surgery, but it is important to avoid compression of the finger or other part. Wrapping the limb lightly with gauze may help to fix the probe in position. Another method is to slip the cut finger of a glove over the probe (125). The probe should be protected from bright light (Fig. 24.12).

Stabilizing the Signal

The search that the pulse oximeter goes through when a probe is initially applied (or dislodged) includes sequential trials of various intensities of light in an effort to find a signal strong enough to transmit through the tissue but not so strong that the detection system is saturated (12). Once a pulse is found, there is usually a delay of a few more seconds while SpO_2 values for several pulses are averaged.

Appearance of a satisfactory waveform is an indication that the readings are reliable. Comparison of the pulse rate shown by the oximeter and that by an electrocardiograph monitor is also an indication that saturation readings are reliable. A discrepancy between the rates is frequently an indication of probe malposition or malfunction. A discrepancy can also occur during certain dysrhythmias.

Reusing Disposable Probes

Because disposable probes are costly, many institutions reuse

them (126,127,128,129,130,131,132,133,134). Although concerns about this have been raised (135,136), several studies show that the failure rate of reprocessed probes is equal to or less than that of new probes, and the accuracy is not affected (132,133,134,137).

Testing

Devices that can be used to test pulse oximeters are available (138). Some allow the tester to set the plethysmographic waveform at different amplitudes and to test the accuracy of the heart rate as well as the SpO_2.

Applications

Monitoring Oxygenation

Anesthetizing Areas

Oxygen desaturation can occur at anytime during anesthesia, regardless of the skill and experience of the anesthesia provider. Desaturation greater than 10%

occurs in up to 53% of anesthetized patients (139,140,141,142). Pediatric patients are especially at risk (121,143,144,145,146,147). Most severe desaturations occur during induction or emergence. During maintenance, desaturations are milder but more frequent (148). Studies have shown that a reduction in the number of hypoxemic events occurred when pulse oximetry was used (144,149). The incidence of myocardial ischemia was also decreased (150).

Pulse oximetry may help to detect inadvertent bronchial intubation (8,151,152,153). This method is not always reliable, particularly if an elevated inspired oxygen concentration is being used (12,154). The absence of desaturation does not rule out bronchial intubation (155). Methods to detect bronchial intubation are discussed in Chapter 19.

Oximetry is useful in managing one-lung anesthesia to help assess the effectiveness of measures taken to increase the oxygen saturation (156) Chapter 20).

Oximetry is useful for patients undergoing regional and monitored care anesthesia (157,158). Often, the signs of hypoxia are confused with restlessness from an inadequate block. Instead of supplying oxygen and assisting respiration, additional sedation is provided, which compounds the problem. With oximetry, the patient's oxygenation status can be assessed and measures taken to improve SpO_2.

Pulse oximetry may be useful to confirm correct tracheal tube placement when a functional carbon dioxide monitor is not available (159). If oxygen saturation rises after intubation, correct tube placement is likely. However, a pulse oximeter should not be relied on for this purpose because preoxygenation may delay the onset of desaturation beyond the time when esophageal intubation would be considered likely.

Other problems that can cause a drop in oxygen saturation include fat embolism, amniotic fluid embolism, pulmonary edema, breathing system disconnections and leaks, aspiration, tracheal tube obstruction, hypoxic gas mixture, oxygen delivery failure, hypoventilation, anaphylaxis, bronchospasm, pneumothorax, malignant hyperthermia, and pulmonary embolism (8,160,161,162,163,164,165,166,167,168). Causes of hypoxia related to equipment are discussed in Chapter 14.

Postanesthesia Care Unit

The recovery room is another location where desaturation is common (141,169,170,171,172,173,174,175,176,177). Routine oxygen administration to recovering patients may not be necessary when patients are monitored with pulse oximetry (178). Before leaving the recovery room, a trial of breathing room air while monitoring oxygen saturation may provide an indication of the need to continue oxygen beyond the postanesthesia care unit (PACU) or to retain the patient in the unit for a longer time (179).

Transport

Unrecognized oxygen desaturation may occur while the patient is being transported between the operating room and the PACU and between that unit and other areas (180,181,182,183,184,185,186,187,188,189). Pulse oximetry is included on most transport monitors, and portable pulse oximeters are available.

Other Intrahospital Areas

Patients frequently experience hypoxic episodes in the postoperative period after leaving the PACU (190,191,192,193,194). Pulse oximetry can detect these episodes and aid in deciding when oxygen therapy should be discontinued. Telemetric pulse oximetry monitoring may be a cost-effective method of maximizing quality of care when used to monitor patients on a general care floor (195).

Pulse oximetry is useful for monitoring patients in the intensive care unit (196). It may be helpful during weaning from artificial ventilation (197,198).

Pulse oximetry has been used during cardiopulmonary resuscitation (199,200,201). Because of artifacts and lag times, it is more useful in primary respiratory arrest than in cardiac arrest. It is useful in assessing oxygenation during newborn resuscitation (203).

Another area where pulse oximetry has proved useful is the emergency department (204,205,206).

Reflectance pulse oximeters can be useful for assessing fetal status during labor and delivery by applying a forehead probe (207).

Pulse oximetry is useful in identifying which patients with tonic-clonic seizures are at risk of hypoxic cerebral brain damage (208).

Out-of-hospital Use

Pulse oximetry is useful in the prehospital setting, including when transporting patients by helicopter or ambulance (209,210,211,212,213,214,215,216).

Controlling Oxygen Administration

Pulse oximetry allows the lowest safe oxygen flow and concentration compatible with safe levels of arterial oxygenation to be administered. Keeping the oxygen concentration and flow low will help to decrease the risk of a fire (Chapter 32).

Monitoring Peripheral Circulation

Pulse oximetry can detect arm positions that compromise circulation (217). The pulse oximeter that is attached to a toe can help to warn of decreased perfusion at the foot in patients in the lithotomy position (218). However, it cannot reliably detect inadequate perfusion (219,220).

Monitoring oxygen saturation during shoulder arthroscopy has been recommended as a test for

brachial artery compression (221). However, an adequate pulse signal may be present with brachial plexus compression (222).

Patients with limb fractures may have compromised circulation distal to the fracture. Pulse oximetry may serve as a useful guide to blood flow to that area (223,224,225). However, it may not be helpful in warning that a compartment syndrome is developing, because diminution of the arterial pulse distal to the compartment is a late sign (226).

Patients who undergo mediastinoscopy are at risk for brachiocephalic artery and aortic arch compression between the mediastinoscope and the sternum. Arterial compression may be detected by measuring pulse wave amplitude on a pulse oximeter (227,228).

Pulse oximetry may be used to evaluate the effect of a sympathetic block as indicated by an increase in peripheral blood flow (229,230). It may be useful during and after angiography to detect inadequate blood flow (231).

Pulse oximetry may be used to determine the best site of amputation or arterial bypass surgery (232). It has been used to monitor reimplanted or revascularized digits (233,234,235).

Pulse oximetry can be used to measure palmar collateral circulation (236,237,238,239,240,241,242,243,244). However, its usefulness for this has been disputed (245,246). There is a report of radial artery occlusion that was detected by pulse oximetry (247). It has proved useful in evaluating a painful hand after creation of an arteriovenous fistula (248). A similar test of the collateral circulation may be performed on the foot by using pulse oximetry (237).

Determining Systolic Blood Pressure

A pulse oximeter can be used to determine the systolic blood pressure (249,250,251,252,253,254,255,256). The blood pressure cuff is applied to the same arm as the pulse oximeter. The cuff is inflated slowly, and the pressure at the point at which the waveform is lost is noted. It also can be determined by inflating the cuff well past the systolic pressure and looking for the onset of a signal as the cuff is deflated. One study found that the best agreement with Korotkoff sounds and noninvasive blood pressure equipment occurred when the average of blood pressures estimated at the disappearance and reappearance of the waveform was taken as the systolic pressure (257). In pediatric patients, blood pressure determined by this method was found to be more accurate than that determined by an automatic noninvasive blood pressure monitor (258).

Pulse oximetry has been used for patients with pulseless diseases of the extremities to monitor saturation and systolic blood pressure (259).

Locating Arteries

When the axillary artery cannot be palpated, it may be located by placing a pulse oximeter on a finger on that side and pressing in the axilla until the pulse wave disappears (260,261,262). Pulse oximetry has also been used to locate the femoral and dorsalis pedis arteries by using a pulse oximeter applied to a toe (231,263,264).

Avoiding Hyperoxemia

In premature neonates, administration of oxygen may be associated with development of retinopathy and other pathologic conditions. Pulse oximetry can aid in titrating inspired oxygen by detecting hyperoxemia (265,266,267,268,269). It is recommended that the high SpO_2 alarm be set at 95% or lower for this purpose (269,270,271).

Monitoring Vascular Volume and Sympathetic Tone

If the pulse oximeter begins skipping beats or performing intermittently, the cause could be hypovolemia (272). A correlation between pulse waveform amplitude variation during positive-pressure ventilation and hypovolemia has been reported (272,273,274,275,276). If brief interruption of ventilation causes the waveform to return to normal or more constant function, a trial of fluid therapy may be warranted.

One of the most useful and commonly overlooked plethysmographic features is waveform amplitude (277). Amplitude changes can be concealed by the auto-gain function found on most pulse oximeters. When the auto-gain is turned OFF, certain observations can be made. The plethysmograph signal amplitude is directly proportional to the vascular distensibility over a wide range of cardiac output. During anesthesia, the ungained pulse oximeter signal may be used to determine the extent of attenuation of the sympathetic response to stimuli.

Another important feature of the waveform is the dicrotic notch (277). The notch tends to descend toward the baseline during increasing vasodilation and gets higher with vasoconstriction.

Other Uses

Other situations where oximetry may be useful include high-frequency jet ventilation and determining the effectiveness of therapeutic bronchoscopy. It can be combined with measurement of mixed venous oxyhemoglobin saturation to estimate oxygen consumption (278,279).

Pulse oximetry has been used to gauge pulmonary blood flow in infants and children with cyanotic congenital heart lesions (280,281).

Pulse oximetry can give warning of fluid extravasation (282).

Advantages

Accuracy

Pulse oximetry is accurate, and accuracy does not change with time. Numerous studies have shown that the difference between saturation determined by pulse oximetry and arterial blood gas analysis is clinically insignificant above an SpO_2 of 70% (13,14,26,28,46,57,60,121,156,267,283,284,285,286,287,288,289,290,291,292,293,294,295,296,297,298,299,300). Most manufacturers claim that errors are less than ยฑ3% at saturations above 70% (243). This accuracy should be sufficient for most clinical purposes, except possibly neonatal hyperoxia. Changes in accuracy are negligible over temperatures encountered in clinical use (301).

Pulse oximetry is accurate in patients with dysrhythmias, provided that the SpO_2 is stable and the plethysmogram is noise-free and has reasonable amplitude (302). The SpO_2 may be correct even if the pulse rate is not.

Independence from Gases and Vapors

Pulse oximetry readings are not affected by anesthetic gases or vapors.

Fast Response Time

Pulse oximetry has a fast response time, especially compared with transcutaneous measurements (156).

Noninvasive

Pulse oximetry is noninvasive, which allows it to be used as a routine monitor. It is readily accepted by awake patients, so it can be applied before induction of anesthesia. The bleeding, arterial insufficiency, embolization, and infection sometimes seen after arterial puncture are avoided. Temporary elevation of the PaO_2 induced by pain and apprehension is avoided.

Continuous Measurements

Saturation, pulse rate, and blood flow are continuously monitored. Developing trends can be detected and remedial action taken before severe hypoxia ensues.

Separate Respiratory and Circulatory Variables

Continuously monitoring the quality of the peripheral pulse may be helpful in determining whether a hypotensive patient has good cardiac output. If blood pressure is low and pulse signal strength is high, the patient is probably vasodilated but perfusing adequately. If, however, both blood pressure and pulse strength are low, perfusion may be inadequate.

Perfusion is indicated by the pulse signal strength, and oxygenation is indicated by saturation. Unlike trans-cutaneous monitoring, the values displayed do not require interpretation. Most oximeters will signal if the flow is not adequate to provide a saturation value. This is helpful in determining a truly low saturation value as opposed to one caused by low flow.

Convenience

The probe is simple and fast to apply. Site preparation is minimal. ĩ€Arterializationĩ€ of the skin is not usually not necessary, except when the earlobe is the monitoring site. No calibration or changing of electrolyte or membrane is required. A variety of different probes are available for different site applications.

Fast Start Time

There is minimal delay in obtaining the oxygen saturation. Readout typically begins within a few beats after application of the probe. This is a distinct advantage over transcutaneous monitoring, which requires a prolonged warm-up time.

Tone Modulation

Changes in pulse tone with varying saturation allow the user to be continuously updated on SpO_2 without taking his or her eyes off the patient. Tone modulation allows a much quicker recognition of hypoxic episodes than does a fixed tone (40). Most anesthesia providers can detect the direction (but not the magnitude) of a change in saturation by listening to the change in pitch of a pulse oximeter tone (303).

User-friendliness

Most instruments are user-friendly. Minimal training is required to learn to operate the instrument.

Light Weight and Compactness

The console can be made lightweight and compact. This facilitates use during transport. Hand-held pulse oximeters are available. Oxygen saturation monitoring is available in nearly all physiologic monitors.

Probe Variety

The wide variety of probe configurations confers broad clinical applicability to all types of patients, including preterm infants. The ability to use various vascular beds offers advantages from the standpoint of access during surgery and avoids disturbing the surgical field.

No Heating Required

Heating the skin is not required. The probe can usually be left in place for extended periods without risk of thermal injury.

Battery Operated

Most stand-alone units and those incorporated into transport monitors can be operated on batteries.

Economy

The use of pulse oximetry can save money by limiting oxygen administration to situations where it is really needed and by decreasing the number of blood gas analyses (178,194,304,305,306). It may be cost-effective to monitor certain patients at high risk for transfer to the intensive care unit (307). The use of monitors with superior artifact filtering ability may result in cost savings (308,309,310).

Limitations and Disadvantages

Failure to Determine the Oxygen Saturation

There is a small but definite incidence of failure with pulse oximetry (140,311,312,313,314,315). Factors that are reported to contribute to higher failure rates include ASA physical status 3, 4, or 5 patients; young and elderly patients; orthopedic, vascular, and cardiac surgery; electrosurgery use; hypothermia; hypotension; hypertension; duration of intraoperative procedure; chronic renal failure; low hematocrit; and motion (140,312,313,314,316,317,318,319). The actual failure rate varies with the monitor (320).

A pulse oximeter may zero out, meaning that it displays ‾00‾ for the SpO_2 and pulse rates values when it fails to produce a measurement or it might display ‾_____‾ for the values (321). Some pulse oximeters blank the display or give a message such as ‾Low Quality Signal‾ or ‾Inadequate Signal.‾ Others freeze the display.

Poor Function with Poor Perfusion

Pulse oximeters require adequate pulsations to distinguish light absorbed from arterial blood from venous blood and tissue light (322). Readings may be unreliable or unavailable if there is loss or diminution of the peripheral pulse (proximal blood pressure cuff inflation, external pressure, improper positioning,

hypotension, hypothermia, Raynaud's phenomenon, cardiopulmonary bypass, low cardiac output, hypovolemia, peripheral vascular disease, a Valsalva maneuver such as seen in laboring patients or in those with infusion of vasoactive drugs (78,140,251,287,319,322,323,324,325,326,327,328,329,330,331,332,333).

Methods to improve the signal include applying vasodilating cream, performing sympathetic and digital nerve blocks, administering intra-arterial vasodilators, and warming cool extremities (49,51,52,83,334,335,336,337). The use of a probe on a better perfused site such as the cheek, tongue, nasal septum, or esophagus may be helpful. Improved signal technology by newer pulse oximeters can improve performance during low-perfusion conditions (320,330,338,339,340,341).

Difficulty in Detecting High Oxygen Partial Pressures

At PaO_2 values above 90 mm Hg, small changes in saturation are associated with relatively large changes in PaO_2. Thus, it has limited ability to distinguish high but safe levels of arterial oxygen from excessively elevated levels (342).

Delayed Hypoxic Event Detection

While the pulse oximeter response time is generally fast, there may be a significant delay between a change in alveolar oxygen tension and a change in the oximeter reading. It is possible for arterial oxygen to reach dangerous levels before the pulse oximeter alarm is activated (343). Setting the low SpO_2 alarm threshold higher will decrease the delay.

Delayed response can be related to probe location (62,85). Desaturation is detected earlier when the probe is placed more centrally. Lag time will be increased with poor perfusion (251,344,345). Venous obstruction, peripheral vasoconstriction, cold, and motion artifacts will cause increases in the time to detect hypoxemia (32,325,327).

The algorithms that are used to prevent false alarms may increase the delay in detecting hypoxic events (346). A pulse oximeter may respond to a noisy or weak signal by simply holding on to an old value (321). Increasing the time over which the pulse signals are averaged also increases the delay time.

Erratic Performance with Dysrhythmias

Irregular heart rhythms can cause the pulse oximeter to perform erratically (347). During aortic balloon pulsation, the augmentation of diastolic pressure exceeds

that of systolic pressure. This leads to a double- or triple-peaked arterial pressure waveform that confuses the pulse oximeter, so it may not provide a reading (348,349). Pulse oximetry works in patients who have had an aortomyoplasty (105).

Inaccuracy

Different Hemoglobins

Most pulse oximeters are designed to detect only two species of hemogobin: reduced and oxygenated. Whole blood often contains other moieties such as carboxyhemoglobin, sulfhemoglobin, and methemoglobin. This disturbs the absorbance ratio of the wavelengths used to determine oxygen saturation (350).

Methemoglobin

Normally less than 1% of the total hemoglobin, methemoglobin (metHb) is an oxidation product of hemoglobin that forms a reversible complex with oxygen and impairs the unloading of oxygen to tissues (351,352). Methemoglobinemia can be congenital (353) or acquired. Drugs causing methemoglobinemia include nitrobenzene (354), benzocaine (355,356), prilocaine (357,358,359), and dapsone (352,360,361). Methemoglobin absorbs light equally at the red and infrared wavelengths that are used by most pulse oximeters. When compared with functional saturation, most pulse oximeters give falsely low readings for saturations above 85% and falsely high values for saturations below 85% (351,362,363,364,365,366). The discrepancy between SpO_2 and functional saturation increases as the level of metHb increases and functional hemoglobin saturation decreases (351). With treatment of the methemoglobinemia, the SpO_2 readings become more accurate (357,358,361,365).

If there are conflicting results between the pulse oximeter and arterial blood gas analysis, methemoglobinemia should be suspected, and the diagnosis should be confirmed by multiwavelength co-oximetry. The standard blood gas analysis is not capable of detecting and measuring metHb (367).

A new pulse oximeter capable of measuring metHb as well as carboxyhemoglobin is now available (Fig. 24.18).

Carboxyhemoglobin

Carboxyhemoglobin (HbCO, COHb), formed when hemoglobin is exposed to carbon monoxide (CO), has an absorption spectrum similar to that of oxyhemoglobin, so most pulse oximeters will over-read SpO_2 by the percentage of carboxyhemoglobin present (18,368,369,370,371,372,373,374,375). In one study, the pulse oximeter reading did not go below 96% with carboxyhemoglobin levels as high as 44% (376). In vitro CO-oximetry can measure the percentages of other moieties by using more than two wavelengths.

Figure 24.18 Pulse oximeterÎ€“carbon monoxide monitor.

An increase in HbCO may occur during laser surgery in the airway, but the levels are not high enough to keep pulse oximetry from reliably estimating saturation (377). Carbon monoxide production in association with dry carbon dioxide absorbent is discussed in Chapter 9.

Pulse oximeters that differentiate between oxyhemoglobin and carboxyhemoglobin and that can measure carboxyhemoglobin are now available (Fig. 24.18).

Fetal Hemoglobin

Most studies show that fetal hemoglobin (Hb F) does not appear to affect the accuracy of pulse oximetry to a clinically important degree (378,379,380,381,383), although very high levels may cause it to read slightly low (382).

Hemoglobin S

The use of pulse oximetry in the patient with sickle cell disease is controversial. Several investigators have concluded that pulse oximetry is inaccurate in these patients, which makes it unreliable for detecting serious hypoxemia (383,384,385). Other studies have found it to be sufficiently accurate to be useful (386,387,388,389,390).

Sulfhemoglobin

Sulfhemoglobinemia may be caused by drugs such as metoclopramide, phenacetin, dapsone,

and sulfonamides (391). Sulfhemoglobin causes the pulse oximeter to display artifactually low oxygen saturation.

Other Hemoglobinopathies

Hemoglobin Koln is associated with artifactually low oxygen saturation as measured by the pulse oximeter (392,393).

Hemoglobin Hammersmith and Hemoglobin M (Milwaukee) affect pulse oximeter reading so much that oximetry is not useful (394,395,396).

Hemoglobin-H disease will cause the pulse oximeter to indicate a higher saturation than is actually present (397).

A patient with hemoglobin Constant Springs and alpha-thalassaemia 2 in which pulse oximetry readings were consistently low has been reported (398).

Heinz Body hemolytic anemia causes the pulse oximeter to read low (399).

Bilirubinemia

Severe hyperbilirubinemia can cause an artifactual elevation of metHb and carboxyhemoglobin when using in vitro oximetry but does not affect pulse oximetry readings (283,378,400,401,402,403).

Low Saturations

Pulse oximetry becomes less accurate at low oxygen saturations (10,26,57,58,61,84,284,285,288,291,293,294,297,298,306,404,405,406,407,408,409,410,411,412,413,414). This inaccuracy is greater in patients with dark skin (415). It should be used with caution in patients with cyanotic heart disease (410,411,416). Measuring PaO_2 or SaO_2 at low saturations is recommended for important clinical decisions.

Malpositioned Probe

Oximeters with probes that are not applied well vary greatly in their behavior, depending on both the actual SpO_2 and the manufacturer and model of the oximeter (70,417,418,419,420,421,422). If the probe is not properly positioned, it may allow the light from the emitter to the detector to only graze the tissue instead of passing through it. This penumbra effect reduces the signal-to-noise ratio and may result in spurious SpO_2 values in the low 90s in normal patients. If the

patient is hypoxic, the oximeter may overestimate the true value (418,423). In one case, the probe was completely unattached but continued to provide apparently accurate readings. Closer examination of the waveform revealed an unusual pattern (424).

To avoid the problems of probe position, the position should be checked frequently and inaccessible locations avoided. The use of too large or too small a probe may result in inaccurate readings (33,34,300). Long fingernails can cause inaccurate positioning (425).

Venous Pulsations

Pulse oximeter design assumes that the pulsatile components of light absorbance are due to arterial blood. Prominent pulsations of venous blood may lead to underestimation of the SpO_2 (70,426,427,428,429,429A). Pulse rate determination may be correct. The error may be worse when probes are used on the head (86,87) but less when the probe is placed on the finger. In patients with low systemic vascular resistance, the pulse oximeter may under-read the saturation, possibly because the oximeter is sensing pulsatile venous flow (430).

High airway pressures during artificial ventilation may cause phasic venous congestion, which may be interpreted by the oximeter as a pulse wave (431). In some cases, it may be necessary to turn the ventilator OFF to obtain a correct reading.

Mixing Probes

SpO_2 measurements may not be accurate if one manufacturer's probe is used with a different manufacturer's instrument (432,433).

Severe Anemia

The pulse oximeter may overestimate SpO_2, especially at low saturations, in patients with severe anemia (434,435,436,437). However, it is accurate for non-hypoxic SaO_2 values in these patients (438).

Skin Pigmentation

Although some earlier studies have shown that pulse oximeter readings were slightly high in patients with dark skin (286,439,440), newer studies have shown that pigmentation does not make a significant difference in pulse oximeter accuracy (26,441,442). Spurious readings were reported in a patient with oculocutaneous albinism who was taking a herbal remedy (443).

Dyes

Certain dyes including methylene blue, indocyanine green, lymphazurin (isosulfan blue), indigo carmine, nitrobenzene, and patent blue when injected intravenously, intra-arterially, into the lymphatics, intradermally, or into the uterine cavity can result in decreases in SpO_2 without actual decreased saturation

(354,360,444,445,446,447,448,449,450,451,452,453,454). In vitro oximetry may also be affected by dyes (360,445,455,456,457). Usually, the interference lasts only a few minutes but may persist much longer, even hours, when lymphatics are injected (451,452).

The reaction of the pulse oximeter to exogenous dyes has been used as a means of confirming intravascular catheter placement. The dye is injected into the catheter, and the pulse oximeter is observed (458). The pulse oximeter may be useful to estimate cardiac output by the dye dilution method (459).

Fingerprinting ink will cause a low saturation reading (460). Henna, a stain used by some Middle Eastern women on the fingers and toes, can cause a low saturation reading (461). Children who have been finger painting with blue paints may exhibit low SpO_2 readings (462).

Optical Interference

Stray light or light flickering at frequencies similar to the frequencies of the LEDs, including sunlight, fluorescent lights, operating room lights, infrared heating lamps, infrared radiant warmers, light sources for various scopes, xenon lamps, bilirubin lights, phototherapy, or surgical imaging instruments, can enter the photodetector and result in inaccurate or erratic readings (14,332,463,464,465,466,467,468,469,470,471,472,473,474). Having probes on two adjacent fingers can cause an abnormal trace (475).

One clue that optical interference is occurring is inconsistency between the pulse rate on the pulse oximeter and that on other monitors (350). Although excessive ambient light usually prevents the oximeter from tracking the pulse, it can result in apparently normal but inaccurate measurements in some instances (470).

Oximeters vary significantly in their susceptibility to optical interference (326,466). Some manufacturers try to minimize the effect of stray light by taking intermittent readings when both of the LEDs in the probe are turned OFF and then subtracting these background readings from measurements taken by the photodetector when either LED is turned ON. Sensitivity to light may be increased with reduced pulse amplitude.

There are a number of ways to minimize the effects of optical interference. These include selection of the correct probe for the patient and use, applying the probe so that the detector is across from the LEDs, making certain the probe remains properly positioned, and shielding the probe from light and other nearby probes (Fig. 24.12). Extraneous light can be eliminated by covering the probe with an opaque material such as a surgical towel, gauze, finger cot, blanket, alcohol wipe packet, or other foil shield (59,127,476). This may also help to stabilize the probe. All light may not be adequately shielded by a simple covering (463,470).

Nail Polish and Coverings

Some shades of brown, black, blue, and green (but not red or purple) nail polish may cause significantly lower saturation readings (477,478,479). Synthetic nails may interfere with pulse oximetry readings. The presence of onychomycosis, a yellowish gray color caused by fungus, can cause falsely low SpO_2 readings (480). Dirt under the nail can also cause difficulty in obtaining reliable readings (481). Although there is one report of dried blood on a finger that caused erroneous low saturation readings (482), other authors have found that dried blood does not affect pulse oximeter accuracy (483,484). Patients receiving docetaxel may have discolored fingernails that cause lower saturation readings (485).

In most cases, this problem can be overcome (without removing the polish or the synthetic nail) by turning the probe 90 degrees so that it transmits light from one side of the finger to the other side (55,481).

Electrical Interference

Electrical interference from an electrosurgical unit can cause the oximeter to give an incorrect pulse count (usually by counting extra beats) or to falsely register a decrease in oxygen saturation (486). This problem may be increased in patients with weak pulse signals (13). Manufacturers have made significant progress in reducing their instruments' sensitivity to electrical interference (13,207,243,326). Some monitors display a notice when significant interference is present. Some freeze the SpO_2 display during such interference, which may give a false sense of security. Additional steps to minimize electrical interference include locating the electrosurgery grounding plate as close to, and the oximeter probe as far from, the surgical field as possible; routing the cable from the probe to the oximeter away from the electrosurgery apparatus; keeping the pulse oximeter probe and console as far as possible from the surgical site and the electrosurgery grounding plate and table; and operating the unit in a rapid response mode. The electrosurgical apparatus and pulse oximeter should not be plugged into the same power circuit (486).

Motion Artifacts

Motion of the probe can cause an artifact that the pulse oximeter is unable to differentiate from normal arterial pulsations. Motion artifact creates both false-positive (false alarm) and false-negative (missed hypoxemia) errors (32,487). Changing alarm thresholds to reduce one of these errors will often increase the incidence of the other type of error (488).

Motion is usually not a problem during general anesthesia, but if the patient is shivering, has a condition such as Parkinson's disease, or is moving about or being transported, motion artifacts can be significant (489,490). Evoked potential monitors and nerve stimulators can produce motion artifacts if the pulse oximeter probe is on the same extremity (491,492,493,494,495). Motion artifacts have been caused by patients tapping their

fingers while under regional anesthesia (496).

The oximeter's ability to deal with motion artifact depends on the correlation with the onset of the motion and the start of monitoring. If the motion precedes the onset of monitoring, there is a greater decrement in performance (497,498).

In the 1990s, pulse oximeter manufacturers began to make design improvements, and the newer generation

instruments have improved ability to filter motion artifacts (320,321,338,341,488,497,498,499,500,501,502,503,504,505). In addition to reducing alarms, the use of these instruments has resulted in less need for arterial blood gas measurements and faster weaning from high concentrations of oxygen (309). They are also associated with a shorter loss of signal when placed distal to a blood pressure cuff or tourniquet (506).

Lengthening the averaging time will increase the likelihood that enough true pulses will be detected to reject motion artifacts (15,507) but may delay detection of hypoxemia. Most pulse oximeters allow the user to select one of several time-averaging modes.

Motion artifacts can usually be recognized by false or erratic pulse rate displays or distorted plethysmographic waveforms. Increased pulse amplitude indicates movement but not necessarily artifactual SpO_2 readings (487,508).

Motion artifacts may be decreased by applying the probe to a less active site. Flexible probes that are taped in place are less susceptible to motion artifacts than are clip-on probes (13,15). Larger fingers may be less susceptible to motion artifact (32).

Pressure on the Probe

Pressure on the probe may result in inaccurate SpO_2 readings without affecting pulse rate determination (429).

Hyperemia

If a limb becomes hyperemic after blood flow is interrupted, the oxygen saturation shown by the pulse oximetry may be artificially low (509). A pulse oximeter placed near the site of blood transfusion may show transient decreases in oxygen saturation with rapid blood infusion (510).

Probe Damage

A damaged pulse oximeter probe can cause the oxygen saturation to be higher than the actual value (511,512). The use of a cleaning agent that is not recommended by the manufacturer on a reusable probe can result in damage to the probe, preventing its reuse (513).

False Alarms

A high percentage of pulse oximetry alarms are spurious or trivial (489,503,505,514,515,516,517). Artifact-induced alarms occur in two ways. When an artifact is mistaken for a pulse, it

can corrupt the measurement and result in an alarm. When an artifact obscures the pulse, it can result in a loss-of-pulse alarm.

False alarms are most commonly caused by motion artifact but are also associated with poor signal quality, probe displacement, external pressure, and interference. False alarms are a more significant problem outside the operating room because patients are commonly moving, they are often poorly perfused, and there are many sources of electronic and optical interference.

False alarms do not represent a direct danger to the patient but may encourage the care provider to take inappropriate actions such as disabling the alarm, setting the limits to inappropriate values, or lowering the alarm volume. Misinterpretation of alarms can result in failure to treat hypoxemia or unnecessary treatment.

Some false alarms can be avoided by simple measures such as putting the probe on a different extremity than the automated blood pressure cuff and in a location where it is unlikely to be affected by external pressure.

Newer pulse oximeters that are designed to reduce motion-related artifacts can significantly reduce the incidence of false alarms (320,497,498,499,503,518,519,520,521,522,523,524,525,526). However, some of these have shown less reliability in identifying hypoxic episodes and bradycardia than older models (346).

Delaying the time between detecting low SpO_2 and alarm activation, using a longer averaging time, and setting the low SpO_2 alarm limit lower can reduce the number of false alarms (311,517,527,528,529) but may increase the lag time before detecting hypoxemia. With some pulse oximeters, turning OFF the low pulse rate alarm prevents alarming when the blood pressure cuff is inflated (13).

Synchronizing the pulse oximeter with the electrocardiogram (ECG) monitor can lessen artifacts (32,39). However, the oximeter may synchronize with ECG artifacts generated by motion or shivering, resulting in erroneous readings (13). Furthermore, with this system, the pulse rate displayed by the oximeter will necessarily be equal to the pulse rate shown by the ECG monitor, so equality of the pulse rates cannot be used as an indication that the displayed saturation data are valid.

Failure to Detect Impaired Circulation

The presence of a pulse oximeter signal and a normal reading does not necessarily imply that tissue perfusion is adequate. Some pulse oximeters show pulses despite inadequate tissue perfusion (251,327) or even when no pulse is present (200,530,531,532). Ambient light may produce a false signal (471).

Pulse oximetry is not reliable in diagnosing impaired perfusion with increased intracompartmental pressures (533,534).

Discrepancies between Readings from

Different Monitors

A discrepancy in readings between different brands of oximeters on the same patient at the same time is not uncommon (17,270,535,536,537,538). There is also variation in

the time that it takes various monitors to detect resaturation (539).

Failure to Detect Hypoventilation

Hypoventilation and hypercarbia may occur without a decrease in hemoglobin oxygen saturation, especially if the patient is receiving supplemental oxygen (540,541,542). Pulse oximetry cannot be relied on to detect leaks, disconnections (543), or esophageal intubation (544). Methods to detect esophageal intubation are discussed in Chapter 19.

Problems with Sound Recognition

There is considerable variation in the volume and audio spectrum of available pulse oximeters between models and even within models (545). Some clinicians have trouble detecting changes in the pitch of the sound emitted by pulse oximeters as the saturation changes (303,546).

There is wide variation in the pitch frequency of different pulse oximeters (547). Thus, in locations where different pulse oximeters are encountered, the potential for confusion exists.

Lack of User Knowledge

Pulse oximetry is often used by personnel whose knowledge of it is limited. Physicians, nurses, and others who use the instrument often do not know the basic principles and make serious errors in interpreting readings (548,549,550,551).

Interference with Other Monitors

Electromagnetic interference from the pulse oximeter power supply may cause artifacts and false readings on certain thoracic impedance monitors (552).

If a pulse oximeter probe is placed in front of certain plasma display touch screens, a normal-appearing waveform and 100% saturation is displayed (553).

Patient Complications

Corneal Abrasions

Patients recovering from general anesthesia frequently rub their eyes. If there is a pulse oximeter on the index finger, a corneal abrasion may result (65,554,555). A finger other than the index finger may be a more appropriate location for the probe during recovery (556).

Pressure and Ischemic Injuries

Injuries ranging from persistent numbness to ischemic injury at

the site on which a probe was placed have been reported (557,558,559,560,561,562,563,564,565,566,567,568). Loss of the signal may occur (569). These risks are increased by prolonged probe application, compromised perfusion of the extremity, and tight application of the probe. Frequent examination of the site and moving the probe to different sites will reduce the likelihood of injury. Patients with large fingers should not have a circumferential probe placed on the finger. If the pulse oximeter reading appears to be weak, the site should be checked for increased pressure.

Burns

Injuries ranging from reddened areas to third-degree burns under pulse oximeter probes have been reported (562,570,571,572,573,574,575,576,577,578,579,580,581). Considering the millions of long-term applications, the incidence of these burns is quite low (43).

Burns can result from incompatibility between the probe from one manufacturer with the pulse oximeter of another (575,578). A number of pulse oximeter probes have connectors that fit different pulse oximeters, but the probes are not compatible. The use of a damaged probe can result in a burn (570,577). A pulse oximeter probe may provide an alternate pathway for electrosurgical currents (582).

Burns that are associated with hypothermia have been reported (579). Burns have been reported when a pulse oximeter was used during photodynamic therapy (583,584).

To avoid these injuries, frequent inspection of the probe site and site rotation are recommended (585). When a probe is placed on a finger or toe, the light source should be placed on the nail rather than on the pulp (576). A glove can be placed on the finger to protect it from thermal injury without affecting the accuracy of the instrument (36). If the pulse oximeter display freezes, the cause should be investigated. Only the probes recommended by the oximeter manufacturer should be used (578).

Burns that are associated with pulse oximetry during magnetic resonance imaging (MRI) as a result of induced skin current beneath looped cables acting as antennae have been reported (586,587,588). The MRI environment is discussed in Chapter 30. During MRI, the danger of burns can be reduced by the following measures:

1. All potential conductors should be checked before use to ensure that there is no frayed insulation, exposed wires, or other hazards.
2. All unnecessary conductive materials such as unused surface coils should be removed from the MRI system bore before patient monitoring is initiated.

3. The probe should be placed as far from the imaging site as possible.

4. Cables, leads, or wires from monitoring devices should be positioned so that no loops are formed. A braid should be made of the slack portion of wires.
5. If possible, no potential conductors should touch the patient at more than one location.
6. A thick layer of thermal insulation should be placed between any wires or cables and the patient's skin.
7. Monitoring devices that do not appear to be operating properly should be removed from the patient.

Electric Shock

An electrical shock related to diathermy has been reported (589). In this case, there were bare wires in the pulse oximeter probe.

Carbon Monoxide Monitoring

Carbon monoxide can accumulate in the breathing system from various sources, including the reaction between anesthetic agents and desiccated absorbent. This is discussed in detail in Chapter 9. It is difficult to determine if CO is present in the inspired gases when the patient is anesthetized.

In 2005, a combination pulse CO-oximeter capable of measuring carboxyhemoglobin (SpCO) became available (Fig. 24.18). The same sensor is used for measuring both SpCO and SpO_2. It alarms with CO concentrations between 5% and 50%. The instrument utilizes an eight-wavelength sensor to distinguish between oxygenated blood, deoxygenated blood, and blood containing CO. It can also measure metHb.

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Questions

For the following question, select the correct answer

1. In which wavelength does reduced hemoglobin absorb more light?

A. The purple band

B. The red band

C. The infrared band

D. The near infrared band

E. The blue band

View Answer

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

2. Cause(s) of burns associated with pulse oximeters probes include(s):

A. Hypothermia

B. Incompatible probe and pulse oximeter

C. Photodynamic therapy

D. Voltage surges

View Answer

3. Fractional oxygen saturation is

A. The ratio of oxyhemoglobin to all the functional hemoglobins

B. Close to functional oxygen saturation in patients with low levels of dyshemoglobins

C. Determined by in vitro oximetry

D. The ratio of oxyhemoglobin to the sum of all the hemoglobin present

View Answer

4. Effects on pulse oximeter readings of a methemoglobin level higher than 1% include

A. The discrepancy between SpO_2 and functional saturation increases as the level of metHb increases and functional hemoglobin saturation decreases

B. Normally, there is less than 1% methemoglobin in the blood

C. Saturation readings may be falsely low for readings above 85%

D. Since methemoglobin has the same absorption coefficient in the red and infrared bands, there will be no difference in the pulse oximeter readings

View Answer

5. Which of the following do not affect pulse oximeter readings significantly?

A. Hyperbilirubinemia

B. Hemoglobin S

C. Hemoglobin F

D. Severe anemia

View Answer

6. When using a finger probe,

A. Response time is quicker if the probe is placed on the thumb

B. Insertion of a radial artery catheter improves pulsation

C. The probe can be placed sideways to avoid dark fingernail polish

D. Smaller fingers cause fewer motion artifacts

View Answer

7. Pulse oximetry can be used to

A. Detect brachial artery compression during shoulder arthroscopy

B. Monitor circulation to reimplanted or revascularized digits

C. Determine the best site for arterial bypass surgery

D. Evaluate a sympathetic block

View Answer

8. Factors reported to contribute to higher failure rates with pulse oximetry include

A. Physical status 3, 4, or 5; young and elderly patients

B. Orthopedic, vascular, and cardiac surgery

C. Hypertension

D. Low hematocrit

View Answer

9. Measure(s) to improve the peripheral pulsation include

A. Application of vasodilating cream

B. Digital nerve blocks

C. Administration of intra-arterial vasodilators

D. Sympathetic block

View Answer

10. Reflectance pulse oximetry differs from transmission pulse oximetry in which ways?

A. The reflection originates from homogeneity in the optical path

B. The reflectance oximetry relies on backscattered light to determine the oxygen saturation

C. The tissue does not need to be well perfused to obtain a strong signal

D. If the probe is over an artery or vein, the reading may be artificially low

View Answer

11. Concerning the nose as a monitoring site for pulse oximetry,

A. Nasal probes are slower to respond than finger probes

B. Nasal probes have a higher failure rate than other sites during periods of hypothermia

C. The Trendelenberg position improves the accuracy of pulse oximeters readings

D. The nasal probe is recommended when vasoconstrictor drugs are infused

View Answer

12. Which of the following statements about ear probes are true?

A. Response time is faster than with a finger probe

B. Tricuspid incompetence may cause erroneous readings

C. The ear is relatively immune to vasoconstrictive effects of the sympathetic system

D. The amplitude of ear plethysmography does not respond to changes in pulse pressure

View Answer

13. Problems with the tongue as a location for pulse oximetry include

A. Tongue quivering can mimic tachycardia

B. Excessive secretions

C. Venous congestion with the Trendenberg position

D. Decreased resistance to electrosurgical signal interference

View Answer

14. Situations where buccal pulse oximetry may be preferable are

A. Low pulse pressure states

B. Increased systemic vascular resistance

C. Hypothermia

D. Decreased cardiac output

View Answer

15. Advantages of using pulse oximetry include

A. Usually accurate in patients with dysrhythmias

B. An indication of the adequacy of perfusion

C. Readings are not affected by anesthetic gases and vapors

D. Accurate readings to an SpO_2 of 50%

View Answer

16. What factors cause delayed detection of hypoxemia by a pulse oximeter?

A. Peripheral location of the pulse oximetry sensor

B. Peripheral vasoconstriction

C. Poor perfusion

D. Decreased time over which the pulse signals are averaged

View Answer

17. Concerning carbon monoxide and pulse oximetry,

A. The absorption spectrum of carboxyhemoglobin is similar to that of oxyhemoglobin

B. The pulse oximeters does not read below 94% when carboxyhemoglobin is present

C. Pulse oximeters that can differentiate oxyhemoglobin and carboxyhemoglobin are available

D. Standard pulse oximeters can warn that CO is present but cannot quantitate it.

View Answer

18. Which hemoglobin(s) does(do) not affect the pulse oximeters?

A. Hemoglobin H

B. Sulfhemoglobin

C. Hemoglobin S

D. Fetal hemoglobin

View Answer

19. Causes of probe position problems include

A. Too small a probe

B. Long fingernails

C. Too large a probe

D. The penumbra effect

View Answer

20. Concerning pulse oximeter inaccuracy resulting from venous pulsations,

A. The pulse oximeter underestimates the SpO_2

B. Venous pulsations are more prominent in the finger than in the head

C. The pulse oximeter reads venous pulsations as if they were arterial pulsations

D. High systemic vascular resistance promotes venous pulsations

View Answer

21. Conditions in which the pulse oximeters reads high SpO_2 values include

A. Venous pulsations

B. Certain intravenous dyes

C. Skin pigmentation

D. Severe anemia

View Answer

22. Which dye(s) affect the pulse oximeters?

A. Indocyanine green

B. Isosulfan blue

C. Patent blue

D. Indigo carmine

View Answer

23. Optical interference to pulse oximetry can come from which source(s)?

A. Bilirubin lights

B. Xenon lights

C. Infrared heating lamps

D. Sunlight

View Answer

24. What colors of nail polish interfere with pulse oximeters?

A. Brown

B. Green

C. Black

D. Red

View Answer

25. What other substances besides nail polish interfere with pulse oximeters?

A. Onychromycosis

B. Dirt under the fingernail

C. Synthetic nails

D. Dried blood

View Answer

26. What are some of the motion artifacts that may affect

pulse oximeters?

A. Electrosurgery

B. Nerve stimulators

C. Surgical movements

D. Evoked potential monitors

View Answer

27. Causes of false alarm(s) include

A. Poor signal quality

B. Probe displacement

C. External pressure

D. Motion artifact

View Answer

28. What are the common causes of pressure and ischemic injuries related to pulse oximetry probes?

A. Prolonged probe application

B. Tight application of the probe

C. Compromised perfusion under the probe

D. Probes held on by a clip

View Answer

Chapter 25

Neuromuscular Transmission Monitoring

Muscle relaxants are employed in anesthesia to provide muscle relaxation and/or abolish patient movement. Numerous studies have documented enormous variation in patients' responses to muscle relaxants. Disease states and perioperative medications can also modify the responses of these medications (1). The depth of neuromuscular block (NMB) should be monitored when muscle relaxants are used to avoid drug overdosage or underdosage and residual NMB during recovery (2,3,4,5,6,7).

Equipment

Monitoring the magnitude of NMB is accomplished by delivering an electrical stimulus near a peripheral motor nerve and evaluating the evoked response of the muscle(s) innervated by that nerve.

Stimulator

Several stimulators are shown in Figure 25.1. Desirable features include compactness, light weight, and

simplicity. Most are battery-operated with a means to check the battery status. Mounting brackets for securing the device are desirable. A stimulator may be in a module in a multiparameter monitor. The ability to deliver information to an automated record (Chapter 28) should be considered when choosing a stimulator.

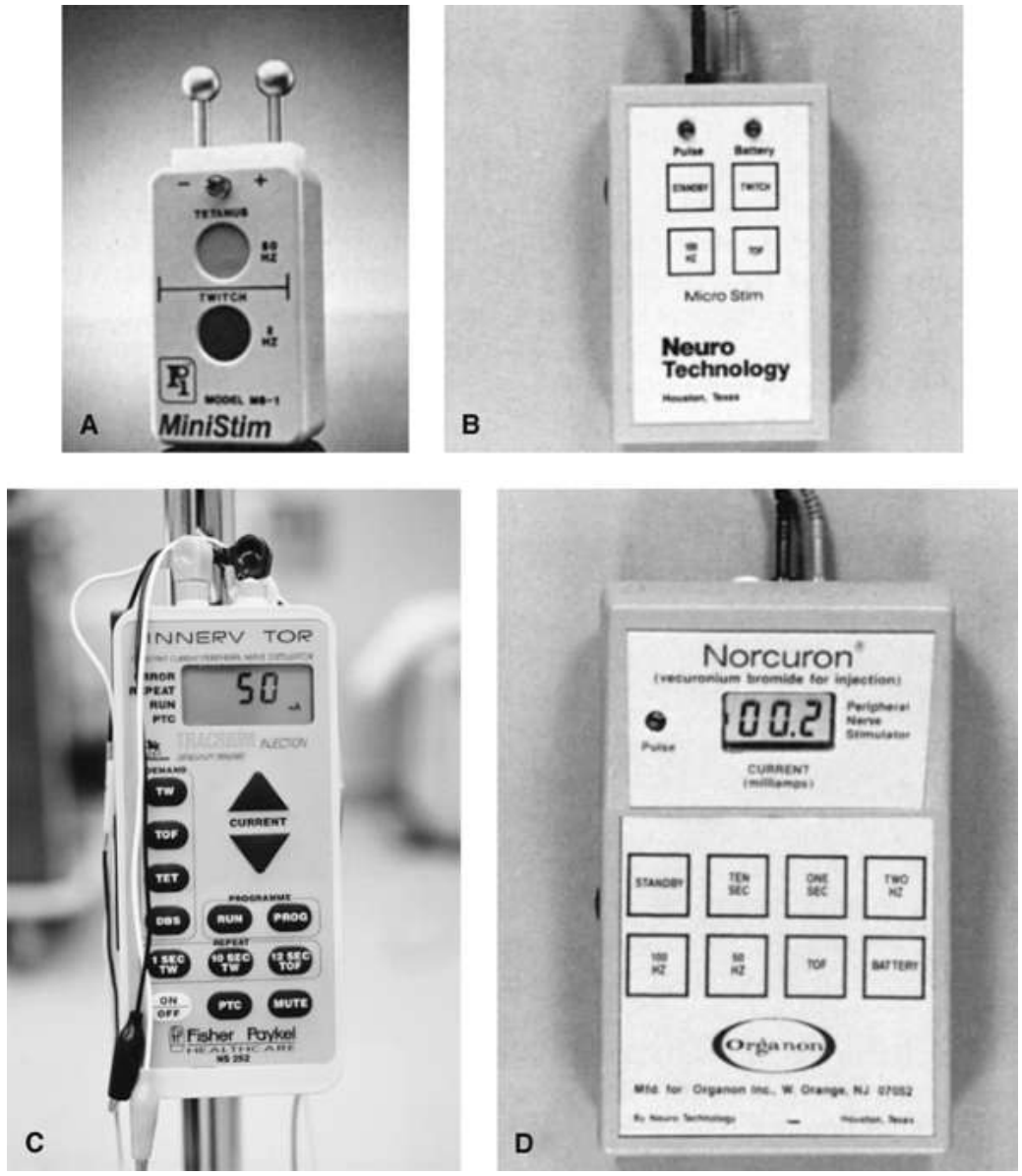

Figure 25.1 Neuromuscular stimulators. **A:** This simple device has only two patterns of stimulation: tetanus and single twitch. The delivered current cannot be varied and is not displayed. Note the metal ball electrodes. (Courtesy of Professional Instruments, a subsidiary of Life Tech, Inc.) **B:** This unit has three modes of stimulation: single stimulus (twitch), tetanus, and TOF. The current is varied by using a rheostat at the side, but there is no display of the current being delivered. **C:** This unit has four patterns of stimulation: single twitch (available at 0.1 and 1 Hz), TOF (which can be repeated automatically every 12 seconds), 50-Hz tetanus, and DBS. It also is capable of delivering the stimulus pattern for obtaining a PTC. The selected current is displayed in the window. Failure to deliver this current will cause a mark to be displayed to the right of the

word *ERROR*. Note that the connections for the lead wires are of different colors. **D:** This unit has three modes of stimulation: single stimulus (which can be delivered at 0.1, 1, or 2 Hz), tetanus (which is available at a frequency of 50 to 100 Hz), and TOF. Stimulus current is varied by using a rheostat at the side. The delivered current is displayed in a window, to the left of which is an indicator that lights when a stimulus is being delivered. A battery status check button is present.

Current

Current, not voltage, is the determining factor in nerve stimulation. Because skin resistance may change, only a stimulator that automatically adjusts its output to maintain a constant direct current can ensure unchanging stimulation with changes in skin resistance. Wiping the

skin with alcohol will remove insulating skin oils and lower the resistance.

The force of muscle contraction is proportional to the number of activated muscle fibers. If a motor nerve is stimulated with sufficient current, all of the muscle fibers supplied by that nerve will contract. The current required for this is called the *maximal current*. In the clinical setting, stimuli of greater than maximal (supramaximal) intensity are used to ensure that maximal stimulation is delivered if resistance increases. In the majority of patients, a current of 30 milliamperes (mA) will produce a supramaximal response when the ulnar nerve is stimulated (8). When the posterior tibial nerve is stimulated, higher currents are needed (9). A supramaximal current is generally 2.5 to 3 times higher than the lowest current capable of eliciting an evoked response (threshold current) (10). Higher currents may be needed in patients with edema (11,12) or diabetes (13). Much lower currents (5 to 8 mA) are needed when needle electrodes are used (14).

A current display is useful in alerting the user to the possibility of a disconnection, broken lead, weak battery, or poorly conducting electrodes, because these problems will cause the current to be reduced. Some stimulators have an alarm to warn when the selected current is not being delivered.

A submaximal current may be better for awake patients or for those recovering from anesthesia, because patient discomfort increases with the intensity of the stimulating current (15,16,17,18). Use of a submaximal current may result in more

reliable detection of residual NMB when visual or tactile monitoring is used (19). A submaximal current is not reliable for general NMB monitoring.

Frequency

The frequency of stimuli is usually expressed in Hertz (Hz), which is cycles/second. One Hz is one cycle/ second, and 0.1 Hz is equal to 1 stimulus every 10 seconds. With a nondepolarizing block, increased stimulus frequency will shorten the onset time and prolong the duration of action (20,21).

Waveform

The stimulus waveform should be rectangular (square wave) and monophasic. Biphasic waves may produce repetitive stimulation, which can lead to underestimation of the depth of NMB present.

Duration

The duration should be 300 ยตs or less (20). If the duration of the pulse is over 0.5 msec, a second action potential may be triggered.

Stimulation Patterns

Single Twitch

Single-twitch (T_1) stimuli are usually delivered at a frequency of 0.1 or 1 Hz. A frequency greater than every 10 seconds is associated with a progressively diminished response and could result in overestimating the NMB.

The control response strength is noted (Fig. 25.2A). The strengths of subsequent twitches are then compared with the control and expressed as a percentage of the control (single-pulse or -twitch depression, T_1%, T1%, T_1:T_c). With both a nondepolarizing and a depolarizing block, there will be progressive depression of the response as the block develops. A decrease in temperature will also cause a reduced response (22,23,24,25,26).

The single stimulus is useful in establishing a supramaximal stimulus and for identifying when conditions satisfactory for intubation have been achieved. It can be used (in conjunction with a tetanic stimulus) to monitor deep levels of NMB (the post-tetanic count, discussed below).

There are several disadvantages associated with using single twitch. There needs to be a control. It cannot distinguish between a depolarizing and nondepolarizing block. Most importantly, the response's return to control level does not guarantee that full recovery from NMB has occurred.

Train-of-four

Train-of-four (TOF, T_4, T_4/T_1) consists of four single pulses of equal intensity delivered at intervals of 0.5 seconds (2 Hz) (Fig. 25.2B) (27). TOF should not be repeated more frequently than every 10 to 12 seconds (4). Many modern stimulators do not allow the TOF to be repeated more often. Use of TOF every 10 seconds will result in a shorter onset time for NMB than if it is used every 20 seconds (21,28).

With the control response (before any relaxant has been given), all four responses are the same. The pattern seen with a depolarizing block differs from that of a nondepolarizing block (Fig. 25.2B). With a partial depolarizing block, there is an equal depression of all four twitches. With a nondepolarizing block, there is progressive depression of height with each twitch (fade). As the block is deepened, the fourth twitch will be eliminated first, then the third, and so on (Fig. 25.3). Counting the number of twitches (train-of-four-count or TOFC) permits quantitative assessment of a nondepolarizing block. With recovery or reversal of a nondepolarizing block, the TOFC increases until there are four responses, then fade decreases.

The train-of-four ratio (T_r, T_4 ratio, T_4:T_1, T_r%, TR%, TOF ratio, TOFR) is the ratio of the amplitude of the fourth response to that of the first, expressed as a percentage or a fraction. It provides an estimation of the degree of nondepolarizing NMB. In the absence of nondepolarizing block, the TOFR is approximately 1 (100%). The deeper the block, the lower the TOFR (Fig. 25.3). Since determining the TOFR requires that four twitches be present, it cannot be used to monitor a deep block.

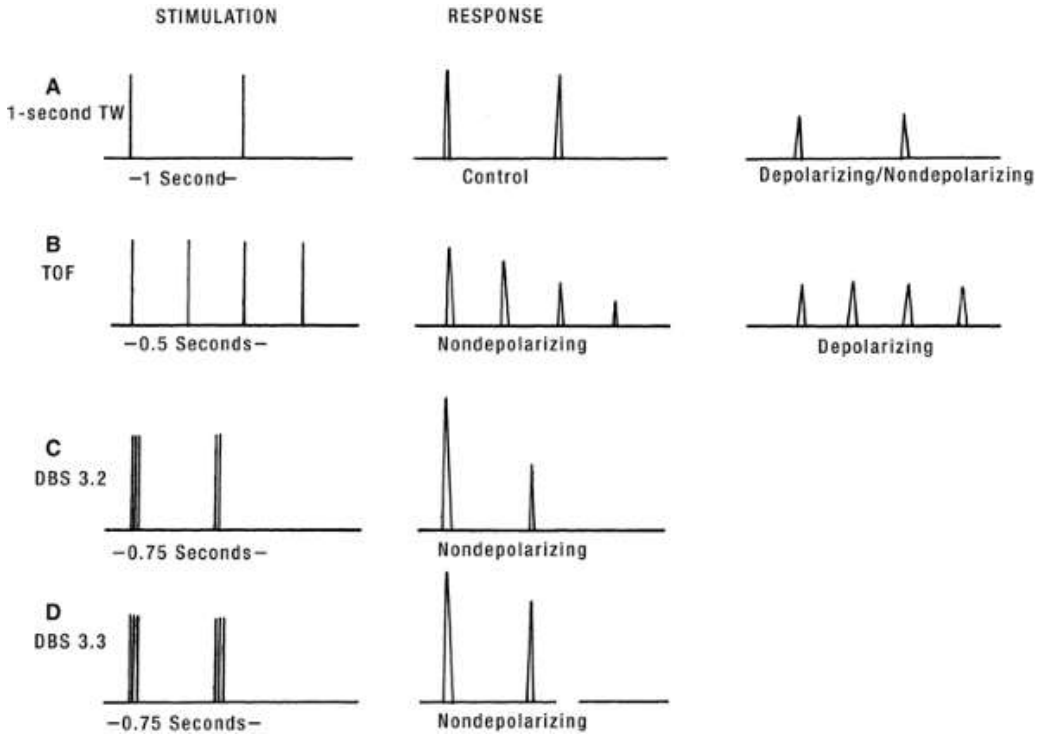

Figure 25.2 Patterns of stimulation and response. **A:** Single-stimulus stimulation at 1 Hz (1 stimulus/second). The height of the control twitches are noted. With either a depolarizing or a nondepolarizing block, twitch height is decreased. **B:** Train-of-four stimulation. Four successive single stimuli are delivered with 0.5-second intervals. With a nondepolarizing block, there will be progressive depression of the response with each stimulus (fade). With a depolarizing block, the responses will be depressed equally. **C, D:** Double-burst stimulation. Three stimuli are delivered at 50 Hz, followed 0.75 seconds later by two or three similar stimuli. There will be depression of the response to the second burst with a nondepolarizing block. Note the increased height of the response to the first burst compared with that seen with TOF stimulation. TW, time weight TOF, train of four; DBS, double-burst stimulation.

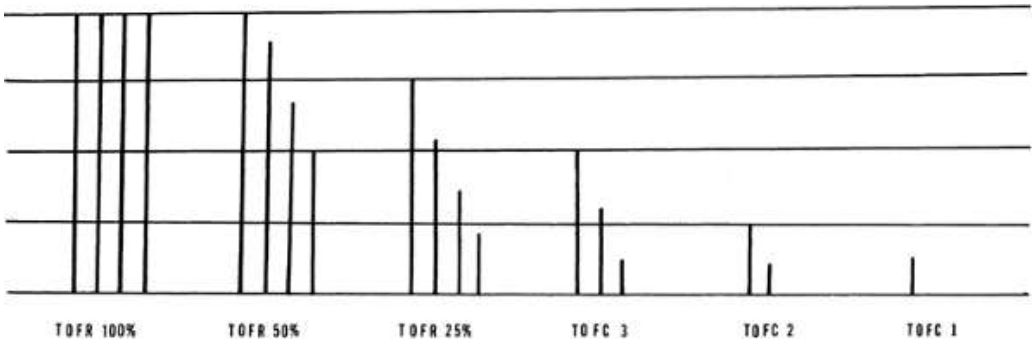

Figure 25.3 Onset and progressive deepening of nondepolarizing block using train-of-four stimulation. When there is no NMB present, all four responses are equal. With onset of the block, there is progressive depression of twitch height with each twitch (fade). As the block progresses, the last twitch is lost and the TOFC is less than 4. TOFR, train-of-four ratio; TOFC, train-of-four count.

Accurate assessment of the TOFR may not require a supramaximal stimulus (15). Testing at 10 mA above the lowest current at which four responses can be elicited may provide values that are consistent with those of supramaximal testing (29).

The TOF pattern has several advantages. It is a more sensitive indicator of residual NMB than the single twitch. A control is not necessary. It can distinguish between a depolarizing and a nondepolarizing block and is of value in detecting and following the development of a phase II block following succinylcholine administration.

The main disadvantage of TOF is its poor performance at both extremes of NMB, deep relaxation or near complete recovery (4,30,31,32,33,34,35). Tactile or visual observation of the TOFR is of little value above a ratio of 0.4Ī€“0.5.

Tetanus

Tetanus is a rapidly repeated (e.g., 50, 100 or even 200 Hz) stimulus. In the absence of NMB, this causes sustained contraction of the stimulated muscles. With a depolarizing block, the response will be depressed in amplitude but sustained. With a nondepolarizing block, the response is depressed in amplitude and the contraction is not sustained (fade or decrement). With

profound NMB, there is no response. Fade after 50 Hz tetanic stimulation is a more sensitive index of NMB than single twitch but not sufficiently sensitive to be used for assessing adequate recovery (36). Studies differ on the significance of fade after 100 Hz (36,37).

The most commonly used frequency is 50 Hz, because it stresses the neuromuscular junction to the same extent as a maximal voluntary effort. Fade may not be seen at lower frequencies when a significant nondepolarizing block is present. Use of 100 Hz allows more sensitivity in evaluating residual paralysis (37) and is more useful in monitoring profound NMB (38).

The duration of the tetanic stimulus is important because it affects fade. The standard duration is 5 seconds. Tetanic stimulation should not be repeated more often than every 2 minutes (39,40). Some newer stimulators limit how frequently it can be used.

Post-tetanic facilitation (potentiation, PTF) is a temporary increase in response to stimulation following a tetanic stimulus. It is seen with a nondepolarizing, but not a depolarizing, block (39,41). It is maximal at around 3 seconds and lasts up to 2 minutes.

When the NMB is so profound that there is no response to single twitch or TOF stimulation, it may be possible to estimate NMB by using the post-tetanic count (PTC) (42). This is performed by administering a tetanic stimulus of 50 Hz for 5 seconds. After a 3-second pause, single-twitch stimuli are applied at 1 Hz, and the number of (post-tetanic) responses is counted. The number of twitches elicited increases as the depth of NMB decreases. The time to appearance of the first twitch in a TOF is inversely related to the number of post-tetanic twitches present (43,44,45,46,47,48,49). An even deeper block can be monitored by counting the number of responses following 100-Hz tetanus (38).

A significant disadvantage of tetanic stimulation is that it is very painful and should be avoided in the conscious patient.

Double-burst Stimulation

Double-burst stimulation (DBS, minitetanus) consists of two short sequences of 50 Hz tetanic stimuli separated by 750 msec. The two most commonly used are $DBS_{3,3}$ and $DBS_{3,2}$. $DBS_{3,3}$ consists of three 0.2-msec impulses at 50 Hz, followed 750 msec

later by an identical burst (Fig. 25.2C). $DBS_{3,2}$ consists of three impulses followed by two such impulses 750 msec later (Fig. 25.2D). Another permutation of DBS is $DBS_{3,3}$ 80-40, which is three stimuli at 80 Hz followed 750 msec later by three stimuli at 40 Hz. A modified DBS consisting of first two stimuli of 0.3 ms duration at 50 Hz and then two stimuli of 0.2 ms duration at 50 Hz has also been used (50).

The primary use of DBS has been to detect residual NMB. Studies show that fade (response to the second burst weaker than that to the first) is more readily detected with DBS than TOF using visual or tactile monitoring (19,30,31,32,33,51,52). It also has been used for intraoperative assessment of NMB (53). DBS and TOF have a close relationship over a wide range of NMB (4,54,55). Another use of DBS is to assess deep block, since the first twitch in double burst can be detected at deeper block levels than the first twitch in TOF (53,56,57,58).

DBS causes more discomfort to the awake patient than TOF stimulation but less than tetanic stimulation (16). It can be used at submaximal currents. This causes less discomfort in the awake patient and, in most cases, is more reliable than testing with supramaximal stimuli (10).

DBS should not be repeated at intervals of less than 12 seconds (32). Caution should be used when switching between double-burst and TOF stimulation (59). Up to 92 seconds may be required before the responses are stabilized.

Electrodes

Stimulation is achieved by placing two electrodes along a nerve and passing a current through them. Stimulation can be carried out either transcutaneously using surface electrodes or percutaneously with needle electrodes.

Types

Surface Electrodes

Surface (gel, patch, pad) electrodes have adhesive surrounding a gelled foam pad in contact with a metal disc with a knob for attachment to the electrical lead. They are readily available, easily applied,

disposable, self-adhering, and comfortable. The electrodes can be those usually used to monitor the electrocardiographic

tracing. The electrode-skin resistance decreases with a large conducting area, as do skin burns and pain. However, a large conducting area may make it difficult to obtain supramaximal stimulation and may stimulate multiple nerves, so it may be better to use pediatric electrodes. The best results are obtained if the skin is properly cleansed and rubbed with an abrasive (20).

There are electrodes specially designed for peripheral nerve stimulation. These have a different thickness than electrocardiogram (ECG) electrodes and chemical buffers to maintain skin surface pH.

Metal Electrodes

Some stimulators are supplied with two metal balls or plates spaced about 1 inch apart, which attach directly to the stimulator (Fig. 25.1A). These are convenient to use but may not make good contact. Burns have been reported with their use (60).

Needle Electrodes

Needle electrodes may be useful when supramaximal stimulation cannot be achieved by using surface electrodes. This usually occurs when the skin is thickened, cold, or edematous and in obese, hypothyroid, diabetic, or renal failure patients (20,61).

Additional complications (broken needles, infection, burns, and nerve damage) are associated with their use. Needle electrodes carry a greater risk of direct muscle stimulation than surface electrodes (62).

Polarity

Stimulators produce a direct current by using one negative and one positive electrode. The polarity of the outlet sockets should be indicated on the stimulator. Usually, the positive electrode is red, and the negative is black. Maximal effect is achieved when the negative electrode is placed directly over the most superficial part of the nerve being stimulated (63). The positive electrode should be placed along the course of the nerve, usually proximally to avoid direct muscle stimulation. If the polarity is unknown, the connections can be reversed to determine which arrangement evokes the greater response.

Methods for Evaluating Evoked Responses

Visual

Visual assessment can be used to count the number of responses present with a TOF stimulus, to determine the PTC, and to detect the presence of fade with TOF or DBS. Posttetanic facilitation can also be assessed. Studies have shown that it is difficult to determine the TOFR accurately or to compare a single-twitch height to its control visually (30,64,65,66). Visually recognizing fade with TOF stimulation may be easier with submaximal currents (30). Visually assessing fade with 100-Hz tetanic stimulation appears to be fairly accurate when evaluating residual paralysis (38).

For visual assessment, the observer should be at an angle of 90 degrees to the motion (10).

Tactile

Tactile evaluation is accomplished by placing the evaluator's fingertips lightly over the muscle to be stimulated and feeling the strength of contraction (Fig. 25.4). It is more sensitive than visual monitoring for assessing NMB using TOF (33). It can be used to evaluate the presence or absence of responses and/or fade with train-of-four, double burst, and tetanic stimulation. The PTC can be determined. If there is a response to all four stimuli with TOF stimulation, the TOFR can be estimated. However, it is difficult for even trained observers to detect TOF fade manually unless the TOF ratio is below 40% (31,32,33,34,67,68,69,70,71,72,73). Detecting fade tactilely is somewhat easier with DBS but cannot be depended on to detect residual paralysis (31,32,33,50,72,74). Detection is better when the evaluator uses the dominant hand of the patient (67).

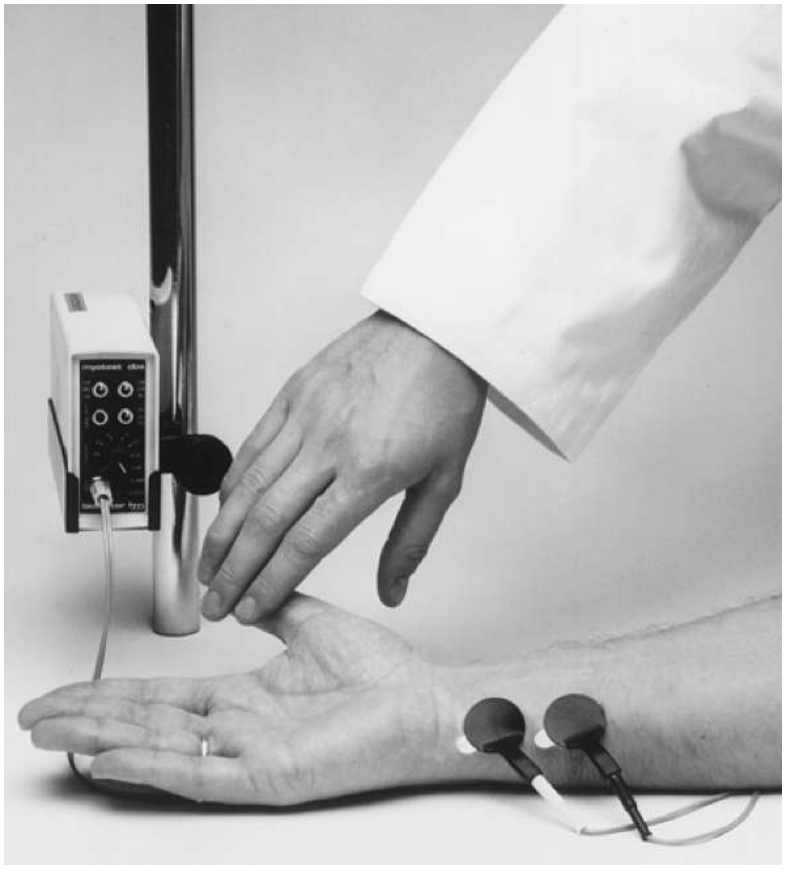

Figure 25.4 For tactile evaluation of thumb adduction, the hand is supine and a slight preload is applied. (Picture courtesy of Biometer.)

Mechanomyography

The mechanomyogram (MMG) utilizes a force-displacement transducer, such as a strain gauge, attached to a finger or other part of the body that can be restrained by a preload and will move when stimulated. The transducer converts the contractile force into an electrical signal, which is amplified and displayed on a monitor screen or recorded on a chart. Single-twitch height, response to tetanic stimulation, and the T_4 ratio can be accurately measured by using an MMG (75).

Using the MMG entails a number of difficulties. These devices are cumbersome and difficult to set up for stable and accurate measurements (76). Proper transducer orientation, isometric

conditions, and application of a stable preload are required (77). Maintenance of muscle temperature within limits is important for accurate results. Mechanomyography is rarely used clinically but is regarded as the gold standard for scientific measurement of neuromuscular response (5,78).

Acceleromyography

With acceleromyography (ACG, AMG), a thin piezoelectric transducer or a small aluminum rod with electrodes on both sides is fixed to the moving part (79,80) (Fig. 25.5). When the part moves, a voltage which is proportional to the acceleration of the moving part is generated. This method requires unrestricted movement of the muscle being stimulated. An elastic preload can be applied to return the moving part to its original position.

ACG can be used to assess NMB at the hand with the patient's arm tucked at the side as long as the thumb can move freely. A protective device can be used to allow thumb motion while protecting the hand and forearm (81).

Most studies show a fairly close relationship between TOFRs measured by ACG and the MMG (29,80,82,83,84,85,86,87,88,89,90,91) or electromyography (EMG) (75,85,92,93), although the results are not interchangeable. Some studies show poor correlation (94,95). In awake patients, the results are affected by extra movements to which the thumb may be subjected, leading to poor repeatability (96).

Accelerometry is easy and convenient to use, relative inexpensive, and can be interfaced with a computer. It does not require a preload. It gives more accurate results than visual or tactile evaluation (68,92).

Kinemyography

Kinemyography (KMG) utilizes a bending sensor that is placed between the thumb and forefinger (Fig. 25.6). The core of the sensor is a piezoelectric material (97). Movement is determined by the change in shape of the material when it is bent by adductor pollicis muscle contraction. When the piezoelectric material changes shape, the electrical charge in the material is redistributed, and this leads to an electron flow to balance the charges. This flow is measured as a potential change that is proportional to the amount of distortion. The hand need not be immobilized since the position and direction of the thumb do not

affect the measurement as long as the thumb is able to move freely. This device is in a module that can be

added to a multipurpose monitor (Fig. 25.7). The results of the neuromuscular testing are displayed on the monitor screen. This technology can measure TOF, double burst, and single twitch.

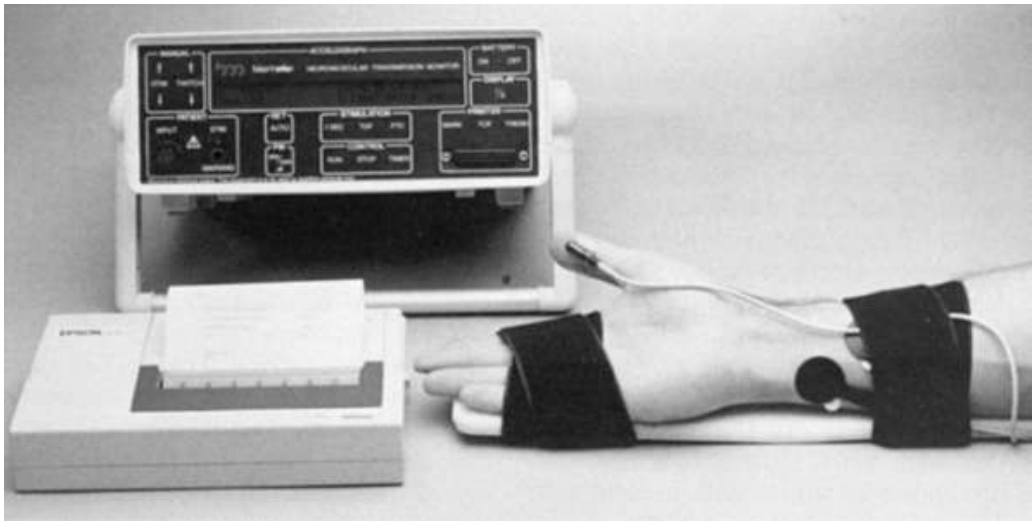

Figure 25.5 Accelerography. The piezoelectric wafer is attached to the moving partâ€”in this case, the thumb. When the thumb moves, an electrical signal proportional to the acceleration is produced. The monitor allows determination of single-twitch depression, TOF count or ratio and/or the PTC. Responses can be displayed by using the printer. (Courtesy of Biometer International A/S.)

Figure 25.6 Sensor for kinemyography. The sensor is secured with tape.

KMG has been compared with mechanomyography (98,99). There was agreement as to the time to intubation and recovery, but KMG lagged behind the MMG in determining recovery from NMB.

Piezoelectric Film

This method uses a disposable piezoelectric film (100). This is placed so that it spans a movable joint (101). Muscle movement from evoked stimulation bends the film and generates a voltage that is proportional to the amount of bending. It has been used on the thumb, fifth digit, and the great toe (101,102). It can be used with the patient's hands tucked at his or her sides.

This method is not as accurate as mechanomyography or EMG but may predict recovery of the TOFR better than visual or tactile evaluation (100,103,104,105).

Electromyography

Electromyography (EMG) is the process of recording the electrical activity of a muscle (106,107). When a motor nerve is stimulated, a biphasic action potential is generated in each of the muscle cells it supplies, unless some degree of NMB exists. The sum of a number of these action potentials can be sensed by using electrodes placed over the muscle being stimulated.

Five electrodes are used. Two stimulating electrodes are placed over the nerve to be stimulated. Three electrodes, two receiving (sensing, recording) and one ground, are used for recording. The best signal is usually obtained by placing the active receiving electrode over the belly of the muscle with the indifferent (reference) electrode over the tendon insertion site. The ground electrode, whose function is to decrease stimulation artifacts, is placed between the stimulating and recording electrodes. Best results will be seen when the electrodes have been in contact with the skin for at least 15 minutes (cure time) before calibration. Careful skin preparation will help to give good results (20). Movement artifact can be minimized by fixation or by applying a constant preload to the muscle being recorded (108,109).

EMG of the larynx can be accomplished by using either a specialized tracheal tube with incorporated wire electrodes or a superficial electrode attached circularly around the tube and placed between the vocal cords (110).

The evoked EMG signal is filtered, rectified, amplified, and then displayed and/or recorded at a much slower speed. Measurements may be made of peak-to-peak amplitude of the major deflection. The sum of the amplitudes of the major positive and negative deflections, or the area under the curve (integrated EMG), can be measured (78,111).

An EMG machine (Fig. 25.8) automatically determines the supramaximal stimulus, establishes a control

response, stimulates at a selected interval, measures the response, and compares it with the control. Available features include an alarm to warn when the single pulse response exceeds a chosen value and a printer to provide a permanent record. Most have alarms for functioning errors, loose connections, increased skin resistance, absence of supramaximal stimulation, and the like. Most show the EMG waveform and automatically adjust the gain so that it occupies the full scale.

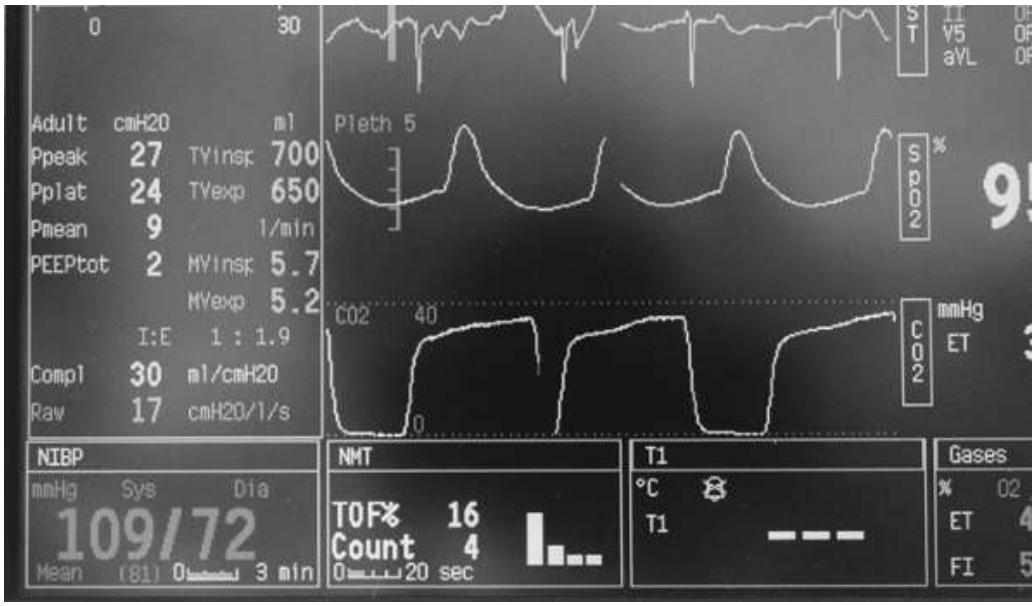

Figure 25.7 The TOF count and ratio are shown on the monitor. The scale at the bottom shows the frequency of stimulation (every 20 seconds) and how much time has elapsed since the last stimulus. This information comes from a Kinemyograph.

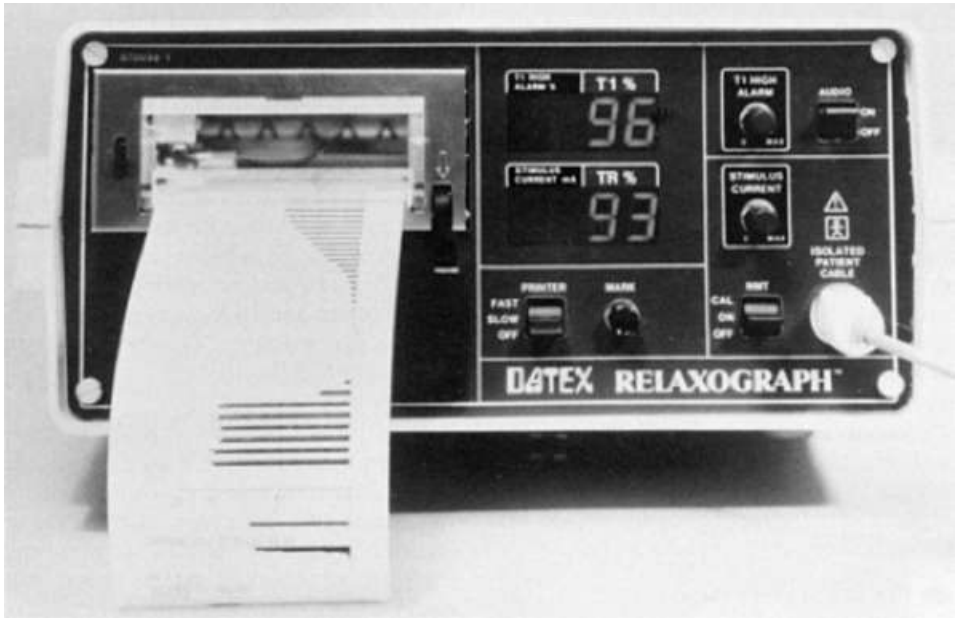

Figure 25.8 Electromyography monitor. The T_1%, TOFR, and TOFC

can be measured and are displayed in the boxes to the right of the printer. Responses can be recorded by using the printer. A T_1% high alarm is present. TOF stimulation is performed automatically every 20 seconds. (Courtesy of Datex Medical Instrumentation, Inc.)

With a nondepolarizing NMB, the action potential amplitude is decreased, and there is fade with TOF. Frequently, the amplitude does not return to 100% of control with recovery, although the TOFR will equal approximately 100%. Different hand positions may affect the results (112).

A number of studies comparing EMG and MMG have been published (86,113,114,115,116,117,118,119,120,121,122,123,124). With a nondepolarizing block, a fairly good correlation is usually seen, although the two techniques do not give identical information. With a depolarizing block, the relationship is more complex, and studies show contradictory results (125). The TOFR determined by EMG may be less affected by changes in temperature than with the MMG (123).

The neuromuscular trace does not always recover to the level of the initial calibration value. The recovery times of muscle relaxants can be accurately determined if measurements are referenced to the new baseline (126). The loss of supramaximal stimulation is partly responsible for the observed changes in the evoked electromyogram during anesthesia (127).

EMG has several advantages over mechanomyography. Less immobilization is required. It does not require bulky apparatus near the muscle being monitored. The hand and arm do not need to be extended or put on a board (78,128). It can be used to monitor muscles not available to the MMG such as the diaphragm and the laryngeal muscles (20,129,130,131,132,133,134,135). It can be used to assess motor nerve block induced by regional anesthesia (136).

There are disadvantages to EMG. It is sensitive to electrical interference. The response may vary according to the muscle used. The equipment is expensive and takes some time and effort to set up. Skin preparation and electrode placement must be done especially carefully. Since the site is not immobilized, changes in the relative position of the recording electrodes cause variation in EMG response. Temperature plays an important role in the response amplitude with amplitude

increasing with decreasing muscle temperature (20).

Phonomyography

Phonomyography (acoustic myography or monitoring) relies on the fact that when a muscle contracts, low-frequency sounds are emitted. These acoustic waves propagate to the skin, generating waves that can be recorded by a small piezoelectric microphone. The

signal amplitude has been shown to be proportional to the degree of muscle contraction.

This method has been used to measure responses in the hand muscles when the microphone is tightly secured to the thenar mass to monitor the adductor pollicis muscle, or to the groove between the first and second metacarpel bone to monitor the first dorsal interosseus muscle (137,138,139,140,141,142). The corrugator supercilii muscle can be monitored by placing the microphone above the medial portion of the eyebrow (142,143,144,145). The muscles of the larynx can be monitored by placing the sensor in the vestibular fold just lateral to the vocal cords (110,146,147).

Studies comparing phonomyography, ACG, and mechanomyography by using hand and corrugator supercilii muscles show some agreement, although the results are not interchangeable (99,140,141,143,144,145,146).

The phonomyogram is easy to use and can be used on a number of different muscles. It provides a stable baseline with relatively few disturbances from artifacts (145). Data can be transferred to an automated anesthesia record.

Since this method monitors low frequency sounds, artifacts are possible. Vessel pulsations can cause small waves in the baseline. Electrosurgery units may cause interference. The microphone may come off the skin.

Choice of Monitoring Site

The site of stimulation should be away from the surgical field. If visual or tactile monitoring is to be used, the location must be accessible to the anesthesia provider. If a muscle in an arm or leg is used, the blood pressure should be measured on a different extremity. An arteriovenous shunt does not contraindicate that arm being used to monitor NMB (148). If the patient has an upper-motor-neuron lesion, a nerve in an affected

(paretic) extremity should not be used, because it may falsely show resistance to nondepolarizing drugs (149,150). If possible, the nerve stimulator electrodes should be placed on a different extremity from the pulse oximeter probe to avoid artifacts (151,152,153).

Ulnar Nerve

The ulnar nerve is most commonly used, and the adductor pollicis (thumb) muscle is most commonly monitored. Because this muscle is on the side of the arm opposite the site of stimulation, there is little direct muscle stimulation. However, residual NMB may be easier to detect tactilely by using the index finger (71).

The ulnar nerve can be stimulated at the elbow, wrist, or hand (Figs. 25.9, 25.10). Stimulation at the wrist will produce thumb adduction and finger flexion. Stimulation at the elbow produces hand adduction as well. If an MMG or electromyogram is used for measuring the response, the stimulating electrodes should be placed at the wrist to limit hand motion.

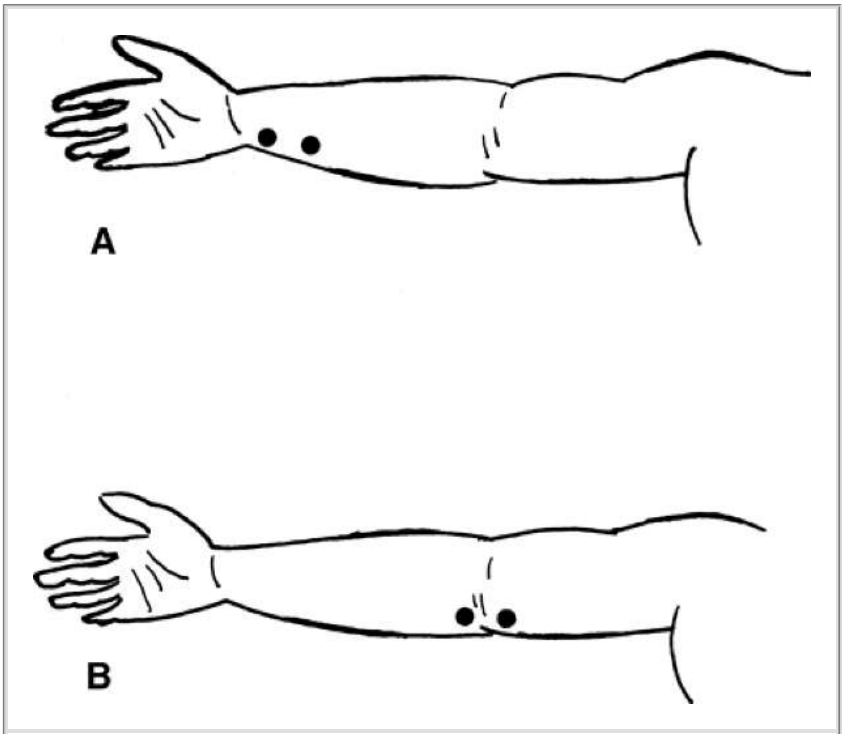

Figure 25.9 Placement of electrodes for ulnar nerve stimulation. **A:** The electrodes are placed along the ulnar aspect of the distal forearm. **B:** The electrodes are placed over the sulcus of the medial epicondyle of

the humerus.

At the wrist, the two electrodes should be placed along the medial aspect of the distal forearm, approximately 2 cm proximal to the proximal wrist skin crease with the negative electrode distal (18) (Fig. 25.9A). There, the ulnar nerve is superficial. Alternately, the positive electrode may be placed on the dorsal side of the wrist (Fig. 25.10). At the elbow, the electrodes should be placed over the sulcus of the medial epicondyle of the humerus (Fig. 25.9B). Caution must be exercised to ensure that the electrodes do not cause ulnar nerve compression (154). The electrodes may also be placed on the hand with the negative electrode on the palm between the base of the thumb and the second finger and the positive electrode in the same position on the dorsal side of the hand (155).

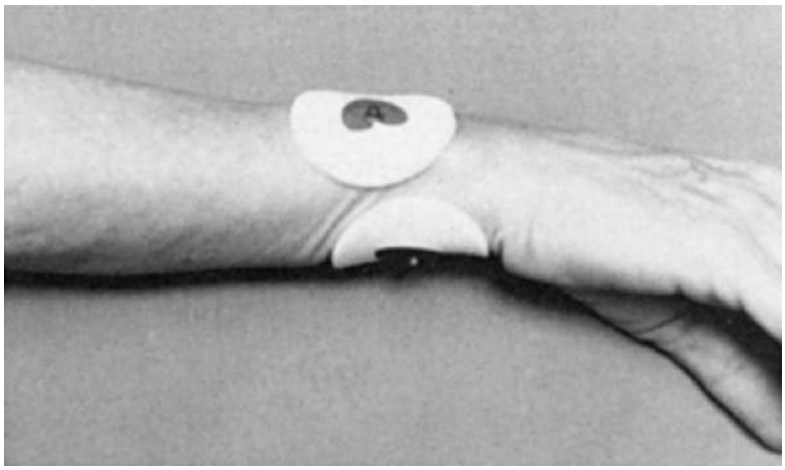

Figure 25.10 Alternate placement of electrodes for ulnar nerve stimulation. The negative electrode is placed along the ulnar aspect of the ventral side of the wrist. The positive electrode is placed on the dorsal side.

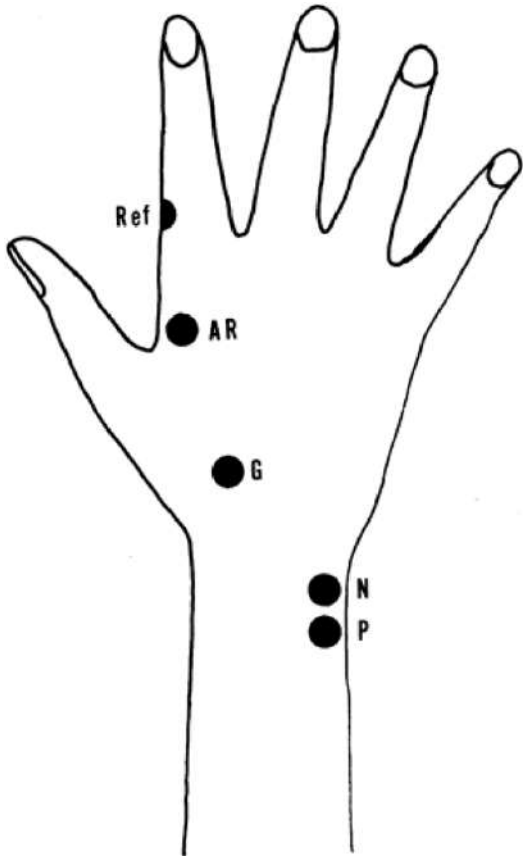

Figure 25.11 Sites for electrodes for electromyography monitoring with ulnar nerve stimulation and recording from the dorsal interosseous muscle. The active receiving electrode is placed in the web between the index finger and the thumb and the reference electrode, at the base of the second finger. Ref, reference electrode; AR, active receiving electrode; G, grounding electrode; N, negative-stimulating electrode; P, positive-stimulating electrode.

When EMG monitoring is used, the recording electrodes can be placed over the hypothenar, thenar, or dorsal interosseous muscle. The electrical resistance of the palm skin may vary because of sweat production and may be increased in manual workers (156). The dorsum of the hand is less affected than the palm in both respects, so the dorsal interosseous muscle may be preferred. To record the reaction of the dorsal interosseous muscle, the active receiving electrode is placed in the web between the index finger and the thumb and the other electrode

at the base of the second finger (Fig. 25.11). Surface electrodes are simple to fix here, easy to maintain in position, and seldom are disturbed by hand movements (157). For the hypothenar EMG, both electrodes are placed on the palmar side over the hypothenar eminence or the active electrode is placed on the hypothenar eminence and the other below the second line on the ring finger or at the base of the dorsum of the fifth finger (Fig. 25.12) (158,159). If the thenar muscle EMG is recorded, electrodes are placed on the thenar eminence and the proximal phalanx of the middle or index finger or the lateral side of the base of the thumb (Fig. 25.13). Abduction of the thumb with a constant pretension will bring the muscles closer to the skin and minimize movement (14,109).

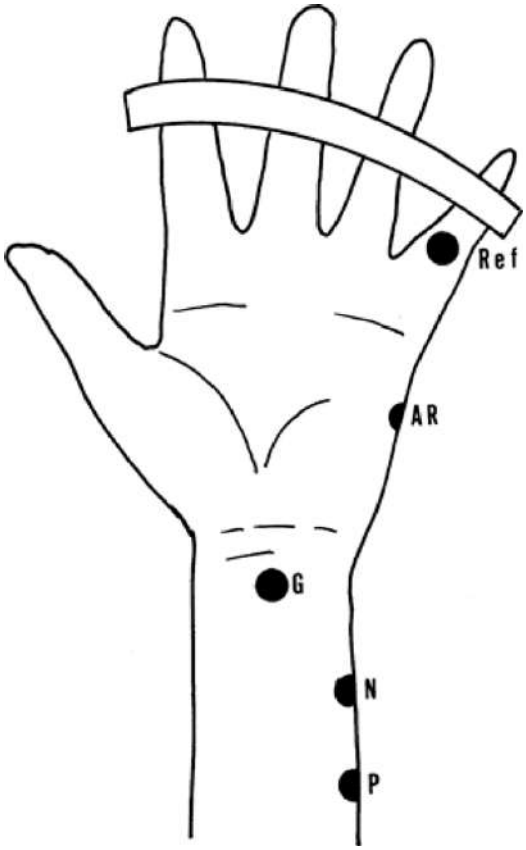

Figure 25.12 Placement of electrodes for electromyography monitoring from the hypothenar eminence. The active electrode is placed over the hypothenar eminence. The reference electrode may be placed more distally on the hypothenar eminence, below the second line on the ring finger or at the base

of the fifth finger as shown. Ref, reference electrode; AR, active receiving electrode; G, grounding electrode; N, negative-stimulating electrode; P, positive-stimulating electrode.

For tactile assessment, the thumb should be held in slight abduction and the observer's fingertips placed over the distal phalanx in the direction of movement (160) (Fig. 25.4). Preloading the thumb with a rubber band may improve visual assessment (161). It should be noted that the adductor pollicis is sometimes supplied by the median nerve (162).

When monitoring the adductor pollicis muscle, it is important to realize that the onset and duration of NMB at the larynx and the diaphragm are shorter than at the peripheral muscles (78,131,132,163,164).

Median Nerve

The median nerve is larger than the ulnar but less superficial (165). It can be stimulated at the wrist by placing the electrodes medial to where the electrodes would be placed for ulnar nerve stimulation or at the elbow adjacent to the brachial artery. This results in thumb adduction. The EMG signal can be monitored from the thenar muscles.

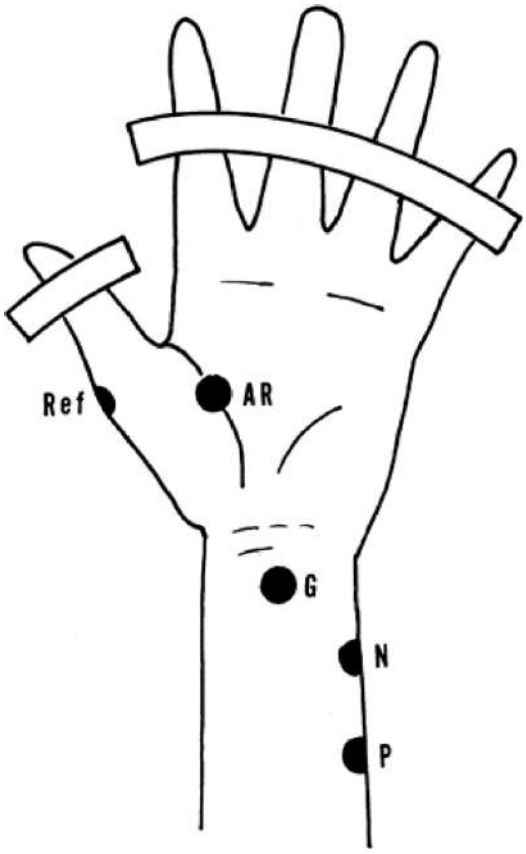

Figure 25.13 Placement of electrodes for monitoring the electromyogram from the thenar eminence. The active receiving electrode is placed over the thenar eminence. The reference electrode may be placed as shown here or at the proximal phalanx of the middle or index finger. Ref, reference electrode; AR, active receiving electrode; G, grounding electrode; N, negative-stimulating electrode; P, positive-stimulating electrode.

Tibial Nerve

To stimulate the tibial nerve at the popliteal fossa, two stimulating electrodes are placed along the lateral side of the popliteal fossa. The gastrocnemius muscle is stimulated. This is usually monitored by the EMG with the sensing electrodes over the lateral head of the gastrocnemius muscle (166). The use of this muscle may cause significant leg movement, which may distract the surgeon (78).

Posterior Tibial Nerve

To stimulate the posterior tibial nerve, electrodes are placed behind the medial maleolus and anterior to the Achilles tendon at the ankle (Fig. 25.14). Stimulation causes plantar flexion of the foot and big toe. ACG can be used at this site (9,167,168,169). If EMG monitoring is used, the receiving electrodes are placed on the flexor hallucis brevis on the plantar surface of the foot or on the intermetatarsal muscles with the reference electrode on the big toe (Fig. 25.15).

The posterior tibial nerve site offers many advantages. It is especially useful in children, when it is difficult to find room on the arm because of other monitors or invasive lines, and when the hand is inaccessible or for other reasons such as amputation, burns, infection, or head and neck procedures (170).

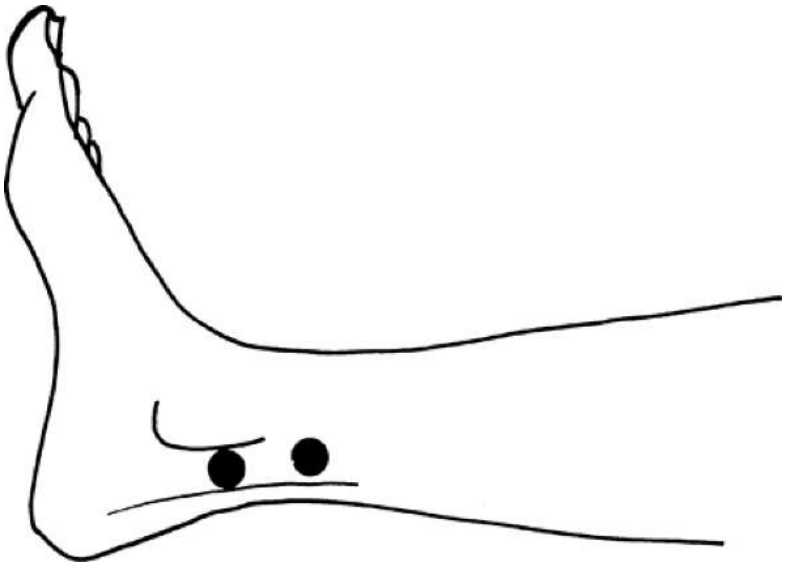

Figure 25.14 Placement of electrodes for stimulating the posterior tibial nerve. The negative electrode is placed behind the medial malleolus, anterior to the Achilles tendon. The positive electrode is placed just proximal to the negative electrode. Stimulation causes plantar flexion of the great toe.

Compared with the ulnar nerve, the posterior tibial nerve displays a lag time with a slower onset of relaxation (169,171,172). Most studies show little difference in the time to recovery from the neuromuscular relaxation

(170,171,172,173,174,175). The probability of tactile detection of fade in response to TOF or DBS is less at the great toe than at the thumb (73).

Peroneal Nerve

To stimulate the peroneal (lateral popliteal) nerve, electrodes are placed on the lateral aspect of the knee (Fig. 25.16). It may be necessary to try different positions to achieve the best response (176,177). Stimulation causes dorsiflexion of the foot. Compared with the ulnar nerve, the peroneal nerve shows a slower onset of relaxation and the muscles show greater resistance to NMB (177).

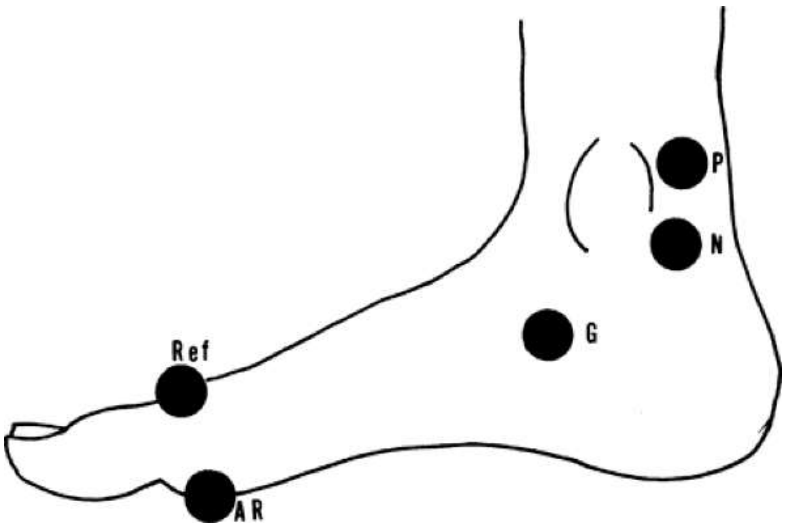

Figure 25.15 Electromyography monitoring using the posterior tibial nerve. The active receiving electrode is placed over the flexor hallucis brevis and the reference electrode, on the big toe. Ref, reference electrode; AR, active receiving electrode; G, grounding electrode; N, negative-stimulating electrode; P, positive-stimulating electrode.

Figure 25.16 Electrode placement for stimulating the peroneal (lateral popliteal) nerve. The electrodes are placed lateral to the neck of the fibula. Stimulation causes dorsiflexion of the foot.

Muscular Branch of the Femoral Nerve

The muscular branch of the femoral nerve can be stimulated and movement in the vastus medialis muscle evaluated. This muscle can be used to monitor neuromuscular function in the prone patient. When compared with the adductor pollicis muscle, the onset of NMB and recovery were quicker (178).

Facial Nerve

The facial nerve, which enervates the muscles around the eye, is

one of the easier muscles to stimulate and observe. It is most useful for detecting the onset of relaxation in the muscles in the jaw, larynx, and diaphragm (179). ACG can be used with the facial nerve (180,181,182,183).

Several different electrode configurations have been used for stimulating the facial nerve:

1. The negative electrode is placed just anterior to the inferior part of the ear lobe, and the other electrode is placed just posterior or inferior to the lobe (Fig. 25.17). Stimulation at this site will make it more likely that muscle contractions are the result of nerve stimulation rather than direct muscle stimulation.
2. One electrode is placed lateral to and below the lateral canthus of the eye, and the other electrode is placed anterior to the earlobe (184) or 2 cm lateral to and above the lateral canthus. This placement may result in direct muscle stimulation. If one of these configurations is used, low currents (20â€“30 mA) should be used (110).

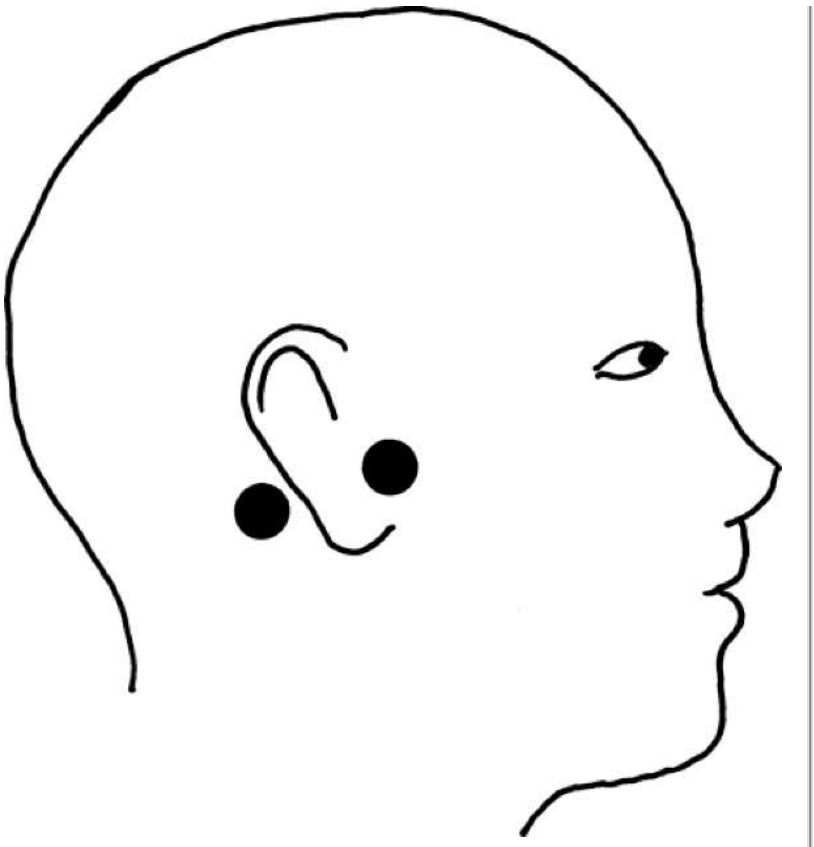

Figure 25.17 Electrode placement for stimulating the facial nerve. The negative electrode is placed anterior to the earlobe. The positive electrode is placed posterior or inferior to the earlobe.

The corrugated supercilii muscle should be observed (185). With ACG, the transducer should be placed in the middle of the superciliary arch (182).

The facial muscles are relatively resistant to NMB drugs (180,186). Therefore, managing NMB by stimulating the facial nerve will result in greater relaxation than from stimulating a limb nerve if equivalent responses are used. The facial nerve should not be used to assess recovery from NMB because the responses may show complete recovery while significant NMB is still present (182,183,184,187,188,189).

Mandibular Nerve

The mandibular nerve, a branch of the trigeminal, supplies the masseter muscle. It can be stimulated by placing the negative

electrode anterior and inferior to the zygomatic arch and by placing the positive electrode on the forehead. Stimulation causes the jaw to close. The onset of NMB in this muscle is faster than in the hand muscles (190,191). In adults, this muscle is more sensitive to both depolarizing and nondepolarizing drugs than the hand muscles (190,192). In children, the sensitivity may be equal (191).

Spinal Accessory Nerve

The spinal accessory nerve can be stimulated by placing the electrodes over the depression between the ramus of the mandible and the mastoid process/ sternocleidomastoid muscle (193). Stimulation causes the sternomastoid and trapezius muscles to contract.

This can cause shoulder and thorax movement with transmission to the abdomen (194).

Recurrent Laryngeal Nerve

The recurrent laryngeal nerve innervates most of the intrinsic muscles of the larynx (110). It can be stimulated percutaneously by using two electrodes between the notch between the thyroid and the cricoid cartilages (110,195). The response can be measured by placing the tracheal tube cuff between the vocal cords and measuring pressure changes within the cuff (195) or by using phonomyography with the microphone placed in the vestibular fold lateral to the vocal cords (146). EMG in the larynx can be accomplished by using a specialized tracheal tube with incorporated wire electrodes (196) or an electrode attached to the tube and placed between the vocal cords (130).

Use

Before Induction

Prior to anesthesia induction, the stimulator should be connected to electrodes that are positioned over the selected nerve. If EMG monitoring is to be used, the receiving electrodes should be placed at least 15 minutes before induction.

Electrode sites should be dry and free of excessive hair or scar tissue or other lesions. The skin should be thoroughly cleansed by using a solvent such as alcohol, then completely dried and rubbed briskly with a gauze pad until a slight redness is visible.

The electrodes should be checked to verify that the gel is moist. It is important to avoid spreading the gel or overlapping adhesive while placing the electrodes. A gel bridge between the electrodes can short-circuit them and lead to poor stimulation. After the leads are attached to the electrode, a piece of tape should be placed over the leads to prevent movement. It is good practice to create a loop to prevent electrode displacement (Fig. 25.18).

Induction

During induction, the neuromuscular stimulator can be used to determine the onset time of NMB, detect unusual sensitivity to relaxants, and determine whether or not the patient is sufficiently relaxed for tracheal intubation.

After induction of anesthesia but before administering any muscle relaxants, the stimulator should be turned ON and set to deliver single-twitch stimuli at 0.1 Hz. Applying stimulation more frequently will make it appear as if the time of onset of NMB is shorter (197,198,199). The output of the stimulator should be increased until the response does not increase with increasing current, then increased 10% to 20%. If maximal stimulation is not achieved with a current of 50 to 70 mA, the electrodes should be checked for proper placement. If maximal stimulation still cannot be achieved, needle electrodes should be used.

Special needle electrodes are available commercially, but ordinary injection needles can be used. They should be short and thin. The needles should be placed subcutaneously. Inserting them deeper may produce direct muscle excitation and/or cause damage to the nerve. The angle of insertion should be parallel to the nerve. There should be at least a few centimeters between the needles. They should be fixed in place with tape. The lead should be attached to the shaft of the needle unless the needle has a metal hub.

Correct EMG electrode placement should be verified by observing the quality of the evoked waveform, which should approximate a sine wave. The gain control should be adjusted so that the waveform occupies the full scale.

Intubation

Complete relaxation of the jaw, laryngeal and pharyngeal muscles, and diaphragm is needed for excellent intubating conditions and to reduce the risk of trauma. It should be kept in mind that the response to intubation is a function of both

muscular block and the level of anesthesia. It

is possible to intubate a patient with less-than-complete paralysis if a sufficient depth of anesthesia is present (200).

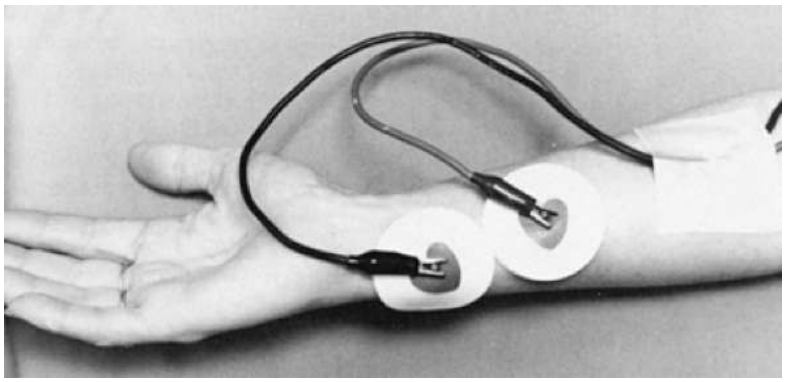

Figure 25.18 Electrodes in place. Creating loops and securing the wires with tape will decrease the likelihood that the wires will be pulled off the electrodes.

The onset of NMB will be faster in centrally located muscles such as the diaphragm, facial, laryngeal, and jaw muscles than peripheral muscles such as the adductor pollicis (110,190,201,202,203,204,205,206,207,208,209,210).

The diaphragm, eye muscles, and most laryngeal muscles are more resistant to nondepolarizing relaxants than are peripheral muscles (211,212). The diaphragm is resistant to succinylcholine, though the laryngeal muscles are sensitive to it. The masseter muscle is relatively sensitive to both nondepolarizing and depolarizing relaxants (192,213). It often reacts with increased tone instead of relaxation to succinylcholine, particularly in children.

Monitoring the response of the eye muscles will reflect the time of onset and the level of NMB at the airway musculature more closely than monitoring peripheral muscles, which will underestimate the rate of onset of NMB in the airway musculature and may overestimate the degree of block (163,179,202,214,215,216,217,218).

If the facial nerve cannot be used, a peripheral nerve will suffice in most cases. In the majority of patients, disappearance of the

adductor pollicis response is associated with good to excellent intubating conditions. If the electromyographic responses are being monitored, monitoring at the hypothenar eminence may be preferable (157).

Whatever nerve is used, it is recommended that single twitch at 0.1 Hz be used and that the clinician wait until a response is barely perceptible before attempting laryngoscopy and intubation. More rapid stimulation may accelerate the onset of block at the stimulated site (198,199). Double burst has been used as an indicator of optimal conditions for tracheal intubation (219).

The response to stimulation will usually disappear for a variable period of time, then appear and increase progressively to full recovery. Additional relaxants should not be given until there is evidence of some recovery to make sure that the patient does not have an abnormal response. However, it is not necessary to wait for complete recovery before giving additional relaxants.

Electroconvulsive Therapy

A common error in electroconvulsive therapy is delivering the electrical stimulus prematurely (220). It is recommended that a single stimulus be applied at 1 Hz to the posterior tibial nerve (221). When there is complete abolition of response, the electroconvulsive therapy should be applied.

Maintenance

During maintenance, the stimulator can be used to titrate the relaxant dosage to the needs of the operative procedure so both under- and overdosage are avoided. Too deep an NMB may make it difficult to reverse the relaxant at the termination of the anesthetic. Underdosage may result in inadequate relaxation or undesirable patient movement. In a study of closed claims against anesthesiologists, eye injuries constituted 3% of claims (222). Patient movement during anesthesia was the mechanism of injury in 30% of those cases. Peripheral nerve stimulators were not used in any patients who made claims for movement under anesthesia.

The degree of NMB required during a surgical procedure depends on many factors, including the type of surgery, the anesthetic technique, and the depth of anesthesia. It is important to prevent cooling of the monitoring site to avoid impaired nerve conduction or increased skin resistance, which may result in

overestimation of the degree of NMB (26,223,224).

It is important to correlate the reaction to nerve stimulation with the patient's clinical condition because there may be a discrepancy between the degree of relaxation of the monitored muscles and that of the muscles at the site of surgery. If the surgeon believes that relaxation is inadequate, the anesthesia provider should confirm that the depth of anesthesia is sufficient and the degree of NMB is adequate. It should be confirmed that the stimulator is working properly. If it does not display the delivered current, electrodes may be placed on the user's arm and a low current used to confirm proper function.

TOF is commonly regarded as the most useful pattern for monitoring NMB during maintenance. Supramaximal currents are traditionally used. A submaximal current may be used, but this is controversial (15,18,19,30,104,225,226). The goal for most cases in which abdominal muscle relaxation is required should be to maintain at least one response to TOF stimulation in a peripheral nerve (227,228). If no response is present, further administration of relaxants is not indicated. If two responses are present, abdominal relaxation may be adequate using balanced anesthesia (229). Presence of three twitches is usually associated with adequate relaxation if a volatile anesthetic agent is used. Deeper levels of NMB may be required for upper abdominal or chest surgery or if diaphragmatic paralysis is needed. If the facial muscles are used, at least one twitch should be added to the mentioned recommendations.

Muscle relaxants are sometimes administered in cases such as eye surgery or laser surgery on the vocal cords to guarantee that movement does not occur. To ensure total diaphragmatic paralysis, the NMB should be so intense that there is no response to post-tetanic

stimulation (i.e., the PTC is 0) (230,231). One approach is to give a bolus of a short-acting muscle relaxant when the PTC is 1 (232). Alternatively, the twitch response at a resistant muscle such as the orbicularis oculi may be monitored and a dose of relaxant given as soon as there is any response.

Recovery and Reversal

At the end of a procedure, a stimulator allows the anesthesia provider to determine whether or not the block is reversible and adjust the dose of reversal agent, if required, to the patient's requirements (233). Numerous studies have shown that some

patients entering the postanesthesia care unit have an unacceptable level of block (69,234,235,236,237,238,239,240,241,242,243,244,245,246,247,248,249,250,251,252,253). A nerve stimulator may detect residual NMB, which could lead to life-threatening complications (74,254,255,256,257,258).

When relaxation is no longer required, administration of NMB drugs should be discontinued. As recovery progresses, the responses to TOF will progressively appear, then fade will disappear. The ease of reversing a nondepolarizing block is inversely related to the degree of block at the time of reversal (6,259). If the first twitch (T_1) is present, it can be estimated how quickly the block can be reversed. The time depends on the relaxant that has been used.

Recovery is governed by the sensitivity of the muscle and rate that the drug disappears from the plasma. It is best to use a peripheral muscle to monitor recovery, because its complete recovery would indicate that residual muscular weakness contributing to problems with airway patency or respiration is unlikely (110,188,202,205,260,261,262). The probability of detecting fade by using the index finger is greater than if the thumb or great toe is used (71,73).

In the past, many investigators thought that a TOFR of 0.7 was adequate (4,263). However, a normal response to hypoxemia, protection from pulmonary complications, and absence of heaviness of the eyelids, visual disturbances, difficulty swallowing, or patient anxiety may require a higher ratio (4,264,265,266,267,268,269,270,271,272,273). Most investigators now recommend that the TOFR at the adductor pollicis be at least 90% measured by mechanomyography before extubation (248,266,275,276). This is probably most reliably accomplished by using ACG and achieving a TOFR at least 90% of the baseline (68,91,92,254,257,277,278,279,280). If EMG monitoring is being used, residual anesthetic effects usually prevent the return of T_1 to the preanesthetic reference level, but the TOFR should exceed 90% (281).

Residual NMB cannot be reliably detected by using TOF stimulation if visual and/or tactile monitoring is used (19). Detection may be somewhat better when using DBS (30,31,52,282). Both may be more reliable at detecting fade at lower currents (19).

Clinical criteria in an awake patient have been used to ascertain whether the return of muscle strength is adequate. These include

the ability to (a) open the eyes for 5 seconds and not experience diplopia, (b) sustain tongue protrusion, (c) sustain head lift for at least 5 seconds, (d) sustain hand grip, (e) sustain leg lifting in children, (f) cough effectively, and (g) swallow. A more sensitive test may be the ability to resist removing a tongue blade from clenched teeth (268). Clinical criteria in an asleep patient include an adequate tidal volume and an inspiratory force of at least 25 cm H_2O negative pressure. Subjecting the patient to negative inspiratory pressure can cause pulmonary edema. These clinical criteria do not exclude clinically significant residual paralysis (248,272,283).

Postoperative Period

Even if a nerve stimulator has not been used during an operation, it can be used postoperatively. If the patient is not fully anesthetized, it is preferable to use less than supramaximal stimulation (15,29,284). This decreases the discomfort associated with stimulation and may improve the visual assessment accuracy (30).

Long-term Muscle Relaxant Infusions

Long-term muscle relaxants infusions are sometimes used in critical care areas. NMB monitoring should be used to avoid overdosage (285,286,287,288,289,290,291,292). A number of factors unique to the critical care setting affect the response to NMB drugs (12,286). Prolonged paralysis is sometimes seen despite monitoring (293,294).

Nerve Location

A peripheral nerve stimulator may be used to locate nerves for regional block (295). The current needed is far below that needed for monitoring NMB. Stimulators with different current outputs for both functions are available (296,297).

Hazards

Burns

Burns have been reported when using a stimulator with metal ball electrodes (298). Needle electrodes may be associated with local tissue burns from electrosurgical units because they provide good contact with minimal resistance for exit of high-frequency current over a small area of skin (299). Severe burns resulting in permanent loss of hand function caused by a nerve

stimulator have been reported (300).

Nerve Damage

The pressure of an electrode on a nerve can result in palsy (154). Thumb paresthesias were reported in patients whose muscular function was monitored by using an MMG (301). Nerve damage can result from intraneural placement of a needle electrode.

Complications Associated with Needle Electrodes

Complications associated with needle electrodes include infection, bleeding, and pain.

Pain

Patient discomfort will be reduced by using lower currents and avoiding tetanic or double-burst stimulation when the patient is not fully anesthetized (16,18).

Electrical Interference

The use of a nerve stimulator may cause changes in the ECG tracing or interfere with an implanted pacemaker (302,303,304,305).

Incorrect Information

With some stimulators, when the batteries are low, only three pulses are generated during TOF stimulation (306). This could lead to incorrect interpretation of the degree of NMB.

A potentially confusing user interface on a neuromuscular transmission module has been reported (307). The module provided a bar graph visual indication of the four responses to TOF stimulation. However, if the responses were greater than 120% of the control response, the bar graph representations were chopped off. As a result, all four twitches could appear to be of the same height when the TOF ratio was below 100%.

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Questions

For the following questions, select the correct answer

1. The waveform for stimulation should be

A. Biphasic

B. Rounded

C. Monophasic

D. Sloping

E. Notched

View Answer

2. The twitch frequency for the TOF stimulation is

A. 1 Hz for 1 second

B. 2 Hz for 2 seconds

C. 2 Hz for 1 second

D. 1 Hz for 2 seconds

E. 3 Hz for 2 seconds

View Answer

3. The time interval between TOF stimulations should be at least

A. 4 seconds

B. 8 seconds

C. 12 seconds

D. 20 seconds

E. 22 seconds

View Answer

4. The frequency of single-twitch stimulation should not exceed

A. 0.01 Hz

B. 0.1 Hz

C. 1 Hz

D. 1.5 Hz

E. 10 Hz

View Answer

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

5. TOF stimulation

A. Can be used if only one twitch is present

B. Can be used to determine reversibility from NMB

C. Can be monitored by ACG

D. Should be performed once every 5 seconds

View Answer

6. Supramaxinal stimulation refers to the

A. Voltage used to stimulate the nerve

B. Current used to stimulate a nerve

C. Voltage above that necessary for maximal stimulation

D. Current higher than that needed for maximal stimulation

View Answer

7. Single-twitch stimulation

A. Cannot distinguish between depolarizing and nondepolarizing blocks

B. Is useful for identifying satisfactory conditions for intubation

C. Is not useful for assessing recovery from NMB

D. Is not useful to determine supramaximal stimulus

View Answer

8. Factors affecting the TOFR include

A. The nature of the NMB (depolarizing or nondepolarizing)

B. Depth of the NMB

C. The nerve being monitored

D. An upper-motor-neuron lesion

View Answer

9. Advantages of TOF stimulation include

A. It is more sensitive than the single twitch

B. It can detect a phase II block

C. It can distinguish between depolarizing and nondepolarizing blocks

D. It is easy to detect fade with visual or tactile methods

View Answer

10. DBS

A. Consists of two short tetanic stimuli separated by 750 ms

B. Is primarily used to determine residual NMB

C. Is more sensitive than TOF stimulation for determining fade

D. Causes less discomfort than TOF stimulation

View Answer

11. With tetanic stimulation,

A. If no relaxants are present, there will be a contraction followed by relaxation of the stimulated muscles

B. If there is a depolarizing block, there will be a sustained contraction of lower magnitude

C. Profound block will show muscle movement after 10 seconds of stimulation

D. If a nondepolarizing block is present, there will be a nonsustained contraction of the muscle

View Answer

12. For tetanic stimulation, 50 Hz is most often used because

A. It is more physiologic

B. If the frequency is greater than 50 Hz, the fade will be less pronounced

C. If the frequency is less than 50 Hz, the fade will be more pronounced

D. It stresses the neuromuscular junction similar to a voluntary effort

View Answer

13. Post-tetanic facilitation

A. Is maximal in 3 seconds and lasts for up to 2 minutes

B. Is temporary

C. Is used to determine the depth of block in profoundly relaxed patients.

D. Occurs with depolarizing blocks

View Answer

14. ACG

A. Utilizes a piezoelectric sensor that produces an

electronic signal proportional to the amount of movement

B. Is useful in patients whose extremities are tucked

C. Requires a preload

D. Can be interfaced with a computer

View Answer

15. The electromyograph

A. Cannot be used to monitor the diaphragm

B. Measures a biphasic action in each muscle stimulated

C. Cannot be used with muscles that cannot be used with the MMG

D. Uses stimulating electrodes placed in a similar fashion as other monitoring technologies

View Answer

16. The facial nerve

A. Is relatively resistant to muscle relaxants

B. Can be used with ACG

C. May show complete recovery when significant NMB still exists

D. Is useful in determining the relaxation of the jaw and diaphragm

View Answer

17. During induction of anesthesia,

A. The stimulator should be applied prior to induction

B. The facial nerve is most useful for determining the time for intubation

C. Supramaximal stimulation should be determined after induction but before the administration of relaxant

D. To determine optimal time of intubation, a nerve should be stimulated at 1 Hz

View Answer

18. The PTC

A. Is the number of responses after application of a tetanic stimulus of 50 Hz for 3 seconds

B. Is painful for the patient

C. Is directly proportional to the degree of neuromuscular block present

D. Is useful for assessing deep NMB

View Answer

19. Needle electrodes

A. May be useful when the skin is cold

B. Are useful with hyperthyroid patients

C. Carry a risk of direct muscle stimulation

D. Should be inserted perpendicular to the nerve to be stimulated

View Answer

20. Clinical criteria useful to determine the adequacy of recovery from NMB include

A. A inspiratory force of at least -20 cm H_2O pressure

B. Sustained hand grip

C. Sustained head lift for 10 seconds

D. Adequate tidal volume

View Answer

21. Concerning recovery from NMB,

A. Monitoring the adductor pollicis is preferable to monitoring the orbicularis oculi

B. DBS is less sensitive than TOF monitoring

C. Recovery is faster in the diaphragm than in adductor pollicis

D. Adequate clinical recovery has occurred when the TOFR is above 0.7

View Answer

22. Concerning DBS,

A. It consists of two bursts of 100 Hz tetanus

B. The two bursts are separated by 750 ms

C. Is not useful in monitoring profound NMB

D. The DBS ratio has similar properties to the TOFR

View Answer

Chapter 26
Alarm Devices

The purposes of an alarm are to transfer information, enhance vigilance, and warn of a potential or actual abnormal or unusual condition (1,2,3,4). It is essential that there be a means of alerting personnel to a change or potential change in equipment function or the patient, for there will always be occasions when operator vigilance will be lowered or attention reduced while performing other tasks.

The number of alarms in anesthetizing areas has increased greatly. To add further confusion, alarm sounds may come from sources other than from anesthesia apparatus, including electrosurgical equipment, lasers, hearing aids, and beepers (5,6,7). The Joint Commission on the Accreditation of Healthcare Organizations has made it a goal to improve the effectiveness of alarm systems (8,9).

Standards

An international standard for alarm systems was published in 2003 (10).

Terminology (10)

1. *Alarm Condition Delay*: Time from the occurrence of a triggering event to when the alarm system determines that an alarm condition exists.
2. *Alarm Signal Generation Delay*: Time from the onset of an alarm condition to the generation of its alarm signals.
3. *Alarm Limit*: Threshold used by an alarm system to determine an alarm condition.
4. *Alarm Off*: State of indefinite duration in which an alarm system or part of an alarm system does not generate alarm signals.
5. *Alarm Paused*: State of limited duration in which the alarm system or part of the alarm system does not generate

alarm signals.

6. *Alarm Preset*: Set of stored configuration parameters, including selection of algorithms and initial values for use.
7. *Alarm Reset*: Operator action that causes the cessation of an alarm signal for which no associated alarm condition currently exists.
8. *Alarm Settings*: Alarm system configuration, including but not limited to alarm limits, the characteristics of any alarm signal inactivation states, and the values of variables or parameters that determine the function of the alarm system.
9. *Alarm Signal*: Signal generated by the alarm system to indicate the presence of an alarm condition.
10. *Alarm System*: Parts of medical electrical equipment that detect alarm conditions and, as appropriate, generate alarm signals.
11. *Audio Off*: State of indefinite duration in which the alarm system or part of the alarm system does not generate an auditory alarm signal.
12. *Audio Paused*: State of limited duration in which the alarm system or part of the alarm system does not generate an auditory alarm signal.
13. *Default Alarm Preset*: Alarm preset that can be activated by the alarm system without operator action.
14. *False-negative Alarm Condition*: Absence of an alarm condition when a valid triggering event has occurred.

15. *False-positive Alarm Condition*: Presence of an alarm condition when no valid triggering event has occurred.
16. *High Priority*: Indicates that immediate operator response is required.
17. *Information Signal*: Any signal that is not an alarm signal or a reminder signal. Examples include the tone of the pulse oximeter or electrocardiograph, the waveform of the electrocardiograph, and the heart rate numeric.
18. *Intelligent Alarm System*: Alarm system that makes logical

decisions based on monitored information without operator intervention. Intelligent alarm system methodologies include analysis of trends, limit comparisons, data redundancy, data fusion, rules, fuzzy logic controllers, and neural networks.

19. *Latching Alarm Signal*: Alarm signal that continues to be generated after its triggering event no longer exists until stopped by deliberate operator action.
20. *Low Priority*: Indicates that operator awareness is required.
21. *Medium Priority*: Indicates that prompt operator response is required.
22. *Reminder Signal*: Periodic signal that reminds the operator that the alarm system is in an alarm signal inactivation state.

Inhibit, *silence*, and *suspend* have been used in past terminology for alarms. Unfortunately, different meanings were attributed to these terms. For this reason, these terms will not be used.

Alarm Prioritization

All alarms are not equally important. The information that an alarm conveys may represent an emergency, the potential for an emergency, or just an unusual condition. Prioritized alarms help to differentiate life-threatening situations from those that are less urgent. Alarm conditions priorities are shown in Table 26.1. It may be possible to increase the priority of an alarm, but the priority cannot be decreased.

A high-priority alarm indicates a condition that requires immediate action. Examples include asystole, ventricular fibrillation, cardiac support device (intra-aortic balloon pump, cardiopulmonary bypass machine) failure, high airway pressure, extreme hypoxemia, and sustained high-energy radiation beam.

Medium priority implies a potentially dangerous situation that requires a prompt response. Examples include many cardiac arrhythmias, high or low blood pressure, apnea (unless prolonged or associated with extreme hypoxia), mild hypoxemia, and high or low partial pressure of carbon dioxide (pCO_2).

A low priority alarm indicates that only operator awareness is

required. Examples include failure of an infusion pump for maintenance intravenous fluids and failure of an enteral feeding pump.

The object of prioritization is to minimize distraction from less important alarms during an emergency. It has been suggested that only the alarm sound corresponding to the most urgent of the prevailing alarm conditions should be annunciated; all other sounds should be temporarily audio paused (2). Once the most urgent alarm condition is resolved, the sound corresponding to the

next highest priority condition would then be initiated. This priority interlock should be limited to audible annunciation; lower priority visual signals need not be suppressed because they are relatively unobtrusive.

TABLE 26.1 Alarm Condition Priorities

Potential Result of Failure to Response to the Cause of Alarm Condition	***Onset of Potential Harm[a]***		
	Immediate[b]	***Prompt[c]***	***Delayed[d]***
Death or irreversible injury	HIGH PRIORITY	HIGH PRIORITY	MEDIUM PRIORITY
Reversible injury	HIGH PRIORITY	MEDIUM PRIORITY	LOW PRIORITY
Minor injury or discomfort	MEDIUM PRIORITY	LOW PRIORITY	LOW PRIORITY or no alarm signal

An information signal may be used to indicate the potential for delayed minor injury or discomfort

[a]Onset of potential harm refers to when an injury

occurs and not to when it is manifested.

[b]Having the potential for the event to developed within a period of time not usually sufficient for manual corrective action.

[c]Having the potential for the event to develop within a period of time that is usually sufficient for manual corrective action.

[d]Having the potential for the event to develop within an unspecified time that is greater than that given under ‘prompt.’

From International Standards Organization. Medical electrical equipment’-Part 1’8: general requirements for safety. Collateral standard: general requirements, tests and guidelines for alarm systems in medical electrical equipment and in medical electrical systems (ISO-IEC 60601-1-8). Geneva, Switzerland: Author, 2003.

Audible Signals

The primary purpose of auditory alarm signals is to get the operator's attention. In addition, they should help the operator to identify the onset of alarm conditions, the urgency of the required operator response and the location of the device generating alarm signals.

An audible signal will attract attention faster and more reliably than one that is visual (11). Ideally, it should do this in a timely, non-startling, and non-irritating fashion (12). Unfortunately, the qualities that cause sounds to attract attention also tend to make them intrusive or startling. Some are so unpleasant that the response may be to inappropriately disable or deactivate the alarm system.

There are a number of available options in alarm sound technology, including variations in pattern, pitch, tone, frequency, and loudness. The international alarm standard specifies the characteristics of auditory alarm signals (10).

One problem associated with alarm sounds is that clinicians may not hear them. Background noise and other alarms can interfere with hearing an audible alarm signal (13). If an audible signal is allowed to continue to sound, other audible signals may not be noticed (14,15). An anesthesia provider with a hearing deficit

may have difficulty determining the source of a sound. One study found that many anesthesiologists have an abnormal audiogram and that 7% had one or more alarm intensities below the detectability threshold (16). Audible alarms should be adjusted so that the signal will be perceived despite background noise.

Once an audible signal has been perceived, the next step is to identify its origin. This is important because many monitors are not in the clinician's immediate field of view, and the operator cannot always turn around to view them. Many anesthesia providers have trouble identifying audible alarms (13,17,18,19). Inability to identify an alarm may delay or prevent the appropriate remedial action (15,20).

After an audible signal has succeeded in capturing attention, audio pausing (muting, silencing) will provide time to correct the situation. The continuous presence of an audible signal can degrade task performance and impair detection of new alarm conditions and the ability to distinguish between existing and new alarm conditions. The visual component of the alarm indicator and associated functions should stay activated until the condition that triggered the alarm is corrected. If another alarm condition occurs while an alarm is audio paused, the additional alarm should have both audible and visual indications.

Most manufacturers provide a means of audio pausing. The time varies with the instrument and can sometimes be varied. Some monitors indicate elapsed time. The alarm standard requires that there be a visual indication that any alarm signal has been inactivated (10).

Some alarms can be turned to AUDIO OFF (defeated, disabled) for an unlimited time. The volume of some alarms can be decreased to a point where the audible signal cannot be heard (21). Using AUDIO OFF or low volume is dangerous, as either can lead to a false-negative alarm.

Visual Signals

Visual signals help the operator locate the equipment where response or awareness is needed and identify the specific alarm condition. Their principal drawback is that they can go unrecognized for a much longer time than audible signals (22). In a situation where the individual responsible for reacting to an alarm is required to use his or her vision for other tasks, a visual

message may go unnoticed. It may not be possible for the individual to turn and look at the source of the alarm (e.g., during laryngoscopy). Graphical symbols for alarm systems from the international standard are shown in Figure 26.1 (10).

Table 26.2 shows the color and flashing requirements for alarm indicator lights or graphical simulation of indicator lights in the international standard (10). The alarm standard also requires that the presence of an alarm condition and its priority be correctly perceived from a distance of 4 m and be legible from at least 1 m from the operator's position.

Alarm Organization

Alarm messages sometimes arrive in an unorganized pattern. The single, integrated display is designed to aid alarm identification. Thus, anesthesia personnel need to look in only one place to identify problems.

P.831

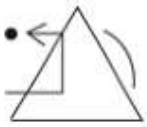
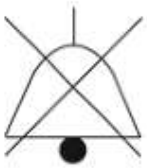
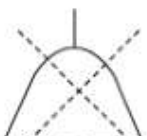
P.832

A disadvantage of this is that a crowded display may be difficult to read during a crisis. It may not be possible to integrate all monitors into a single display.

TABLE 26.2 Characteristics of Alarm Indicator Lights

Alarm Category	*Indicator Color*	*Flashing Frequency*
HIGH PRIORITY	Red	1.4 Hz to 2.8 Hz
MEDIUM PRIORITY	Yellow	0.4 Hz to 0.8 Hz
LOW PRIORITY	Cyan or yellow	Constant

Graphic	Description
	ALARM CONDITION

	ALARM CONDITION *Note 1:* The alarm condition may be indicated inside, beside, or below the triangle. *Note 2:* If there is a need to classify alarm conditions according to priority, this may be indicated by adding one, two, or three optional elements (e.g.,! for low priority,!! for medium priority, and !!! for high priority).
	ALARM RESET *Note:* The alarm condition may be indicated inside, beside, or below the triangle.
	ALARM OFF This is to identify the control for alarm OFF or to indicate that the alarm system is in the alarm OFF state. *Note 1:* The alarm condition may be indicated inside, beside, or below the triangle. *Note 2:* The symbol may also be used to identify equipment that has no alarm system.
	ALARM PAUSED This is to identify the control for alarm paused or to indicate that the alarm is in the alarm OFF state. *Note 1:* The alarm condition may be indicated inside, beside, or below the triangle. *Note 2:* A numerical time remaining counter may be placed above, below, or inside the triangle.
	AUDIO OFF This is to identify the control for audio OFF or to indicate that the alarm system is in the audio OFF state. *Note:* The alarm condition may be indicated inside, beside, or below the bell.
	AUDIO PAUSED This is to identify the control for audio paused or to indicate that the alarm system is in the audio paused state. *Note 1:* The alarm condition may be indicated inside,

beside, or below the bell.

Note 2: A numerical time remaining counter may be placed above, beside, or below the bell.

Figure 26.1 Graphic symbols for alarm systems. (From ISO IEC 60601-1-8, *Medical electrical equipment*—Part 1-8: general requirements for safety—collateral standard general requirements, tests and guidelines for alarm systems in medical electrical equipment and in medical electrical systems, 2003).

Alarm Limits

An alarm limit (set point, threshold value, threshold, setting) may be non-adjustable, operator-adjustable, or an algorithmically determined criterion (12). The alarm standard requires that if an operator-adjustable alarm limit is provided, the limit shall be indicated continuously or by operator action so that it can be determined if the set values are appropriate for the patient and procedure (10) (Figs. 26.2, 26.3).

Default alarm limits can be set by the manufacturer, the health care facility, or the operator. Those set by the manufacturer may be default values or may be bracketed around the value of a monitored variable at a point in time, recent values of a monitored variable, or a current control setting (10). Most monitors allow the operator to alter the default settings.

Realistic alarm limits need to be set. Wide limits result in fewer false alarms but increase the risk of missing a true alarm (good specificity but poor sensitivity) (12). With pressure and volume alarms during artificial ventilation, a low setting may result in a partial disconnection or small leak being missed. Constrictions in the breathing system that increase resistance can cause the airway pressure to remain above a low alarm set point although a total disconnection would probably not be missed (23).

Ensuring that an alarm is activated before a dangerous condition has occurred without creating frequent spurious alarms requires intelligence on the part of both the alarm system and the operator. Some operators set limits to extremes unlikely to be encountered clinically. The farther thresholds are from normal values, the greater the probability that a dangerous condition will

occur without activating the alarm. Others simply use the limits set by the last person who used the device. Others keep the thresholds close to the manufacturer-preset limits.

It is good practice to record alarm limits on the anesthesia record. This provides evidence that the alarms were activated. It may also increase the operator's awareness of the alarms and/or make it more likely that appropriate values will be used. It is possible that the set alarm limits may be recorded in the electronic record.

False Alarms

Actual alarm malfunctions are rare (24,25). The anesthesia provider can reduce the number of false-positive and false-negative alarms by carefully preparing the patient interface, securely attaching probes, selecting monitors with artifact rejection capabilities, using wider limits, increasing the alarm signal generation delay, and tailoring the alarms to the patient or operation (25,26,27,28,29). Positioning the pulse oximeter probe away from electrosurgery

wires may also help, as may locating the electrosurgery grounding pad far away from the pulse oximeter probe and electrocardiogram electrodes (30).

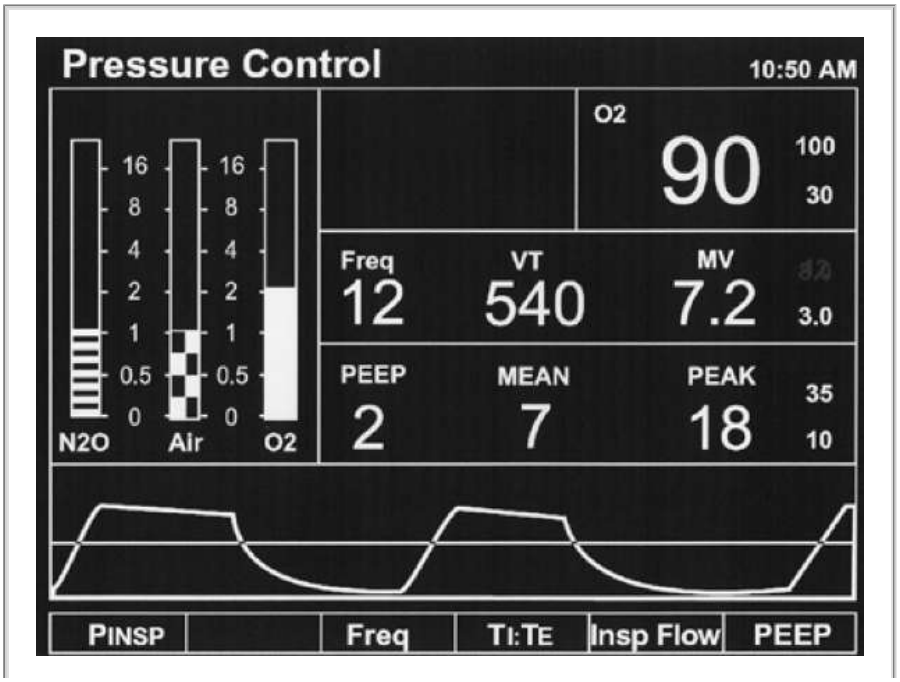


Figure 26.2 Alarms limits are displayed continuously to the right of the values for the parameters. (Picture courtesy of Draeger Medical, Inc.)

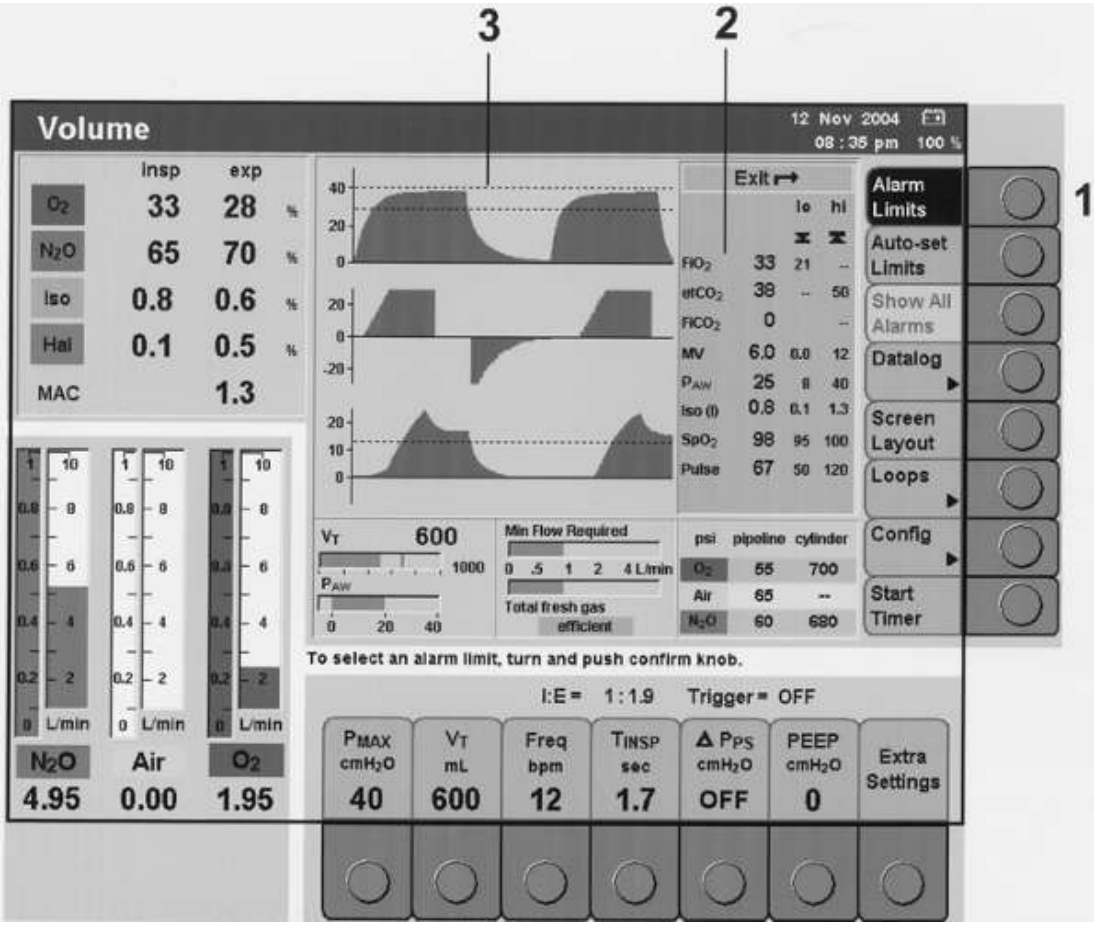


Figure 26.3 The complete set of alarm values is displayed. To display the alarm limits menu, the alarm limits soft key *(1)* is pressed. The menu *(2)* lists the parameters, their current measured values (larger numbers), and the current low and high alarm limits. The alarm limits also appear on the curves as *dashed lines (*3*)*. (Picture courtesy of Draeger Medical, Inc.)

False-positive Alarms

Many alarms are spurious. Only a small number indicate actual risk (31,32,33,34,35,36,37,38,39,40).

An alarm activated without proper cause requires time and effort to check the actual conditions. This will result in less attention to other tasks and may lead to an inappropriate action. False-positive alarms are a source of irritation and distraction and are a threat to patient care, because the anesthesia provider becomes increasingly likely to ignore the signals, lower the alarm volume, turn OFF the entire alarm system, use the AUDIO OFF or AUDIO PAUSE without looking for the cause, or set the alarm limits at such extremes that the alarm system is effectively disabled (12,41,42,43,44,45). False-positive alarms may frighten patients and relatives.

False-positive alarms are a fact of life. While there are strategies for minimizing them, they cannot be entirely eliminated.

False-positive alarms may be caused by alarm malfunction, artifacts, extraneous sounds being mistaken for alarm signals, and inappropriate set points.

The start-up sequence on equipment can prevent false-positive alarms. Medical equipment that automatically enables the alarm system when a patient is connected to the equipment when a valid physiologic signal is first detected, or through an ‚€admit new patient‚€ function activated by the operator will decrease the number of such alarms.

False alarms may be reduced by changing alarm limits at certain times, since clinical ranges vary during different phases of anesthesia (46). For example, the high heart rate alarm limit might be set higher during intubation than during maintenance.

The ALARM PAUSED state can be used to avoid nuisance alarm signals before performing an action that is likely to cause an alarm condition (10,38). Examples of such actions are intentional breathing system disconnection to perform airway suctioning, opening a transducer to air for zero calibration, intubation, and trying to restore spontaneous breathing at the end of a case.

Monitors with artifact rejection such as pulse oximeters with motion-resistant algorithms can decrease the

number of false-positive alarms (47,48,49,50). Filtering in the

algorithm that is monitoring for an alarm condition often causes alarm condition delay (10). For instance, a heart rate monitor can average the R-R interval for several heartbeats. An abrupt change in R-R intervals will not immediately cause an alarm condition, because it will take several consecutive heartbeats for the calculated heart rate to exceed the alarm limit. Some electrocardiogram monitors have automatic lead switching so that monitoring can continue even if one or two electrodes come OFF. This can decrease false-positive alarms.

False alarms can be reduced by integrating monitors (38,51). An example is synchronizing the pulse oximeter and noninvasive blood pressure monitor. If the oximeter probe is on the same arm as the blood pressure cuff, no alarm will sound if no pulse is detected when the cuff is inflated. Another example is the pulse oximeter and electrocardiogram (ECG). SpO_2 values are rejected unless the pulse rate measured on the oximeter matches that on the ECG.

False-negative Alarms

If an alarm system fails to generate a signal when it should (false negative), the patient's safety may be threatened. An alarm condition may be rejected or missed because of spurious information produced by the patient, the patient-equipment interface, other equipment, or the equipment itself.

Another cause is the alarm being turned OFF. Subsequent users may not be aware that it has been turned OFF. Automatic enabling is present on many newer monitors. Once a monitored parameter is sensed, the alarm becomes active. This eliminates the problem of forgetting to turn an alarm ON or not being aware that an alarm has been turned OFF by a previous user. Appropriate application of reminder signals should reduce the chance that the alarm system is unintentionally left in an alarm signal inactivation state (10).

Speaker failure, setting the audible volume too low, and setting the alarm limits too widely may also cause false-negative alarms (52).

False-negative alarms may be reduced by not setting the limits too widely, using the AUDIO PAUSE rather than the AUDIO OFF state, and checking alarm systems at regular intervals to detect

problems such as a faulty loudspeaker or low audible volume that can result in an audible signal not being heard.

Intelligent Alarm Systems

An intelligent (smart, expert) alarm system may do one or more of the following without operator intervention: determine an alarm condition on the basis of time, weightings, multiple variables, or other advanced processing; generate alarm signals for two or more alarm conditions of equal priority; change the previously assigned priority or relative prioritization of a particular alarm condition; change the alarm signal generation delay or alarm condition delay; change the characteristics of the generated alarm signals (e.g., to indicate a change in urgency); provide the operator with a list of conditions that could have triggered the alarm(s); and present information that is helpful in dealing with the condition that triggered the alarm (36,46,53,54,55,56,57,58,59,60).

Smart alarms can reduce the number of false alarms by discriminating between artifacts and truly threatening conditions. Human response times are longer and have greater variability with conventional alarms than intelligent alarms (61).

Alarm Condition Logging

Many modern monitors and life-supporting equipment are equipped with alarm condition logging. Logging can be used to determine the cause of a transient alarm condition, for quality assurance purposes, to study critical incidents, and to determine when an alarm condition occurred. The log should include the value of the variable that caused the alarm condition, the alarm limits, and the alarm status (ON, Audio Paused, Paused, Audio Off, etc). This information can then be made available if a problem occurs.

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Questions

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

1. Purposes of an alarm include

A. Warning of a potential or actual abnormal or unusual condition

B. Getting attention

C. Transferring information

D. Transferring legal responsibility from the manufacturer to the user

View Answer

2. Problems associated with determining the source of an alarm include

A. The hearing of the anesthesia provider

B. Difficulty in recognizing tone patterns

C. Noise levels in the operating room

D. Audible signals that do not sound continuously

View Answer

3. Visual signals

A. Give less specific information than audible signals

B. May go unrecognized for a longer period of time than audible signals

C. Use continuous lights for more crucial information

D. Require the anesthesia provider to be looking at the monitor instead of the patient

View Answer

4. Causes of false-positive alarms include

A. Activation by an inappropriate device

B. Extraneous sounds that sound like an alarm signal

C. Alarm malfunction

D. Widely set limits

View Answer

5. Means to reduce the incidence of the false-positive alarms include

A. Altering alarm limits during the procedure

B. Synchronizing monitors

C. Delaying the time between detection of an alarm condition and alarm activation

D. Decreasing the averaging time

View Answer

6. Concerning alarm prioritization, which of the following are true?

A. Low-priority visual signals need not be suppressed

B. With multiple alarm conditions, all alarms will be annunciated

C. All alarms are not equally important

D. Alarm priorities may be increased or decreased.

View Answer

7. The purpose(s) of alarm signals include(s)

A. Gaining attention

B. Notifying the operator of the alarm urgency

C. Identifying the onset of an alarm condition

D. Identifying the device that provides the alarm

View Answer

8. The characteristics of a false-negative alarm include

A. Automatic enabling

B. The alarm may be turned OFF

C. Narrow alarm limit range

D. Failure to generate a signal when there is a threat to patient safety

View Answer

9. Which are some of the functions that a smart alarm may perform?

A. Determining the alarm condition on the basis of multiple variables

B. Changing the alarm signal generation delay

C. Presenting a list of conditions that may have generated the alarm

D. Changing the alarm priority

View Answer

10. Alarm condition logging

A. Should include the value of the variable that caused the alarm condition

B. Can help to determine the cause of transient alarm conditions

C. Is useful for quality assurance

D. Can determine when an alarm condition occurred

View Answer

Chapter 27

Noninvasive Blood Pressure Monitors

Introduction

Frequent blood pressure determinations during anesthesia aid drug titration and fluid management and provide warning of conditions that could affect patient safety (1,2). There are a number of devices that automatically measure blood pressure noninvasively (indirectly). The original automated devices were stand-alone monitors. Now, the majority of blood pressure monitors for operating room use are incorporated into a physiologic monitor or anesthesia workstation.

Intermittent Blood Pressure Monitors

Intermittent noninvasive measurement of blood pressure requires a distensible cuff or bladder enclosed in an unyielding cover. The cuff is inflated, and blood flow through the underlying artery is obstructed. The cuff is then deflated in a controlled manner, causing the pressure applied to the artery to decrease. Pulsations are detected, and the results are displayed or recorded as blood pressure. Most devices also display pulse rate.

Standards

An American standard on automated sphygmomanometers was published in 2002 (3). It states that blood

pressure measurements determined by the device must be equivalent to those obtained by a trained observer using the auscultatory method or by direct monitoring using an intra-

arterial catheter within the limits of the standard.

An international standard was published in 1999 (4). It limits the maximum cuff pressure obtainable during normal use to 300 mm Hg for equipment specified for adults and 150 mm Hg for equipment specified for neonates. In addition, means must be present to prevent the cuff from remaining inflated for long periods of time.

Operating Principles

The majority of automated noninvasive monitors employ oscillometry (5,6). The cuff is inflated above the point where pressure oscillations are present. As the cuff is deflated, pressure pulsations (oscillations) caused by movement of the arterial wall are transmitted to the cuff. The magnitude of these oscillations increases to a maximum, then decreases (Fig. 27.1). The monitor measures these oscillations. After the determination is complete, the remaining air in the cuff is rapidly exhausted.

During the first cycle, the cuff is inflated to a predetermined pressure that is held constant while the monitor tries to detect oscillations. If significant pulsations are still present, the cuff is inflated further. When first turned ON, most automatic blood pressure monitors stop inflation at 160 torr or less (7). On pediatric units, a lower pressure is used. If the initial cuff pressure is greater than necessary to determine systolic pressure, the monitor may decrease this pressure during the next cycle. If the initial pressure is too low, the monitor will increase it during the next cycle. When no oscillations are detected, the pressure in the cuff is decreased in a stepwise or linear manner (Fig. 27.1).

Noninvasive blood pressure (NIBP) monitors rely on measurement, extrapolations. and clinically tested algorithms to arrive at values for mean, systolic, and diastolic pressures (6,7,8). The point of maximum amplitude corresponds to the mean pressure (5,9,10,11). Systolic and diastolic blood

pressures are then calculated from the increasing and decreasing magnitude of the oscillations according to an empirically derived algorithm. These algorithms are proprietary and vary from manufacturer to manufacturer and sometimes from device to device (10). Consequently, different devices do not always yield the same pressures (12).

With oscillometry, accurate bladder placement is not necessary, and the risk that the cuff bladder will become dislodged is minimal. These monitors do not require a low-noise environment, are not sensitive to electrosurgical interference, and work well when there is peripheral vasoconstriction. Venous engorgement has little effect on accuracy (7). These monitors can reject most artifacts caused by patient movement or external interference, based on analysis of the shape of the oscillometric pulse waveform and the timing of the oscillometric pulses (5).

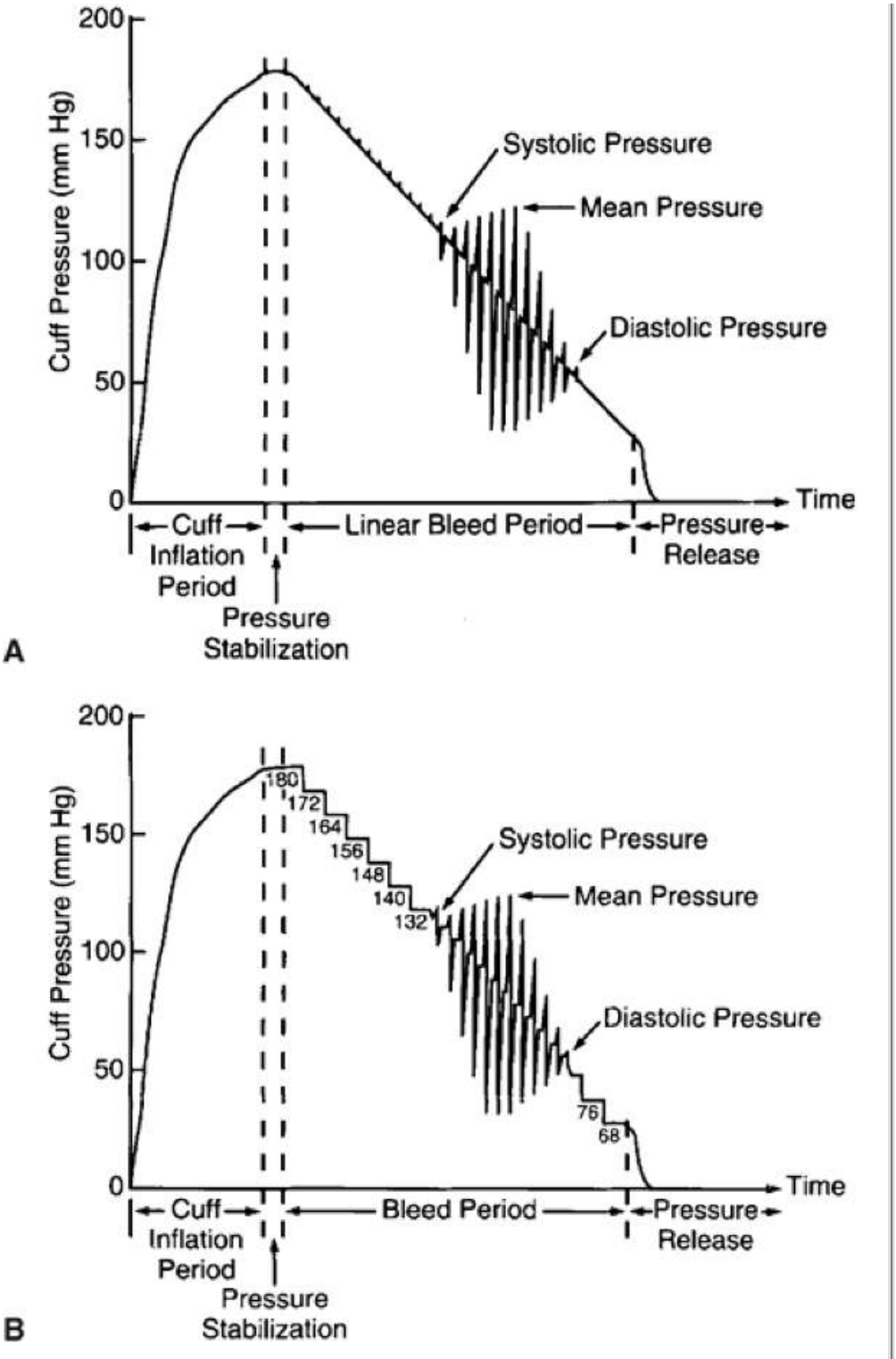

Figure 27.1 A, B: Sequence of oscillometric blood

pressure determination. Cuff deflation may be linear **(A)** or in steps **(B)**. Pressure oscillations increase in magnitude, then decrease. The oscillations are analyzed to determine systolic, mean, and diastolic pressures. (Reprinted with permission from Nellcor Puritan Bennett, Pleasanton, CA.)

Equipment

These monitors use electricity, either line or battery, as the power source. Many units are equipped with a connection for a printer or data management system. Some can display trends. Many manufacturers offer different models for different-size patients.

Inflatable Cuff

Cuffs come in different sizes. Disposable and latex-free cuffs are available. Some have an antimicrobial agent

on the cuff fabric to help prevent bacterial growth and mildew. Some cuffs are color coded by size. The international standard requires that cuffs are marked with an indication of the limb circumference for which they are appropriate (4).

Pressure Tubing(s)

One or two tubings serve as a means to inflate the cuff and sense the pressure within the cuff. A Y-piece near the cuff can be used to mix single- and two-hose systems (13). Blood pressure tubings should not have Luer connections, because these may allow a pressure tube to be connected to another device such as an intravenous line (14).

Cuff Inflation and Deflation Mechanism

The cuff inflation mechanism consists of a pump and a reservoir

that holds a quantity of air that can be quickly released into the cuff. A bleed valve deflates the cuff. The speed and manner of deflation vary from manufacturer to manufacturer. Some adjust the rate as a function of pressure.

Sensing Mechanism

A pressure transducer detects the pressure in the cuff and transduces it into an electrical current that can be measured. The pressure-sensing mechanism is built into the cuff in most monitors. An autozero valve that periodically opens the transducer to atmosphere, automatically establishing zero pressure, may be present (7).

Timing Circuitry

The timing circuitry regulates the frequency of blood pressure determinations. Most instruments also allow manual cycling. Most offer a short-term automatic (STAT) mode that allows a number of determinations to be made in quick succession.

Control Circuitry

The control circuitry determines such parameters as the maximum pressure in the cuff, artifact rejection, electrosurgical interference suppression, deflation rate, and automatic cutoff. The overpressure switch may be set differently for adult and pediatric models. Some machines have automatic cuff deflation when the cycle time exceeds a predetermined limit.

Alarms

Monitors vary according to which parameter(s) will trigger an alarm. Some monitors automatically set alarms around the initial values. Some have default alarm limits that can be changed by the operator. Some monitors activate an alarm when they are unable to determine the blood pressure.

Accuracy

Factors Affecting Blood Pressure Determinations

Cuff/Arm Relationship

Accurate blood pressure measurement depends on the relationship between arm circumference and cuff width (10). Typically, a cuff that is too small for the patient's arm circumference will overestimate blood pressure, whereas a cuff that is too large will underestimate blood pressure (10,15,16). It is important that different sizes cuffs are readily available. If a sufficiently large cuff is not available, it may be possible to place a cuff more distally on the limb. Current recommendations are that a cuff's width should be approximately 40% to 50% of the circumference (125% to 150% of the diameter) of the limb on which it is used at the limb's midpoint (17,18,19). Cuff length has little effect as long as the bladder encircles at least 50% of the arm's circumference (17).

In the past, it was the practice in pediatric patients to use a cuff that was two thirds to three fourths of the upper arm length. This resulted in underestimation of blood pressure (20).

Another misleading criterion for determining proper cuff size is a label such as infant, child, pediatric, small adult, adult, and large adult. These terms are open to interpretation by the user and can lead to inappropriate cuff selection (20).

Site

The site where the cuff is placed will affect the measured pressure. As the site moves more peripherally, the systolic pressure tends to increase and diastolic pressure to decrease (21). Increased vascular tone may result in an increase in pulse pressure. Vascular disease and peripheral vasoconstriction may cause reduced pressures at distal locations.

The forearm or wrist may be used when the upper arm is inaccessible and/or a standard blood pressure cuff does not fit (22,23,24,25). The ankle may also be used (26,27). The mean and diastolic pressures measured at the ankle are comparable with those measured in the arm but the systolic pressure is higher. A poor correlation was found between blood pressures measures on the arm and calf of women who were undergoing cesarean section (28).

Arm Position

If the cuff and the patient's heart are not at the same level, a correction must be made. For each 10 cm of vertical height, 7.5 mm Hg (for every inch 1.80 mm Hg) above or below the heart level should be added to or subtracted from the pressures measured (21).

Arrhythmias

The oscillometric technique is vulnerable to error in patients with arrhythmias (29,30,31,32).

Improper Calibration and Maintenance

Studies performed with instruments in common use have shown problems with calibration, maintenance, and accuracy (10). Errors in the algorithm may occur (33,34).

Correlation with Other Methods of Blood Pressure Determination

Many feel that the standard of comparison should be the pressure measured directly in an artery, most commonly the radial. However, indirect pressure readings will never exactly match invasive pressures. One reason is that simultaneous measurements often cannot be made. Another reason is that direct and indirect monitors measure different physical

properties. The direct method measures both the systolic and diastolic pressures and calculates the mean. Oscillometry measures the mean and calculates the systolic and diastolic pressures.

Many studies have compared pressures obtained with NIBP monitors with those obtained directly (16,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52). In general, correlation of directly measured blood pressures with indirectly measured blood pressures is best in normal healthy patients and least accurate at the extremes of blood pressure. Although errors can occur in either direction, oscillometric devices tend to overestimate low pressures and underestimate high pressures. The STAT mode does not denigrate values and is subject to the same variations as measurements taken under normal circumstances (53).

Most studies have concluded that an NIBP monitor is not sufficiently accurate if vasoactive drugs are being administered or in critically ill patients although it may be useful for trending purposes. Another problem is that with moderate to severe hypotension, the automated machine often cycles repeatedly before indicating a failure to measure (2).

Proper Use

If possible, the cuff should not be applied to the limb in which an intravenous infusion is placed because infusion of fluids and drugs will be slowed or blocked and the increased pressure may cause blood to flow retrograde into the infusion set tubing or extravasation (7). Check valves in the intravenous tubing between the fluid bag and the patient usually prevent backflow into the tubing. A simple method to avoid, or at least reduce, this problem is to route the infusion tubing under or through the blood pressure cuff (54). Other means to prevent this problem have been suggested (55,56,57). In some cases, it may be possible to place the cuff distal to the infusion site.

If used on the arm, the cuff should be placed as high as possible, and the inflation tubes should exit proximally (58,59). If the upper arm is very large or conically shaped, it may be better to measure blood pressure at another location such as the ankle, thigh, or forearm. The cuff should not be applied over a superficial nerve, bony prominence, or joint.

Padding should be placed around the skin under the cuff to prevent skin creasing, petechiae, blistering, nerve damage, and problems from residual cleaning materials (60).

Prior to applying the cuff, all residual air should be expelled. The cuff should be applied snugly enough to allow only one finger to be slipped under it. Too tight a cuff may cause discomfort and venous distention. Too loose a cuff may cause falsely elevated readings and may prevent the monitor from determining the blood pressure. The cuff should be placed and several inflations made while the patient is awake to elicit complaints. Nothing should be allowed to press against the cuff during measurements.

Blood pressure measurements should be made no more frequently than clinically necessary. In one study, it was shown that except when rapid changes in blood pressure are anticipated, a one- or two-minute cycle time offers no advantage over a five-minute cycle time, but the shorter time may increase the complication rate (61).

The cuff site and extremity should be inspected periodically during prolonged applications. It is good practice is to occasionally switch the cuff to another site, if possible.

Complications

Damage to Underlying Tissues

Petechiae, erythema, edema, thrombophlebitis, and skin avulsion at the cuff site have been reported (62,63,64,65,66,67,68,69). Predisposing factors to the development of petechial

hemorrhages include patients taking anti-inflammatory drugs, steroids, or anticoagulants and patients with thin or redundant skin (70). Petechia often occur under folds in the cuff. Wrapping the space under the cuff with cotton may avoid these problems.

Neuropathies

Neuropathies of the median, ulnar, and radial nerves have been reported following use of an automatic NIBP monitor (58,59,69,71,72). All resolved spontaneously. Locating the cuff close to the axilla and away from the elbow will help to prevent radial nerve injury. Excessive movement makes it difficult for the device to determine pressures, so it will cycle more often, possibly to higher pressures. This can contribute to nerve injuries.

Compartment Syndrome

Cases of compartment syndrome associated with prolonged use have been reported (73,74,75). In one case, the patient had hyperactivity and tremor. In another case,

the blood pressure was labile, causing the monitor to cycle longer and with higher pressures than usual. In a third case, the cuff was applied across the antecubital fossa.

Mechanical Problems

Failure of an NIBP monitor is not uncommon and may be associated with serious morbidity or mortality (2,76). A common problem is a leaking cuff, hose, or connector (7,76,77).

Artifacts

Oscillometric devices are sensitive to both intrinsic and extrinsic motions (79). Intrinsic motion artifacts are caused by movements such as deliberate patient motion, shivering, tremors, convulsions, restlessness, or vigorous skin preparation (79,80).

Extrinsic motion artifacts are caused by actions that compress the cuff, such as bumping by personnel or equipment (7) or massaging the arm where the blood pressure cuff is located (81). Synchronization with the electrocardiogram can reduce artifacts (82).

Blood pressure readings were reported in a patient where the cuff was under the patient's head (83). It is surmised that head movements caused enough motion in the cuff to produce the artifactual readings. In another case, a cuff became unfastened, but the bladder remained between the arm and the thorax (84). It was still able to detect oscillations and displayed a fictitious pressure.

Air Embolism

If the line used to inflate the cuff is connected to an intravenous line, a serious air embolus can result (85).

Advantages

Automaticity

A major advantage of NIBP devices is that they can determine pressures regularly and frequently on an automatic basis. During busy times, this is very helpful, saving time and allowing clinicians to perform other tasks.

Automatic devices eliminate most of the factors that cause errors when blood pressures are determined manually, such as variable concentration, reaction times, hearing acuity, ambient noise, confusion of auditory and visual cues, variable deflation rates, background noise, variable interpretation of sounds, preference for certain digits, and bias due to knowledge of previous readings. They may eliminate some of the mistrust that some individuals have when others measure the blood pressure manually.

Simplicity

Automatic NIBP monitors are simple to use. They do not require extensive training to set up or maintain.

Noninvasiveness

In comparison with direct measurements, NIBP monitors are less expensive, simpler, and avoid the risks (ischemic damage, emboli) associated with direct techniques.

Reliability

NIBP monitors are reliable devices that generally do not require a lot of maintenance or experience a lot of downtime.

Usefulness

Some NIBP devices will work in certain patients (such as those with obesity or sclerosis and infants), in whom an accurate pressure cannot be obtained manually. They will read accurately through bulky dressings (86). Pulse rates between 40 and 200 beats per minute usually do not hinder readings (78).

Versatility

Oscillometric blood pressure measurements can be made on a variety of sites.

Monitor Integration

NIBP monitors can be integrated with other monitors. This integration may allow the number of false alarms to be reduced. For example, it may be possible to set the pulse oximeter so that it does not alarm for a certain period of time after the NIBP cuff is inflated.

Disadvantages

Unsuitable Situations

While non-continuous blood pressure monitoring is helpful in establishing trends, it is unsuitable for detecting rapid changes in blood pressure (87). If rapid changes are anticipated, a continuous method should be used.

Patient Discomfort

Patient discomfort is often associated with a prolonged cycle time. Cycle time will be prolonged with a large cuff, hypertensive patients, poor peripheral circulation, a leak in the monitor, low blood pressure, dysrhythmias, or motion artifacts.

Clinical Limitations

Automated blood pressure devices do not work well with extreme heart rates and pressures. In extreme conditions, even mean pressure may not be measurable.

Studies involving ambulance and helicopter transport have shown that these monitors are not as reliable as needed (88,89,90).

Noncontinuous Measurements

After a blood pressure measurement has been made, the value is usually displayed until the next measurement.

Most monitors give some indication of the age of the displayed value. Some clinicians do not set the blood pressure monitor to automatic until after induction is complete. On occasion, there is a prolonged period until the automatic mode is used (91,92). During this time, the original blood pressure will be displayed.

Continuous Noninvasive Blood Pressure Instruments

Continuous or near-continuous blood pressure monitoring is desirable in patients with cardiac or cerebrovascular disease, in

critically ill patients, and in surgical procedures in which periods of hemodynamic instability are anticipated.

Vasotrac

The Vasotrac consists of a wrist module and a monitor/display connected by a cable (93). The sensor is placed over the radial artery at the wrist. A pressure-sensing mechanism applies variable pressure directly above the artery. The counterpressure in the artery produces a pressure waveform. Analysis of the waveform is used to calculate the systolic, diastolic, and mean arterial pressures. Blood pressure measurements, pulse rate, and an arterial waveform display are updated several times a minute and displayed on a monitor. It is available in a handheld version.

When the Vasotrac was compared with direct arterial pressure, good correlation was found (93,94,95,96,97,98). It was found to be accurate when deliberate hypotension was used (98,99). However, in liver transplantation patients, the Vasotrac was not sufficiently accurate to substitute for direct arterial blood pressure monitoring (100).

Blood pressure can be detected down to 40 mm Hg and up to 240 mm Hg. It is accurate with arrhythmias. The Vasotrac system is susceptible to patient arm movement, but the waveform can alert the caregiver to artifacts.

Although the Vasotrac does not provide continuous blood pressure measurement, it provides much more frequent measurements (3 to 4 times per minute) than the intermittent method. This may decrease the need for intra-arterial cannulation.

T-Line Tensymeter

The T-Line Tensymeter utilizes arterial tonometry, in which a peripheral artery is slightly compressed and the pulse wave is sensed by a transducer placed over it. It consists of three parts:

A disposable wrist splint, a disposable radial artery sensor, and a reusable bracelet. The patient's height and weight must be entered into the monitor.

First, the wrist restraint is applied. The radial pulse is palpated and marked. The sensor is aligned over the point of maximum pulsation. Then, the bracelet is connected over this. The device then automatically and continuously determines the point of maximum pulsation and exerts slight pressure on the artery. Once the optimum site is located, the system does a dynamic pressure search to determine the mean arterial pressure. The pulsation is converted into a displayed waveform, and systolic and diastolic blood pressures are computed by using the waveform, the patient's body mass index, and an algorithm. This provides continuous, beat-to-beat NIBP measurements.

This device requires less time to set up than invasive arterial catheter placement and avoids the risks associated with an invasive arterial catheter. One study found that the blood pressures agreed closely with simultaneous pressures measured invasively from a contralateral radial artery (101).

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Questions

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. is D is correct

E. if A, B, C, and D are correct.

1. During the measurement cycle to determine the blood pressure,

A. The point of maximum amplitude is considered the systolic pressure

B. Systolic and diastolic pressures may be estimated by identifying the region where amplitudes of oscillations increase and decrease rapidly

C. The diastolic pressure is the point where oscillations cease

D. Mean pressure is determined and the systolic and diastolic pressures are calculated

View Answer

2. Which statements regarding accuracy of noninvasive blood pressure monitors are correct?

A. Since most use oscillometric technology, there is close agreement between different instruments

B. Placement of the cuff over the artery is important

C. Patient movement causes a great deal of artifact to an oscillometric technique

D. The position of the cuff in relation to the heart is important

View Answer

3. Accuracy of the automatic blood pressure monitor may be affected by

A. Electrosurgical interference

B. Venous engorgement

C. Peripheral vasoconstriction

D. Cuff size

View Answer

4. Which factors characterize the relationship between the size of the cuff and the size of the arm?

A. Undersized cuffs give falsely low readings

B. The cuff width should be 125% to 150% of the diameter of the limb on which it is used

C. Oversized cuffs give falsely high readings

D. The cuff length has little effect on accuracy

View Answer

5. Factors that can affect the determination of blood pressure by the auscultatory method include

A. Rate of cuff deflation

B. Rate of cuff inflation

C. Hearing acuity

D. Standardized concept of systolic and diastolic end points

View Answer

6. Which techniques constitute proper cuff placement?

A. The cuff should be placed tightly on the limb

B. A loosely applied cuff will usually cause falsely elevated readings

C. The cuff should be kept on the same arm even during long procedures

D. The limb should be wrapped with padding where the cuff is to be placed

View Answer

7. Patients at risk for developing petechiae include

A. Those on anticoagulants

B. Those taking steroids

C. Those taking nonsteroidal anti-inflammatory drugs

D. Those with redundant skin

View Answer

8. Contributing causes of a compartment syndrome include

A. Prolonged use

B. Hyperactive patient

C. Low placement of the cuff

D. Stable blood pressures

View Answer

Chapter 28
Data Management Systems

Progress in monitoring instrumentation has largely outpaced methods used to record and manage the expanding body of clinical data (1). While many anesthesia departments continue to use the traditional method of recording information manually, electronic data management systems are gaining in popularity. The Anesthesia Patient Safety Foundation and the Society for Technology in Anesthesia have endorsed computerized anesthesia records (2,3,4).

Definitions

Anesthesia Information System (AIS or AIMS): A system that manages information throughout the perioperative period.

Applications: Computer programs, usually of a similar type.

Analog Data: Continuous data that can, within limits, assume any value. An analog computer cannot handle alphanumeric data (letters and numbers) but can process waveforms. Analog is the opposite of digital.

Artifact: Data that is not a true representation of a condition.

Automated Anesthesia Record Keeper (AARK): Device that collects, displays, and records intraoperative data from a variety of monitors and other sources.

Closed Architecture or System: Equipment designed to work only with accessories made by one company.

Database: A collection of data, often in storage for later access.

Data Management System: System that records data relating to the patient's care throughout the perioperative period and integrates with other medical data systems to gain or share data.

Decision Support: Any method that takes input information about a clinical situation and produces inferences that can assist practitioners in decision making.

Digital: A way of storing information using numbers. Digital is the opposite of analog.

Editing: The process of changing a recorded value, comment, annotation, or event after it has been made part of the record.

File: A collection of information in a format designed for computer use.

Fileserver (Server): The master computer into which all the other computers on a network are connected. The fileserver stores programs, processes and stores data in a database, and runs the network operating system.

Hardware: The physical parts of a computer. Examples include the printer, screen, keyboard, and electronic components.

Input Device: A means to manually enter data or control a computer. Examples include a keyboard, mouse, trackball, light pen, bar code scanner, touch screen, voice recognition device, and pen pad.

Interface: The common boundary between computers, between computers and their peripheral devices, or between two peripheral devices.

Local Area Network (LAN): A network that is limited to a local area such as a department. A LAN can be integrated into a larger network. Devices connected by a network are referred to as modules.

Macro: A tool used to automate tasks or procedures within a program. Examples are pretyped notes or check-off boxes.

Network: A group of computers connected together.

Open Architecture: The practice of making the design and computer engineering or programs public knowledge.

Operating System: Software that controls how a computer performs its functions.

Output Device: A device that presents information from a computer system to a user for viewing or storage. Examples include printers, screens, floppy disks, and tape drives.

Peripheral: A general term for any of the devices by which a computer gathers its input and disseminates its output.

Software: Programs that control the hardware and determine the functions performed by a computer.

Elements of the Data Management System

A typical anesthesia data management system is shown in Figure 28.1. The data management system consists of one or more central fileservers and a network connecting the components. Each computer receives data and sends it to the server. In a properly designed system, if an individual computer fails, it will not disable the entire system but will affect only those functions that the particular computer was performing.

A data management system may be closed or open. A closed system helps to ensure that all components work together and allows the institution to deal with a single vendor. A closed system may not work well with components from other manufacturers. Because of the great variety of sources used to capture data, closed systems are not frequently used.

In an open system, components from various vendors are used. This enables each department to choose the best devices for its needs while still allowing the information to be accessed by other systems. Institutions selecting an open system must make certain that new components will interface with their network.

A data management system may be centralized or distributed. If the data are copied into a central repository (server), the system is centralized. If the data resides at or near the point of care, the system is distributed. Even in the distributed system, a network connection is necessary to store the data after it has been collected. The distributed system may be more reliable than the centralized system because it offers redundancy (5). Expanding a distributed system is straightforward, as it usually requires simply adding another computer or peripheral device to the network and updating the system's software.

Fileserver

The fileserver processes and stores data and programs in a database and runs the network operating system. There may be one or more fileservers, depending on the size of the system.

Input Sources

Electronic Anesthesia Record

The electronic anesthesia record collects information from various sources, processes the data, presents selected values and trends on a screen (Fig. 28.2), and transports data to other parts of the system. It may perform additional functions such as integrating information and alarms. A choice of display configuration on the screen is usually available. The electronic anesthesia record computer and data screen may be mounted on

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the anesthesia machine, a cart, the floor, or the ceiling. Some are an integral part of the anesthesia workstation.

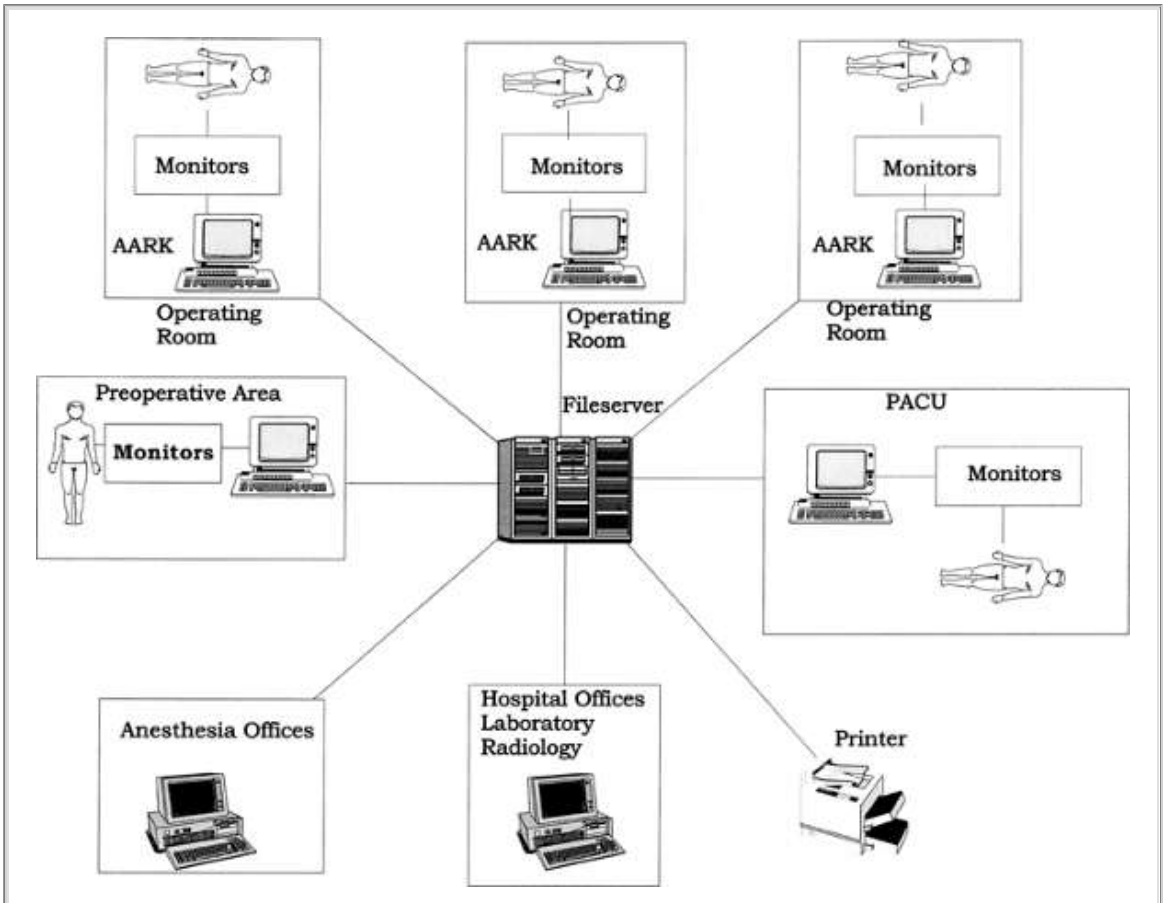

Figure 28.1 Typical anesthesia information management system. Workstations and peripheral devices are physically connected to each other and to the fileserver by wires or cables to form a LAN. Part of the network operating system resides in the fileserver and part at each user workstation. Applications software that runs the AARKs may reside in the

fileserver but are executed in the AARKs. An AARK can be located in other places beside the operating room. AARK, automated anesthesia record keeper; PACU, postanesthesia care unit.

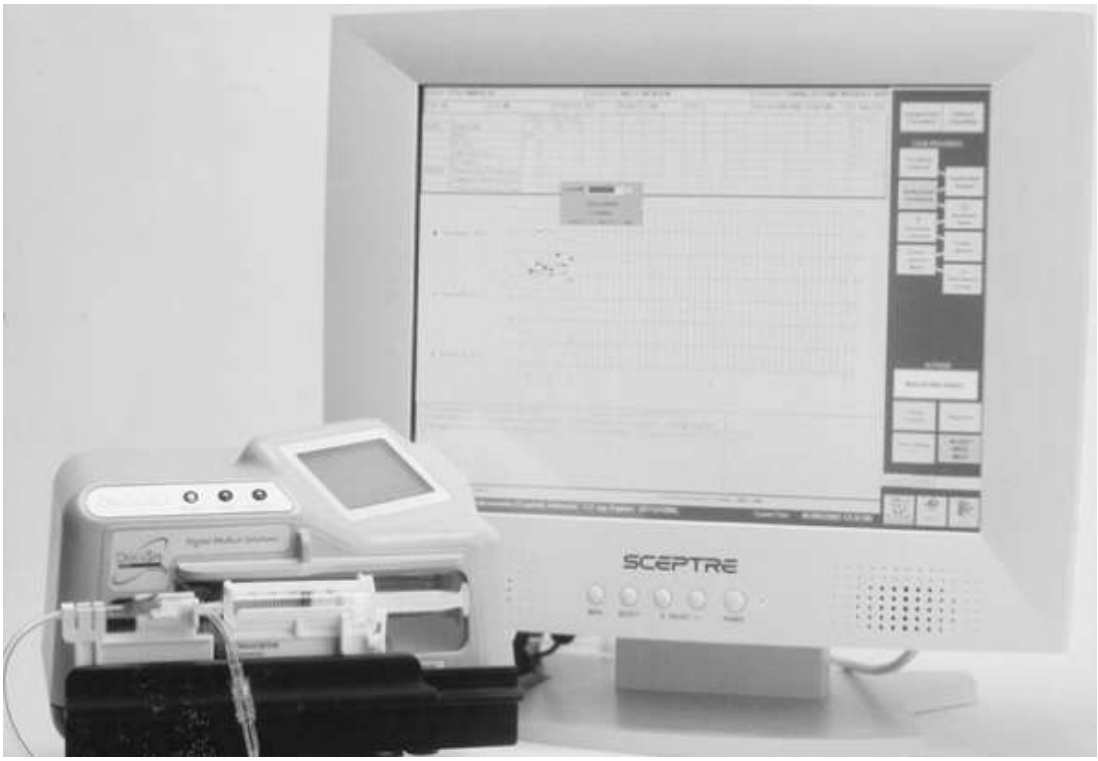

Figure 28.2 Electronic anesthesia record with device for reading the label on the syringe and plunger movement to record the amount of drug administered. (Picture courtesy of DocuSys, Inc.)

The electronic record must provide a means to enter data that cannot be transferred automatically (5,6,7,8,9). Handheld computers offer a convenient way to enter data at the bedside (10). All input devices must be easy to clean to avoid cross infection. A sealed, plastic-covered keyboard may be the most appropriate solution.

Manual entry should be as easy as possible. If it is difficult or takes a lot of time, the record will often be incomplete or incorrect. Macros that enter routine information or user

preferences into the record make data entry easier and reduce the information that must be entered manually.

Because it is not always possible to enter all information at the time it occurred, there needs to be a means to add it after the fact and to indicate when it took place. Available systems handle back dating differently. A common method is to allow the timing of an entry in the past with an indication of when the entry was made.

In order to properly identify the responsible clinician, there must be a way of ending a record with an electronic signature.

Inputs from Other Components of the Data Management System

Input from other computers or servers allows the electronic anesthesia record to acquire information from other areas of the facility and to integrate it into the data management system. Demographic information from the admitting department and pre- and postoperative data may be entered into the record. There may be connections to electronic libraries, the pharmacy, or the Internet.

Wireless technology is being used more frequently (11). Since radio frequency may interfere with medical devices such as infusion pumps or pacemakers, infrared is the most useful means of transmission (12). Wireless technology facilitates using small computers for collecting data (such as preoperative assessment) from sites away from the operating room. This data can subsequently be entered into the computer network (13). A wireless network is relatively inexpensive, easy to install, and easily expanded.

Printer

If a printed (hard) copy of the anesthesia record or other information that cannot be obtained from the computer network is desired, a device capable of printing both graphics and text will be needed. Frequently, the printing is performed in a location such as the postanesthesia care unit (PACU) or an office.

An important consideration is whether the printed record is generated as data becomes available or at the completion of the case, or both. If the record can only be printed at the end of the

case, data could be lost if the data management system malfunctions. Frequent back-up will limit the loss. With a real-time copy, the record can be removed from the printer and completed by hand if the automated system fails (14).

Records

Preanesthesia

The data management system has been found to be efficient and effective for preoperative evaluation (15,16,17). Patient-completed questionnaires can be performed electronically (18). This could be completed and submitted through the Internet from the patient's home (19) or from a physician's office. Based on this information, patients who do not present problems that require a preoperative visit can be separated from those with complicated medical histories. Preanesthesia consultation using telemedicine technology offers the chance to reduce travel costs and to identify patients with problems so that additional workup or consultations can be performed without delaying the surgery (20). This data can allow the clinician to determine which patients are at risk and require more testing and perhaps increased invasive monitoring (21,22). Patients who would benefit from antibiotic prophylaxis can be identified (23). With good preoperative data, an association between the preanesthesia evaluation and perioperative incidents can be evaluated.

Preoperative information can be obtained from the health care facility's or physician's office records. This is usually in the form of a history and physical or progress notes. In addition, laboratory results and radiology information should be available. While laboratory information may be accepted by the data management system, information that is in text style, such as the history and physical, may not lend itself to automatic capture by the data management system and may need to be entered into the system manually.

Intraoperative

Patient Variables

The bulk of entries during surgery are objective patient variables (blood pressure, heart rate, oxygen saturation, inspired and

exhaled carbon dioxide concentrations, oxygen and anesthetic agent concentrations, central and arterial pressures, blood gases, mixed venous oxygen saturation, intracranial pressure, cardiac output, tidal and minute volumes, respiratory rate, compliance, resistance, temperature, electrocardiogram, tourniquet times, electroencephalogram, urine output,

neuromuscular transmission data). Most of this data can be automatically transferred from the monitors to the intraoperative record.

Systems edit automatically captured patient variables differently. Some will not permit editing and require a note to explain an artifact. There may be macros that explain common artifacts. Others require the operator to approve variables before they are recorded, offer a window of time for editing, or make the variables editable at any time. One of the advantages of editing may be algorithms to help reject artifacts.

Workstation and Monitor Information

Much of the information that is generated by monitors and the anesthesia machine, vaporizers, ventilators, and associated equipment [fresh gas flow, vaporizer setting, composition of respiratory gases, breathing system pressures, tidal and minute volumes with controlled ventilation, respiratory rate, inspiratory:expiratory (I:E) ratio, breathing system pressures and flows, end-tidal concentrations, whether alarms are ON or OFF and their settings, drugs administered by infusion pumps] can be transferred automatically to a data management system totally or in part. With some anesthesia machines, gas flows and vaporizer settings can be transferred.

Information from the Anesthesia Provider

Some information, including observations and some interventions, is available only from the anesthesia care provider. This includes pre- and postoperative diagnoses; premedicationâ€”type, amount, time given, and effects; operation(s) performed; position of tracheal tube; difficulties encountered with intubation; heart and lung sounds; echocardiography information; patient appearance (e.g., pale, flushed, sweaty, wrinkled); patient position; estimated blood loss; urine output; the type of breathing system; special safety

precautions; and checks of equipment. The site, size, and type of intravenous catheter(s) and the type, amount, and time of fluid administration need to be noted. Routine procedures such as positioning, padding pressure points, and eye care need to be included. Special procedures such as placing a central or arterial line or a regional block should be recorded with information on how it was performed and any problems that occurred. Events that need to be entered (along with the time) include surgery start and stop, tourniquet inflation and release, clamping and unclamping of major vessels, and cardiopulmonary bypass beginning and end. In many cases, this information can be incorporated into macros that can be easily entered into the record. These entries should always be time stamped by the system.

Most neuromuscular stimulators (Chapter 25) depend on the anesthesia provider to assess the response, so manual entry will be required. However, some instruments both stimulate and assess the response. These can be interfaced to automatic data recording.

The record should contain the dosages and times of all medications administered. Various methods have been used to at least partially automate these entries. The medication can be selected from a menu and its dosage entered. Labels carrying the drug names and bar code can be attached to syringes (24). The anesthesia provider can scan the label to the automatic bar code reader. It is also possible to automatically determine the amount of drug administered from a prefilled syringe (Fig. 28.2).

Information Transfer

An important advantage of the data management system is its ability to import data from and export data to other computer systems in the health care facility. These include the laboratory, radiology, business office, and critical care.

Laboratory information such as hemoglobin, blood gases, clotting values, and electrolytes are often needed during the course of an anesthetic. If the data management system is connected to the laboratory, information should be quickly available. Test results should be entered on the record immediately after the data becomes available. The time that the results arrive should be recorded as well.

If the information on a blood container can be scanned, this can be transferred to the record. If the data management system is interfaced to the blood bank, the information on the container can be checked to determine if the blood is being administered to the correct patient.

Picture archiving and communication systems (PACS) that allow acquisition, storage, and retrieval of digital images can be included in the information system (25). Thus, an esophageal echocardiograph obtained in the operating room can be viewed by clinicians in other areas of the facility.

Postanesthesia

The postanesthesia record can be considered a continuation of the intraoperative record but usually with a different format. Preoperative patient information and the record made during the intraoperative period must be immediately available to the PACU.

Data is extracted from monitors in the same manner as during anesthesia. It is important that monitors used in the PACU be able to communicate with the data management system. Drugs, laboratory results, and incidents are recorded, along with user notes. Patient consciousness, pain levels, and other information required by regulatory agencies should be part of the postanesthesia record. Quality assurance can be conducted from the postanesthesia record (26).

Uses for Data Management Systems

Information from a data management system can be used by the anesthesia department and others for a variety of tasks. Special software modules may be needed for some of these.

Anesthesia Record Generation

An anesthesia information system can provide a timely and accurate record of patient care through the entire perioperative period.

Research

Because a large volume and variety of information can be collected and searched by procedure, patient characteristics,

drugs used, and other parameters, an anesthesia information management system database can be very useful for clinical research (22,27,28,29,30,31,32). Studies have shown that manual records frequently are not sufficiently accurate for research purposes (29,33,34,35,36,37,38). Large retrospective studies are difficult to handle manually and may reflect the bias of the reviewer. Electronic data management makes it easier to collect and analyze the variables being studied. An Internet website can be used for data collection for multicenter research projects (39). After the database has been established, the effects of a change in some aspect of care can be studied.

A necessary factor to be able to examine data from different institutions is a standard anesthesia lexicon. This is being developed by using SNOMED (systemized nomenclature of medicine) as a base (40,41,42,43).

Education

In a training program, an automated record can be used to review and refine the trainee's skills. Since trainees are required to keep a log of their cases, the data management system can be utilized to furnish that information and track each trainee's experience (44).

As departments institute various practice guidelines, the availability of these on line may improve and simplify their implementation. Compliance with these guidelines can also be determined.

Billing

Information necessary for billing includes patient characteristics, case-specific data, and concurrency (the number of anesthetics supervised at one time). A data management system can be used to assign the proper billing codes (45). Proper data can increase billable diagnoses, help the facility increase reimbursement, and decrease the time between the event and payment (15).

If the record is incomplete or does not conform to Health Care Finance Administration rules, the bill may be disallowed or reduced. Even worse, the institution may be accused of and fined for fraudulent billing. A program can be set up to improve documentation by calling attention to required entries.

Administrative Functions

Since all the functions in an operating room environment are interrelated, it makes sense that they should be integrated into the data management system. These include patient tracking, nursing, radiology, scheduling, room utilization, cleaning, instrument care and preferences, transport, and the like. If a problem develops, it is important to determine what occurred and to develop a strategy to prevent its reoccurrence. An integrated data management system may help with this.

The data management system can provide information on utilization of facilities, personnel, equipment, and supplies. It may be used to facilitate scheduling (46,47). Surgical delays can be analyzed and the problems corrected.

The information management system can be used to obtain summaries of an anesthesia provider's or a group's practice patterns, for example, the number of cases of a particular type done in a given period of time. In a group practice, questions often arise as to how the work is divided, time off, call, and number of nights and hours worked. The information management system can be used to track these events.

Quality Assurance

Data gathered electronically is relatively easy to analyze for quality assurance purposes. With manual charting, there may be a considerable deficit in documenting adverse events (27,48,49,50,51,52,53,54,55,56). When an incident occurs, the relationships to drugs or procedures may be determined more accurately from the data management system than from the written record. In one reported case, it would not have been possible to determine the cause of a critical incident from the manual record, but the data management system indicated the source of the problem (57).

A registry of anesthesia-related problems can be compiled (58,59,60,61). Events such as malignant hyperthermia, suspected latex allergy, atypical pseudocholinesterase, and difficult intubation that would be of importance to subsequent anesthesia providers can be sent to a data bank that institutions and anesthesia personnel can access electronically.

Advantages

Accuracy, Completeness, and Legibility

The accuracy, completeness, and legibility of handwritten records often leave much to be desired (6,29,33,34,35,36,62,63,64). There is a bias toward recording more normal values (37,38,65,66).

Studies show that a high number of errors are made when blood gas analysis results are telephoned to the operating room (67). Electronic transfer of laboratory information should be more accurate.

Clinicians are not always able to make timely notations in the written record while responding to emergencies, and their memories are not completely reliable when recording data after an incident. The result is often an incomplete record during periods of significant and rapid changes when increased physical and pharmacologic manipulations occur. With electronic data transfer, recording will continue during these times.

New views of data are available with electronic records (25). Data that would be spread among many pages or reports in a paper record can be formatted to a single page or monitor screen, allowing the clinician to review longitudinal information at a glance.

Decreased Paper Use

Decreased paper use is a goal of data management systems. It is possible that in the future a paper printout will be unnecessary, as it will be possible to call up all records from the electronic database.

Accessibility

Anesthesia providers need access to previous anesthetic records, especially if there was an adverse reaction, difficult intubation, unexplained problem, or nausea and vomiting. In the past, this necessitated having someone locate the old chart. This can be time consuming and may not be possible during evening or nighttime hours. Many old charts are stored at an off-site location. If the record is stored electronically, it should be readily

available at any time at all locations where access is needed. In the future, it may be possible to transfer records between institutions by using the Internet or other secure means.

Integrating Monitored Variables and Alarms

The operating room is an information-intensive location with data provided by a heterogeneous mix of independent devices. It may be difficult to compare variables and determine the relationship between them. A data management system may make it easier to present data in a format that allows rapid and accurate recognition of developing patterns and examination of the relationship between various interventions and responses.

Another problem in the operating room is that several different alarms often occur simultaneously. This may result in confusion as to the source and significance of the alarms. An integrated system can generate more specific and descriptive alarm messages. Ideally, all alarms would be displayed on one central panel designed for maximal visibility and readability, and the alarms on the primary monitors could be turned OFF. This would aid in recognizing what condition(s) require attention. The electronic data system could then analyze the data and suggest diagnoses and, possibly, treatments. See ĺ€Smart Alarmsĺ€ in Chapter 26.

Legal Protection for Anesthesia Providers

Every anesthetic record has the potential to become a legal document (68,69,70,71,72,73,74). No case will come to trial or settlement without a detailed analysis of the anesthesia and perioperative care records. Manual records often lack information that could be essential if legal action occurred. Incomplete or illegible medical records create the impression that care was careless, superficial, or substandardĺ€”even if, in truth, it was good. Clear, complete, and timely anesthesia records will almost always help to defend a case that was properly managed, although it will not help with one that was poorly handled.

A data management system can facilitate documenting protective activities by presenting the clinician with a checklist of relevant safety items. Data management systems can be used to determine population-based normal limits for vital signs during

anesthesia (75). These may play a role in professional liability cases.

The medicolegal significance of the data management system has yet to be determined, as there have not been a large number of legal proceedings in which they were involved. One large survey determined that there were no reported cases in which the data management system hindered the defense process (76). However, since then, a case has been reported where a data transmission failure was not noticed, and the plaintiff's attorney suggested that the absence of data was evidence that the standard of care was not met (77).

Beneficial Effects on the Anesthesia Provider's Time

Studies have shown that 20% of total anesthesia time is used for manual documentation (78). Studies also have shown that charting time is modestly less with a data management system (63,79,80).

Automated Therapy

Electronic data information offers the potential for information integration. Information such as blood pressure, pulse rate, and neuromuscular blockade could then be allowed to control the administration of volatile and intravenous drugs and agents (81).

Decision Support Capability

The data management system should be able to access various sources of information. These can include the pharmacy for information about drugs and their interaction with other medications as well as calculations and drug costs. Other sources could include textbooks and journals. The speed, breadth, and consistency of a computer decision support system far exceed those of even the most dedicated and expert clinician.

Problems

Artifacts

A common concern with data management systems is that

artifacts will be used against the anesthesia provider if there is an untoward occurrence (82,83,84,85,86,87). Artifacts may be caused by mechanical or electrical disturbances (e.g., external pressure on the blood pressure cuff; electrosurgical interference on the ECG, oxygen monitor, or pulse oximeter; malposition, ambient light, or motion on the pulse oximeter sensor; line flushing or sampling on invasive pressure lines; and a plugged gas sampling line). Another source of artifacts is logging errors by the anesthesia provider.

Unfortunately, artifact recognition is not an exact science. Notes that are made to explain an artifact may be retrospective and in error. Often, the data management system makes it difficult to distinguish an artifact from a true value (82,88).

Artifacts can be reduced by using monitors with resistance to interference and artifact rejection capability. Another method is to utilize the data comparison or artifact rejection capabilities of the data management system. For example, heart rate is commonly measured by several different monitors. The computer could compare these measurements and reject one that does not match the others.

When an erroneous value is not filtered, manual notes can be used to explain the questionable reading. Many artifacts can be addressed by using prewritten notes from a list of common causes of artifacts (e.g., saturation of peripheral oxygen (SpO_2) affected by electrosurgery).

Incomplete data entry can occur with electronic records, especially when they rely on free text entries or it is time consuming and difficult to enter coded events (89).

Physical Layout

Contemporary operating rooms are often crowded, so the bulk of the electronic data system may cause problems. Careful consideration should be given to where the system and the necessary cables are placed. It should be in a location that is ergonomically practical but does not interfere with other equipment. In one case, the data management computer shifted in its mount and compressed the transfer tubing between the adjustable pressure limiting (APL) valve and the scavenging interface, blocking gas flow.

Interfacing

All of the devices that are connected to the data management system must be able to communicate with that system. An interfacing device is needed to perform this function. It is important that if a monitor fails to function, another monitor can be attached to the system without having to reboot or reconfigure the system.

Interfacing some equipment to the data management system can be difficult. Some devices must be modified, and unless this is done correctly, they may be rendered unsafe. Also, the warranty may become void. A customized interface may make it difficult to exchange monitors.

Adverse Effects on Operator Vigilance

Another worry about the data management systems is that the clinician will not look at the monitors since there is no need to record the values shown on them (90). The reasoning is that the process of entering data on the record causes the anesthesia provider to mentally absorb and evaluate that information (91). Studies have found that vigilance is not adversely affected by using a data management system (79,80,92).

User Attitude and Acceptance

User attitude can make or break a system. An anesthesia provider who finds computers intimidating or who has the perception that automated records invite lawsuits may be reluctant to invest the time and energy necessary to learn to use an information system. Since the data management system is continually being improved, there will be frequent upgrades, which can be a source of irritation and confusion.

For a system to be successful, it needs to be user-friendly and dependable. Involving the users in choosing and configuring the system will help to win support. A team to carry out data management system implementation should be put together prior to its introduction (53).

Detailed education in both the reasons for the conversion and the actual system operation will be necessary.

The introduction method will affect acceptance. Experience

suggests that in most cases, it is best is to make a quick, clean break with the old system and require all providers to use the new one (93). After the system has been in use for an extended period, user acceptance is usually high, provided that there are not frequent malfunctions (94,95).

Security

Security concerns have become very important for all medical records. There needs to be a means to guard against unauthorized personnel making entries or gaining access to the system as well as a means of identifying personnel who log on to the system.

Confidentiality

Information can be transferred between institutions by way of the Internet (8,70,96,97). A major problem in electronic medical record transfer is protecting patient privacy (98). The system must provide tools to safeguard data confidentiality yet make it easily retrievable for selected users. The anesthesia record will be used by other anesthesia and health care providers, including administrators, nurses, technicians, pharmacists, billing personnel, pharmacy, and peer review personnel. All of these individuals need certain information but not necessarily all the information in the record. It may be advantageous to make the record available in different formats that include only the information needed for specific purposes.

Training

Implementing a data management system requires an initial investment of time for user education. Inadequate training can lead to resistance to using the system. An inadequately prepared provider can cause records to be inaccurate, lost, or unusable. Training cannot be hit or miss. All providers must receive adequate instruction before using the data management system. This can be difficult, especially if there are providers who work only occasionally at the facility.

After users are trained on the data management system, the compliance level needs to be monitored and the cause of any decreased compliance determined. Criteria for determining user compliance have been developed (99). A decrease in compliance

can signify that the user is unwilling to perform within set criteria or that there is a problem in the system that can be corrected.

Mechanical Problems

The operating room can be a hostile environment for computers. Damage may be caused by other equipment or user abuse. Cleanliness can be a problem. Bloody gloves may be used to make entries. Liquids may find their way into the mouse or keyboard.

The system should not be affected by power fluctuations, a brownout, or a blackout. Preventive measures include an uninterruptible power supply (UPS) and a line conditioner to prevent voltage fluctuations.

Problems are inherent in any computer system. There will be times when information is slow in coming or the computer is down. Looking up information may be too time consuming in emergency situations. If the server where all the data eventually ends up is not functioning, the data needs to be retained in the bedside computer until the server is able to receive that information.

Information in the data management system needs to be backed up at frequent intervals and stored in a manner that will ensure that it will not be lost. There needs to be a means to record data if the computer fails.

Inability to Deal with Certain Information

No devices are available for quantifying or measuring physiologic signs such as pupillary size and reactivity, sweating, or blood loss. This type of information needs to be manually entered into the computer.

Difficulty Adapting to Special Situations

In the operating room, the equipment is located in one or two locations. This means that connections between monitors and the data management system and between the data management system and the network do not need to be altered frequently. When anesthesia is administered in a remote area, the monitors in that location may not be able to interface with the data management system. This will necessitate taking the entire

anesthesia machine with its monitors and data management system to the location. Since a connection to the server may not be available in these areas, the information will need to be stored in the computer until it can be connected to the network and the information downloaded for storage and printing. Wireless communication from the monitors in the location where the procedures occur may overcome some problems.

Electroconvulsive therapy poses another problem for the data management system (100). In this situation, several patients can be lined up and anesthesia administered in a rapid manner. This is usually performed in a psychiatry suite or PACU. The total time per patient is only several minutes, and an anesthesia machine is usually not used. To use a data management

system for these cases, monitors would need to be connected and disconnected every few minutes and the record restarted and demographic information added for each patient. All of this would greatly extend the time required to perform this procedure.

Lack of Information Standardization

It is important that data from other sites be integrated. Horizontal integration should include connections between the areas such as the pharmacy, laboratory, and radiology. If these areas use a different format, it may not be easy to add this information electronically.

Long-term Manufacturer Stability

Some early hardware and software providers went out of business, so their systems that had been installed became obsolete. As the technology matures and becomes more popular, it is expected that the companies that maintain the systems will become more stable, and this problem will diminish. A vendor's long-term viability should be considered when purchasing a system.

Financial Considerations

The drugs and equipment used in anesthesia contribute to the cost of the anesthetic. The ability to track drugs and monitoring procedures allows their cost and effectiveness to be assessed. The data management system can be used to determine the

effect of a drug or monitor on overall outcome and costs and whether an expensive drug could be replaced by one of less cost without a decrease in the quality of care (72).

Costs

The initial cost of a data management system is high and depends on the number of operating rooms, what equipment and infrastructure is already in place, the wiring requirements and ability of existing monitors, and other equipment to interface with the system.

There are costs involved in training users and support personnel. These will be repeated each time there is a revision in the program and each time a new user or service person is added.

After purchase and installation, ongoing costs include hardware and software maintenance, upgrades, and support personnel. Other costs to be considered include paper, printer cartridges, prefilled syringes, and adding bar codes. There must be technical backup available to solve problems and to keep the system functional. If the system is difficult to operate, mistakes may result in lost billings.

Savings

Data management systems may reduce losses from charges not captured and inaccurate coding or time billing (101,102). The costs of different techniques can be compared. After each case, the anesthesia provider can be presented with the costs of drugs and other items used. These can then be examined to determine if they were truly necessary and if other less costly ones could be used (103).

Savings can be achieved by reducing last-minute delays and surgery cancellations; improved staffing; better inventory control; and reductions in administrative and overhead costs such as billing, medical records, quality assurance, and compliance with the Joint Commission on Accreditation of Healthcare Organizations and other regulatory bodies.

Savings can be achieved if data management systems aid anesthesia providers and institutions in professional liability litigation. One insurance company offered a discount for using data management systems (71). Some problems that result in

lawsuits, such as injecting the wrong drug, may be avoided.

If central trending and alarm functions are assumed by the automated record system, it may be possible to use monitors without these features and that cost less than the top-of-the-line models (104).

Whether data management systems will be cost effective remains to be demonstrated. While some centers have reported savings (105), it is difficult to document that data management systems save enough to justify the high initial and maintenance costs.

In summary, the data management system offers many advantages as well as a number of disadvantages. Some institutions have used one for a time and then stopped because the work of supporting it was too demanding or the system was flawed (106). Systems presently available are still elementary in relation to their potential, but they are becoming more powerful and easier to use. Many of the potential features discussed in this chapter are theoretical, while many of the potential features discussed have yet to be implemented. Despite the fact that there are little hard data to support the superiority of data management systems, it seems likely that in the future, most medical records will be computerized and integrated into a facility-wide data management system.

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Questions

For the following question, select the correct answer

1. Which of the following definitions is incorrect?

A. Analog data is continuous data that can, within limits, assume any value.

B. Closed architecture refers to equipment designed to work only with accessories made by one company.

C. Analog is a way of storing information using numbers.

D. Peripheral is a general term for any of the devices by which a computer gathers its input and dessiminates its output.

E. A macro is a tool used to automate tasks or procedures within a program.

View Answer

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. if D is correct

E. if A, B, C, and D are correct.

2. Uses of a data management system in anesthesia include

A. Education

B. Quality assurance

C. Research

D. Billing

View Answer

3. Proven benefits of automated records include

A. Legal protection for the anesthesia provider

B. Financial savings

C. Major beneficial effect on the anesthesia provider's time

D. Accuracy

View Answer

Chapter 29

Temperature Monitoring

Indications for Temperature Monitoring

Numerous studies have shown that significant temperature changes routinely occur in anesthetized patients (1,2,3). The monitoring guidelines of the American Society of Anesthesiologists state that ‘€Every patient receiving anesthesia shall have temperature monitored when clinically significant changes in body temperature are intended, anticipated or suspected.‘€ The Standards for Nurse Anesthesia Practice state that one must ‘€monitor body temperature continuously on all pediatric patients receiving general anesthesia and, when indicated, on all other patients‘€ (3A).

Temperature monitoring should be performed whenever large volumes of cold blood and/or intravenous fluids are administered, when the patient is deliberately cooled and/or warmed, for pediatric surgery of substantial duration, and in hypothermic or pyrexial patients or those with a suspected or known temperature regulatory problem such as malignant hyperthermia. Major surgical procedures, especially those involving body cavities, should be considered a strong indication for temperature monitoring.

Standards

A U.S. standard for electronic thermometers, not including infrared thermometers, was published in 2000 (4). Celsius display thermometers must be graduated in intervals of not greater than 0.1ยฐC, while thermometers using a Fahrenheit display must be graduated in intervals of not greater than 0.2ยฐF. The maximum error for an individual reading is shown in Table 29.1.

There is also a U.S. standard for infrared thermometers (5). This specification does not prescribe a method for determining clinical accuracy.

TABLE 29.1 Maximum Error for Electronic Thermometers

Temperature	*Maximum Error*
Celsius Scale	
Less than 35.8ยฐC	ยฑ0.3ยฐF
35.8ยฐC to less than 37.0ยฐC	ยฑ0.2ยฐF
37.0ยฐC to 39.0ยฐC	ยฑ0.1ยฐF
39.0ยฐC to 41.0ยฐC	ยฑ0.2ยฐF

Greater than 41.0ยฐC	ยฑ0.3ยฐF
Fahrenheit Scale	
Less than 96.4ยฐC	ยฑ0.5ยฐF
96.4ยฐC to 98.0ยฐC	ยฑ0.3ยฐF
98.0ยฐC to 102.0ยฐC	ยฑ0.2ยฐF
102.0ยฐC to 106.0ยฐC	ยฑ0.3ยฐF
Greater than 106.0ยฐC	ยฑ0.5ยฐF

(From ASTM 151112â€“00, 2000).

Technologies

A variety of technologies are available to measure temperature. None is suitable for all situations. Many devices simply display the temperature. These are less than optimal, because a high or low temperature may go unnoticed for some time. Most modern devices have alarms that can be set if the temperature exceeds high or low limits. Temperature-monitoring capability is available on most physiologic monitors used in the operating room and perioperative areas. Frequently, they have the ability to measure temperature at two different sites (Fig. 29.1). These devices usually have the ability to trend the temperature and to transfer temperature information to an electronic record.

There are a number of stand-alone devices, both mechanical and chemical. Those stand-alone devices that are battery-powered should have a means to indicate when battery power is low. Trend indicators are available on some of these instruments.

Thermistor

A thermistor is composed of a metal (i.e., manganese, nickel, cobalt, iron, or zinc) oxide sintered into a wire or fused into a rod or bead (6,7). There must be a source of current and a means to measure that current. Resistance of the metal oxide increases as the temperature decreases and vice versa so the resistance can be converted to a temperature. Advantages of thermistors include small size, rapid response time, continuous readings, and sensitivity to small changes in temperature. They are fairly inexpensive. Probes can be interchangeable and disposable.

Figure 29.1 Monitor with capability for monitoring temperature at two sites and alarms. (Courtesy of Fisher Paykel Healthcare.)

Thermocouple

A thermocouple consists of an electrical circuit that has two dissimilar metals welded together at their ends (6,8). One of the two metal junctions remains at a constant temperature. The other is exposed to the area being measured, producing a voltage difference that is measured and converted to a temperature reading. Advantages of thermocouples include accuracy, small size, rapid response time, continuous readings, stability, and probe interchangeability. The materials are inexpensive, so the probes can be made disposable.

Platinum Wire

The electrical resistance of platinum wire varies almost linearly with temperature. By employing an extremely small diameter wire, rapid thermal equilibration is possible. Resistance is measured in a manner similar to a thermistor. These thermometers are accurate and give continuous readings. Probes can be made interchangeable.

If a probe with a thermocouple, thermistor, or platinum wire is to be used inside the body, it must have

an outer sheath. The end of the probe designed to be inserted

into the patient is sealed and the electrical connection made at the other end. The connection needs to be kept dry. If it becomes wet, erroneous readings can result (9,10,11).

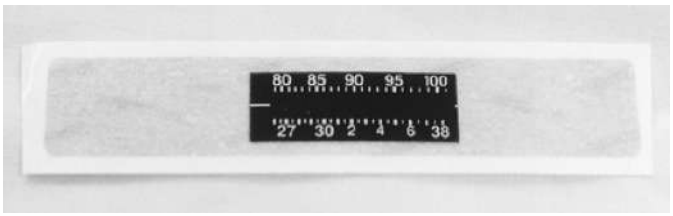

Figure 29.2 The flexible adhesive-backed strip of this liquid crystal temperature monitor has a black background. To use, the covering over the adhesive is removed, and the monitor is placed on the skin.

Liquid Crystal

Certain organic compounds in thermal transformation from a solid to a liquid state pass through an intermediate phase that exhibits anisotropic (optically active) properties (12,13). The term *liquid crystal* is used to describe this state. When light shines on such a material, crystals scatter some of the light, producing iridescent colors. The liquid crystals are encapsulated so that the colors form letters and numbers.

A liquid crystal temperature monitor is shown in Figure 29.2. It consists of a flexible adhesive backing with plastic-encased liquid crystals on a black background that prevents reflection of the transmitted light and enhances the color resolution. The covering over the adhesive is removed, and the disc or strip is placed on the skin. The liquid crystal thermometer is available in two forms: one displays the skin temperature directly; the other has a built-in correction factor (offset) so that the temperature displayed estimates core temperature (7,13).

Liquid crystal thermometers are safe, convenient, noninvasive, easy to apply and read, disposable, nonirritating, and inexpensive. They give fast, continuous readings and involve no electronic circuitry. They can be applied before induction of anesthesia and are easily transferred to the recovery area with the patient.

Disadvantages of liquid crystal thermometers include the need for subjective observer interpretation and the inability to interface with a recording system. They are less accurate than other devices. Extreme ambient temperature, humidity, and air movement can cause inaccuracy (13). Other disadvantages include difficulties with adhesion secondary to skin secretions, allergic reactions to adhesive backing, inaccuracy, and imprecision (14,15). They are capable of measuring temperature only on the skin. If left in the sun for an extended period, an error indicating hyperthermia can be produced. If the device is

frozen, all the numbers can be visible at once (13). Infrared heating lamps may cause erroneously elevated readings (12). There is a report of a liquid crystal thermometer that gave a falsely high temperature (16).

Infrared

An infrared thermometer is an electronic instrument that measures a portion of the infrared radiation from surfaces within its field of view (17,18,19). Electromagnetic radiation is emitted by an object in proportion to its temperature. Because the probe is placed in the outer part of the ear canal and usually has a relatively wide view angle, it detects infrared emissions from parts of both the ear canal wall and tympanic membrane and computes an average or highest temperature. The displayed value may be the actual temperature (unadjusted, calibration mode) or with an offset to estimate temperature at another site based on selected study samples (site equivalent mode) (5,7,17,20).

The instrument has an otoscopelike probe (Fig. 29.3). Disposable probe covers are used for hygiene and to prevent cerumen buildup. The probe should be placed carefully but firmly as far as possible into the ear canal, aiming toward the tympanic membrane. The probe window should be clean and shiny, and a new probe cover should be used each time.

Figure 29.3 The infrared thermometer's probe is inserted into the external ear canal.

Patients tolerate infrared thermometry well (18). Because it does not contact any surface, there should be no trauma associated with its use. Measurements are rapid. This technology is often used in the postanesthesia care unit and other critical care areas.

There are a number of problems with infrared thermometry. Poor penetration, improper aiming, and obstructions such as curvatures of the ear canal can result in significantly lower temperatures. Measurements are intermittent. This device is generally not useful for monitoring in the operating room.

Mercury-glass

These thermometers are not useful for intraoperative anesthesia, as they have a long equilibration period (usually 3 to 5 minutes) and cannot be read without being removed from the monitoring site. In the future, they will be banned to reduce mercury contamination in the environment.

If a new thermometer is used on each patient, there is a waste-disposal problem. If the thermometer is reused, it must be cleaned and sterilized. If a thermometer is broken, the mercury vaporizes and can present a health hazard.

Thermal Compartments

Although arbitrary, it is somewhat useful to divide the body into two thermal compartments: the core that includes the deep, vital internal organs and a shell of peripheral tissue that serves as insulation for the core.

Core

Core temperature is uniform and high compared with the rest of the body. It normally varies between 35.7ยฐC and 37.8ยฐC (21,22,23). When significant changes in body heat are expected, core temperatures should be monitored.

Sites differ in how well they reflect core temperature. The difference may depend on the rate of temperature change. A site that reflects core temperature accurately when temperature change is slow may fail to reflect rapid changes.

Periphery

Normally, thermoregulatory vasoconstriction maintains a temperature gradient between the core and periphery (shell) of 2ยฐC to 4ยฐC. Regional temperature variations exist in the periphery. The correlation between temperatures measured at different body sites depends on several factors, including the stability of the body temperature and whether or not there have been recent cold or warm challenges. Skin and axillary temperatures are usually considered shell temperatures.

Monitoring Sites

Body temperature can be monitored at a number of sites. The temperature can vary considerably in different parts of the body at any time. Factors influencing temperature at any given site include the tissue's heat production, the temperature and rate of blood flow through the area, the amount of insulation from the environment, and external influences on the site (24).

The best site for temperature monitoring depends on the purpose of the measurement, duration of the surgical procedure, the surgical site, the anesthesia technique, and available equipment. Considerations should include accuracy, speed, convenience, access, safety, patient acceptability, and cost-effectiveness. Absolute accuracy is usually not necessary, but measurements must be close enough to detect temperature changes that may influence treatment decisions. It may be helpful to monitor two sites. The difference between core and a second site can provide indirect information on blood flow (slow change = poor blood

flow) and is helpful in guarding against an overshoot during warming or cooling.

Studies comparing temperature measurement among different sites are often confusing. Many try to relate peripheral sites to core temperature and use different sites as the standard for core temperature.

Pulmonary Artery

Pulmonary artery temperature can be measured in patients who have a Swan-Ganz catheter with a thermistor in place. It is thought by many to be the best method of measuring core body temperature (25,26).

Pulmonary artery temperature generally correlates well with intrathecal and jugular bulb temperatures, even with rapid cooling and rewarming (27,28). Poor correlation with brain temperature was found during profound hypothermia (29).

Pulmonary artery readings are not reliable during thoracotomy or cardiopulmonary bypass when there is no flow through the heart and lungs and may be directly affected by the cardioplegia used during cooling.

Esophagus

Esophageal temperature measurement can be accomplished by using a simple probe, an esophageal stethoscope with thermistor (Fig. 29.4), or a gastric tube with the temperature sensor some distance from the end of the tube (Fig. 29.5).

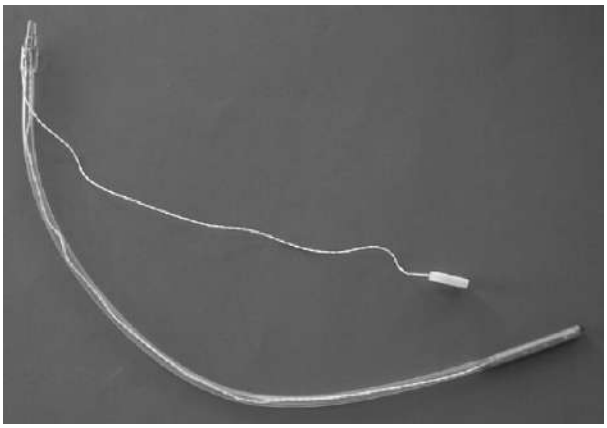

Figure 29.4 Esophageal stethoscope and temperature probe.

Temperatures in the esophagus may vary up to 4ยฐC, depending on the temperature probe location within the esophagus (7). The esophageal temperature should be measured with the sensor located in the lower third or fourth of the esophagus (30). At this depth, the esophagus lies between the heart and the descending aorta. Placing the sensor in this position will minimize (but not

completely eliminate) the effect of respired gases (31). When the sensor is part of an esophageal stethoscope, the ideal depth of placement is 12 to 16 cm distal to the point of maximum heart sounds (32). If the probe is placed higher in the esophagus, the reading will be lower (30,32,33,34). If the probe is placed in the stomach, it may record temperatures higher than core, reflecting liver metabolism. In addition, the response time to temperature changes is slow with the probe in the stomach.

The probe is most accurately placed by using an electrocardiographic lead built into the probe (35,36). The positive lead is attached to the probe, and the negative lead is attached to the right shoulder. A biphasic P wave indicates that the probe tip is at the midatrial level.

In adults, the ideal position is approximately 38 to 42 cm below the central incisors (32) or at least 24 cm below the larynx (30). For nasal insertion, the following formulas can be used (37):

L (cm) = 0.228 ร— (standing height) - 0.194

or

L (cm) = 0.479 ร— (sitting height) - 4.44

where L is the length from the opening to the nares.

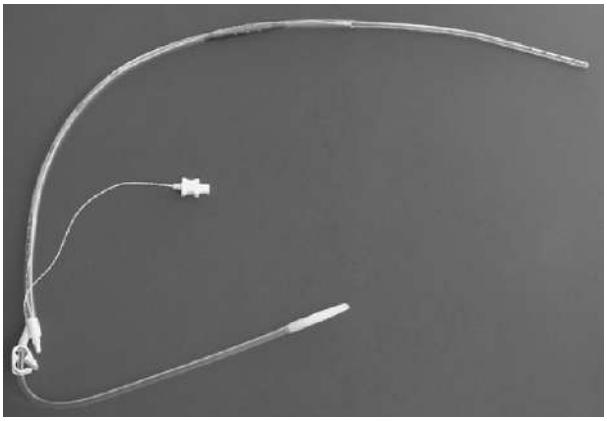

Figure 29.5 Gastric tube with temperature probe. This also functions as an esophageal stethoscope.

In children, the ideal distance in centimeters below the corniculate cartilages is approximated by the following formula (38):

10 + (2 ร— age in years)/3 cm

A temperature probe can be inserted into the esophagus through the drain tube of a ProSeal laryngeal mask. The optimal location for the temperature probe is 15 to 20 cm distal to the drain tube (39).

Esophageal temperature is considered core temperature by many investigators. Temperatures measured in this location have shown good agreement with pulmonary artery temperature

(28,40,41,42,43,44,45). During rapid warming or cooling, esophageal temperature shows less lag time than that measured at most other sites (46), although some studies found that bladder temperature showed a closer approximation to pulmonary artery temperature than the esophageal temperature (47,48). Brain temperature may be adequately reflected by esophageal temperature during mild, but not profound, hypothermia (29).

Patients having active or passive airway humidification have slightly higher esophageal temperatures (31,34).

Contraindications to use of an esophageal probe include procedures on the face, oral cavity, nose, airway, or esophagus and patients who have esophageal disorders. It is poorly tolerated by awake patients. Correct placement may be difficult, and probes may become displaced. Esophageal temperatures are unreliable during thoracic surgery. Continuous gastric suctioning will cause a decrease in esophageal temperature (49). When an esophageal probe is used with the patient in the sitting or prone position, oral secretions can track down to the connection between the probe and monitor cable. This can lead to incorrect readings (9).

Nasopharynx

The temperature of the nasopharynx is measured with a sensor that is in contact with the posterior nasopharyngeal wall posterior to the soft palate. This location should place it close to the hypothalamus.

Although some studies show a good correlation of nasopharyngeal temperature with core temperature (29,46,50,51,52), other studies have found the correlation less satisfactory (53,54,55).

An advantage of this site is that is it usually easily accessible during surgery. Readings taken with a probe in this position are normally not affected by the temperature of inspired gases unless there is a leak around the tracheal tube (53,56).

This site is not useful for patients who are awake. Epistaxis may follow probe insertion (57). Nasopharyngeal temperature is not affected by continuous suctioning through a gastric tube (49).

Urinary Bladder

Urinary bladder temperature monitoring involves inserting an indwelling urinary catheter with a thermistor or thermocouple near the patient end (Fig. 29.6).

Urinary bladder temperature usually correlates well with those measured by nasopharyngeal, pulmonary artery, and esophageal sensors (20,28,45,47,48,51,58,59,60)

but may lag behind during rapid warming or cooling (29,43,46,50,61,62). The correlation will be increased with a high rate of urine flow.

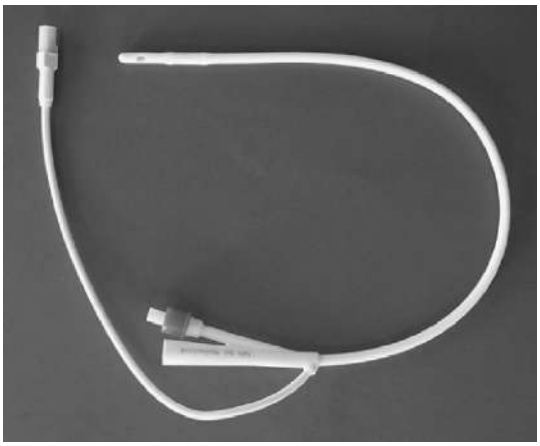

Figure 29.6 Urinary catheter with temperature sensor near the patient end.

Urinary bladder temperature monitoring can be used both during and after surgery. It may be especially useful in the patient with extensive burns (63). It should not be used during genitourinary procedures (64).

Rectum

Electronic rectal thermometers may have two measurement modes: dwell or monitor. In the dwell mode, the temperature is displayed continuously. The dwell mode requires a minimum of 2 to 3 minutes to reach a stable temperature. The predictive mode estimates the temperature on the basis of the curve of temperature rise. This mode requires only 30 seconds. A comparison of the measurements of the two modes yielded similar values during steady-state conditions and mild temperature flux.

Disposable probe covers can be used to avoid cross contamination. Probes should be inserted to at least 8 cm in adults and 3 cm in children (65). The depth of insertion can be marked on the probe. It should be checked for placement after the patient is moved. The probe should be securely taped to the patient's buttocks, and the lead wire should be secured to a garment or sheet to avoid probe displacement.

Rectal temperature is influenced by heat-producing flora, the temperature of the blood returning from the legs, and insulation by feces. Rectal temperature is usually somewhat higher than that measured at more central sites during steady-state conditions (51,66,67,68,69,70,71). The rectum is not a vascular area, and the lag time may be prolonged with shifting temperature (26,52,55,72,73).

The rectum is usually accessible and monitoring relatively noninvasive. Rectal temperature is not influenced by ambient temperature. It is generally disliked by patients as uncomfortable, by hospital personnel as cumbersome, and by both as aesthetically objectionable. Probes are prone to extrusion during recovery from anesthesia. Other disadvantages

are the relative inaccessibility during surgery and the risk of bacterial contamination. Contraindications include gynecologic and urologic procedures. Bowel perforation is a risk (74). A pararectal abscess and pneumoperitoneum have been reported with its use (75,76).

Tympanic Membrane

Two different technologies utilize the ear. One uses a probe that contacts the tympanic membrane, and the other measures infrared radiation.

Contact

The anatomical position of the tympanic membrane is deep within the skull and separated from the internal carotid artery by only the narrow air-filled cleft of the middle ear and a thin shell of bone, making it an attractive site for temperature measurements. The tympanic membrane and the hypothalamus share a common blood supply, so measuring temperature at this site may reflect thermal information at the primary site of thermoregulation (17).

Temperature can be measured by inserting a thermistor or thermocouple probe into the external auditory canal until it contacts the tympanic membrane. Because of the danger of perforating the membrane, clinicians tend not to place the probe far enough into the canal. If it does not touch the membrane, the readings will not be accurate. In the awake patient, it should be inserted until the patient feels the thermocouple touch the tympanic membrane; appropriate placement is confirmed when the patient easily detects a gentle rubbing of the attached wire (77). The lower anterior quarter of the membrane should be used (78). After the probe is inserted, the aural canal should be occluded with cotton wool and covered externally to prevent air movement from cooling the probe (79,80).

Contact tympanic membrane probes are shown in Figure 29.7. The sensor is enclosed in soft foam. It usually has a widened segment, piece of foam, or a feather or barb to hold it in place after insertion. After insertion, the reading should stabilize quickly. If it does not, the probe should be slowly advanced until the reading stabilizes.

Numerous studies have shown a good correlation between tympanic membrane temperature and temperature measured in the esophagus, pulmonary artery, or urinary bladder (31,71,78,79,80,81,82,83,84,85). Temperature may be less accurate during rapid changes (29,40,79).

Head position can cause asymmetric changes in the tympanic temperatures (86). Upon assuming a lateral position, the temperature on the lower side increases while that on the upper side decreases.

Advantages of tympanic membrane temperature monitoring include cleanliness and convenience. It is tolerated by conscious patients, making it useful for postoperative monitoring. The site is readily accessible during most surgical procedures.

Complications have been reported. Oozing from the ear, trauma to the external auditory canal with subsequent external otitis, and

perforation of the membrane have been reported (81,87,88). These complications occurred before the advent of flexible cotton-tipped probes that are less traumatic (7). Recommended methods to avoid trauma include otoscopic inspection of the canal and drum before insertion, stopping insertion as soon as resistance is felt, and placement in awake patients to assess discomfort. Care should be taken that the

probe is not pushed into the canal when the head is moved.

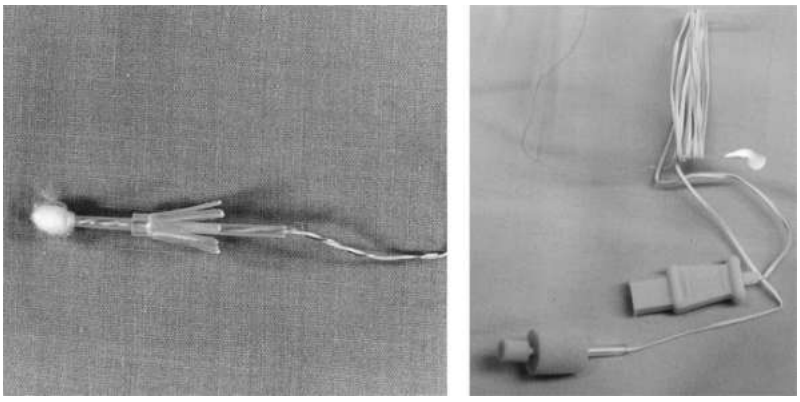

Figure 29.7 Tympanic membrane temperature probes.

Contraindications include any ear abnormality that would prevent correct placement, a skull fracture that passes through the osseous meatus, and perforation of the tympanic membrane.

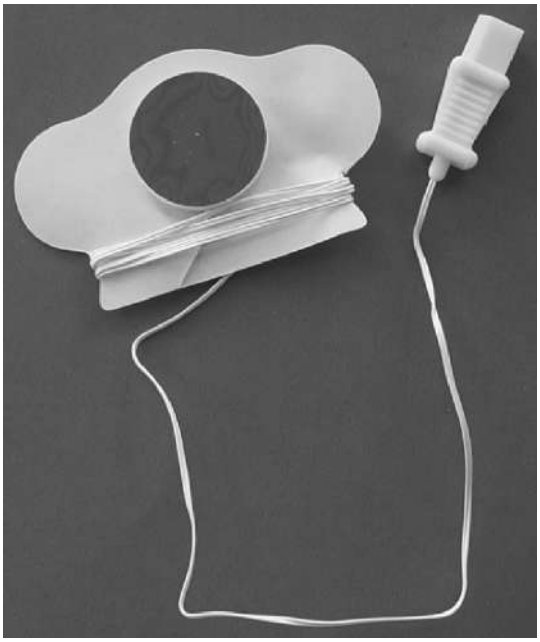

Figure 29.8 Disposable probe for measuring skin temperature.

Infrared

Infrared ear thermometry (infrared emission detection thermometry, infrared tympanic membrane thermometry, infrared tympanic thermometry) is performed by inserting an otoscopelike probe into the external ear canal (19). The tip is usually covered by a disposable cover. The device detects the amount of infrared heat emitted. The wide angle is too large to measure only the tympanic membrane, so it also reads the temperature of the ear canal.

Since these thermometers are known to give temperatures lower than core temperatures, some manufacturers provide offsets to estimate the temperature at other sites (89). These offsets vary for different brands (17,26,90,91).

A tug on the ear to straighten the canal while taking a reading was found by some investigators to improve correlation with core temperatures (92,93,94,95,96). Other studies did not find that an ear tug is helpful (20,69). The device should be inserted with a gentle back and forth motion, and firm but gentle pressure should be applied to seal the canal from ambient air (94).

Many studies have compared temperatures obtained by infrared ear thermometers to temperatures obtained from other sites (19,25,41,42,44,52,58,66,69,70,83,90,91,93,97,98,99,100,101,102,103,104,105,106,107,108,109,110,111,112,113,114,115,116,117,118,119,120,121,122,123). The correlations vary from excellent to poor. There is considerable variation among different instruments and with different users of the same instrument (20,109,114,120). A difference of 1.6ยฐC between the two ears has been reported (114). Readings are affected by the ambient temperature (124,125). If the face is cooled, there will be a decrease in the reading (126). Acute otitis media will not influence the reading unless there is suppuration, in which

case the reading will be slightly increased (98,102,117,127).

Advantages of infrared temperature monitoring include speed and reduced potential for cross contamination. It is noninvasive, requires no clothing removal, and is well tolerated by conscious patients. The site is usually readily accessible. The ease with which the measurements can be obtained has made these the thermometers of choice in many pre- and postoperative units. Because the readings are intermittent and subject to such variability, this technology is not recommended for intraoperative use.

Skin

Skin temperature can be measured by using a liquid crystal device or flat disc or tip of a lead containing a thermocouple or thermistor (6) (Fig. 29.8). Some skin probes have a special backing to attach to the body and material to insulate the sensor from ambient conditions. An opaque dressing and/or tape over the sensor may decrease the effect of environmental factors.

Skin temperature is most commonly measured at the forehead,

because this site has a fairly good blood flow, and there is not much underlying fat. The back, chest, anterior abdominal wall, fingers, toes, and the antecubital space inside the elbow have also been used.

The correlation between skin temperature and core temperature is controversial. Skin surface temperature is typically 2ยฐC to 4ยฐC less than core temperature. Some manufacturers build in an offset to compensate for this difference (128). In some studies, skin temperature has been found to correlate well with core temperature (129,130). However, most investigations have found that skin temperature does not accurately reflect core temperature, and there may not be a relationship between a change in skin and core temperature (29,31,61,78,108,131,132,133).

Monitoring skin temperature carries few risks. The site is easily accessible. The main disadvantage is that skin temperature is a poor estimate of core body temperature and may give erroneous information (16). Skin temperature readings are affected by ambient temperature, skin surface warming devices, intraoperative changes in cardiac output, and regional vasoconstriction (134,135,136,137). The usefulness of skin temperature monitoring as a screening device for malignant hyperthermia is limited, as cutaneous vasoconstriction may occur with this syndrome (138).

Skin temperature may be used to evaluate the quality of a regional block. A rise in skin temperature is an indication that the block is successful. Another use is in microsurgery. An increase in skin temperature may indicate that blood flow to that area has increased.

Axilla

To measure axillary temperature, a mercury-glass thermometer or a probe with a thermocouple or thermistor is positioned over the axillary artery and the arm adducted (31). Significant differences have been found between mercury and electronic axillary temperatures (68,111). Temperature should not be measured on the same side where a blood pressure cuff is on the upper arm. Equilibration may take as long as 10 to 15 minutes (72,138).

Although a few studies found satisfactory correlation with more central sites (133,139,140,141,142), most studies show poor correlation (20,25,29,45,51,58,68,69,98,115,116,129,143,144,145,146,147,148,149).

Axillary temperature measurements are easy to take and are not objectionable to the patient or nursing staff. The site is usually accessible. However, it is not considered accurate or reliable in adults. It is used most frequently on infants and children because the patient's small size and greater surface vasculature make a relatively uniform temperature (17,31). Readings are influenced by contact with the probe, skin perfusion, exposure to the environment, skin warming devices, and proximity of the probe to the axillary artery (20,26,56,148).

Mouth

Sublingual temperature is measured by placing a probe in one of

the pockets on either side of the frenulum of the tongue (151). The patient's mouth should be closed and enough time allowed for the reading to be accurate. This area contains small muscular arteries that respond to mastication or hot or cold liquids by expanding or contracting.

Correlation with temperatures measured at more central sites varies somewhat but in general is fairly satisfactory (20,58,77,113,115,151,152,153).

Sublingual temperatures are well tolerated by patients. Readings are not affected by the presence or absence of teeth, intubation, administration of oxygen, a nasogastric tube on continuous suction, or the temperature of inspired gases (145,150,154). Sublingual temperature may be inaccurate if the patient is a mouth breather or has tachypnea (155). Warm and cold ambient temperatures have a small effect on oral temperatures (124,125).

Trachea

Temperatures in the trachea can be measured by using a tracheal tube with the temperature sensor in the cuff. Studies differ in how well temperatures measured at this site correlate with those at other sites (156,157,158,159).

Inguinal Area

The inguinal area has been used to measure temperature (45,72,160). The leg is first abducted and the femoral pulse determined. The sensor is placed just lateral to the femoral artery, and the leg is adducted to create a seal. A significant drawback to this site is the time required to reach equilibrium.

Hypopharynx

A thermocouple can be attached to the cuff of a supraglottic device to measure temperature in the hypopharynx (161,162). Temperatures measured in this location have correlated well with those at other sites.

Hazards of Thermometry

Damage to the Monitoring Site

Tympanic membrane and rectal perforation and trauma to the nose, external auditory canal, rectum, and esophagus have been reported (74,75,76,81,87,88,163,164). Probes can have sharp edges that could present a hazard to the patient (165).

Burns

Burns can occur at the measurement site if the probe acts as a ground for the electrosurgical apparatus (166,167,168). No insulation can completely block radio frequency currents, and if there is no other satisfactory return path, the current can burn through insulation (169). Using a battery-operated device is no guarantee of electrical safety, because the chassis may be grounded through a metal support. Temperature probes should be examined before use to detect damage to the insulation. Esophageal burns may be avoided by inserting the probe via a

small tracheal tube (170). The probe may be pulled back into the tube during periods of maximal electrical activity.

Incorrect Information

A faulty probe can cause an incorrect temperature to be displayed (171,172,173,174). Secretions or fluids in the connection between the probe and reading instrument can result in falsely elevated readings (9,10). If the battery in a battery-powered device is depleted, the unit may stop functioning or give incorrect information (6). Using jacks that fit the receptacle but have internal electronics incompatible with the monitor can give false readings.

Probe Contamination

Reusable temperature probes may be a source of bacterial or viral pathogens even if protective covers are used (6,175).

Faulty Probes

After a probe is removed from its packaging, it should be inspected. A part of the sheath on a probe could break off and be aspirated.

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Questions

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. if D is correct

E. if A, B, C, and D are correct.

1. Advantages of thermistors include

A. Small size

B. Interchangeable and disposable probes

C. Continuous readings

D. Rapid response time

View Answer

2. With the platinum wire thermometer

A. Current flows in proportion to the temperature difference

B. Rapid thermal equilibration is possible because of the small diameter of the wire

C. Two wires of different metals are welded together at their ends

D. Resistance of the wire varies with temperature

View Answer

3. Advantages of the liquid crystal thermometers include

A. Fast continuous readings

B. Infrared lamps do not interfere with their readings

C. They can be applied prior to induction

D. Accuracy even at the extremes of ambient temperature

View Answer

4. Advantages of infrared temperature monitors include

A. They do not contact the eardrum directly

B. Tolerated well by patients

C. Rapid measurement

D. Continuous measurement

View Answer

5. The accuracy of axillary temperature determinations is influenced by

A. Proximity to the axillary artery

B. Perfusion of the skin

C. Skin contact with the probe

D. Patient age

View Answer

6. Factors influencing the temperature reading in the naso-pharynx include

A. Temperature of the inspired gases

B. Leak in the tracheal tube cuff

C. Gastric suction

D. Temperature in the hypothalamus

View Answer

7. For correct use of the esophageal temperature monitor,

A. The sensor should be located in the lower third to lower fourth of the esophagus

B. Stomach placement of the probe will provide temperatures lower than core

C. The probe should be placed 12 to 16 cm distal to the point of maximum heart sounds

D. Temperature of the respired gases is not a factor in the lower third of the esophagus

View Answer

8. Factors that can cause esophageal temperatures to be unreliable include

A. Airway humidification

B. Thoracic surgery

C. Continuous gastric suction

D. Patient in the sitting position

View Answer

9. When using the tympanic membrane to measure temperature,

A. The probe does not have to actually contact the membrane

B. Perforation of the membrane can occur

C. Readings will be stable if the probe is in close proximity to the membrane

D. The probe should have a means to hold it in place

View Answer

10. Factors that will cause incorrect readings from an infrared ear thermometer include

A. Cerumen

B. Ambient air temperature

C. Otitis media with suppuration

D. Otitis media without suppuration

View Answer

11. Factors affecting the temperature measured in the rectum include

A. Cystoscopy

B. Peritoneal lavage

C. Rectal contents

D. Colon pathology

View Answer

Chapter 30

Equipment for the Magnetic Resonance Imaging Environment

Magnetic resonance imaging1 (MRI) is a noninvasive diagnostic procedure that can produce superior images without using ionizing radiation. MRI studies are not painful but do require patient immobility. Patients who are unable to hold still often require sedation or general anesthesia. Medically unstable patients such as those from intensive care may need scanning. A more recent development is the use of MRI to guide and monitor interventional procedures (1,2,3,4,5,6). MRI-guided procedures may result in smaller incisions as well as more accurate localization and tissue retrieval.

Administering anesthesia in the MRI unit poses a number of technical difficulties. Knowledge of this environment as well as its risks and problems are essential for safe anesthesia practice. The practice guidelines for anesthesia care and monitoring developed by the American Society of Anesthesiologists and the American Association of Nurse Anesthetists apply to the MRI environment just as in other parts of the health care facility (8). In some states, these guidelines are codified into law (9).

Definitions

A device is considered to be *MR safe* if it presents no additional risk to the patient or operator. The presence of such a device may affect the quality of the diagnostic information when it is placed in the MR environment (10,11,12,13,14).

A device is *MR compatible* if it is MR safe, its use in the MR environment does not significantly affect imaging quality, and

there is no significant effect on its operations. A device may be MR compatible or safe for certain MR environments but not others. Therefore, using the terms *MR compatible* and *MR safe* without specification of the MR environment to which the device was tested should be avoided. The term *MR environment* is used to describe the area within the 5-gauss line around the scanner (the perimeter around an MR scanner within which the static magnet field is higher than 5 gauss).

Basic Principles

There is a static magnetic field inside the MRI scanner bore (7,13,15,16,17,18,19,20,21,22,23). Once the magnetic field is established, it is usually not turned OFF. If the magnet is deactivated, it can take up to 96 hours to reestablish the magnetic field. The unit of measurement of magnetic field strength is the Tesla. A field of 1 Tesla is roughly 10,000 times the magnetic field at the earth's surface. One Tesla equals 10,000 gauss. The strength of a magnet is quantified in the middle of the magnet. However, the field extends beyond the margins of the magnet (the fringe field), decreasing in strength with distance from the bore.

Atomic nuclei with an odd number of protons and/or neutrons have a spin that produces a weak local magnetic field. In the absence of a strong magnetic field, these nuclei are randomly aligned. A strong magnetic field causes approximately half of them to rotate and align parallel to this applied field (the low-energy, or ground, state). The remaining nuclei align against the applied field (the high-energy, or excited, state).

Resonance describes the process of inducing a change in energy states of the nuclei caused by absorption of a specific radio frequency (RF) radiation. Adding energy with a short, controlled burst of RF energy causes some low-energy (parallel) spins to jump to the excited (anti-parallel) energy level. Immediately after the RF pulse, the nuclei rotate back into alignment with the static magnetic field. As they return to their original orientation, energy

is released. A receiver coil detects this weak electrical signal and amplifies it for processing and eventual image formation. Relaxation rates vary for specific body tissues, allowing differentiation of body structures.

Facility Design

A member of the anesthesia department should be involved in planning the MRI unit (24,25). An anesthesia induction room that adjoins the scanning area is useful. The anesthetic can be initiated at this location, where ferromagnetic objects can be safely used. The anesthetized patient can then be moved into the scanning area. Consideration should be given to placing a postanesthesia care room near the MRI unit.

Wave guides, specially designed conduits in the walls, can be used to pass pipes, cables, ducts, tubings, and electrical wires through the wall while maintaining RF shielding (26,27) (Fig. 30.1). They are commonly placed low in the room at the farthest point from the magnet and RF coils.

Fluorescent lighting emits RF energy that interferes with imaging (21). Therefore, incandescent lighting at a low wattage is used. Isolated electrical power is used to reduce the problem of leakage currents (10). It is important that there are an adequate number of electrical plugs at convenient locations for portable monitors and other equipment.

There are four basic options for locating monitoring and other equipment that is used to administer anesthesia or sedation and the person attending the monitors and patient:

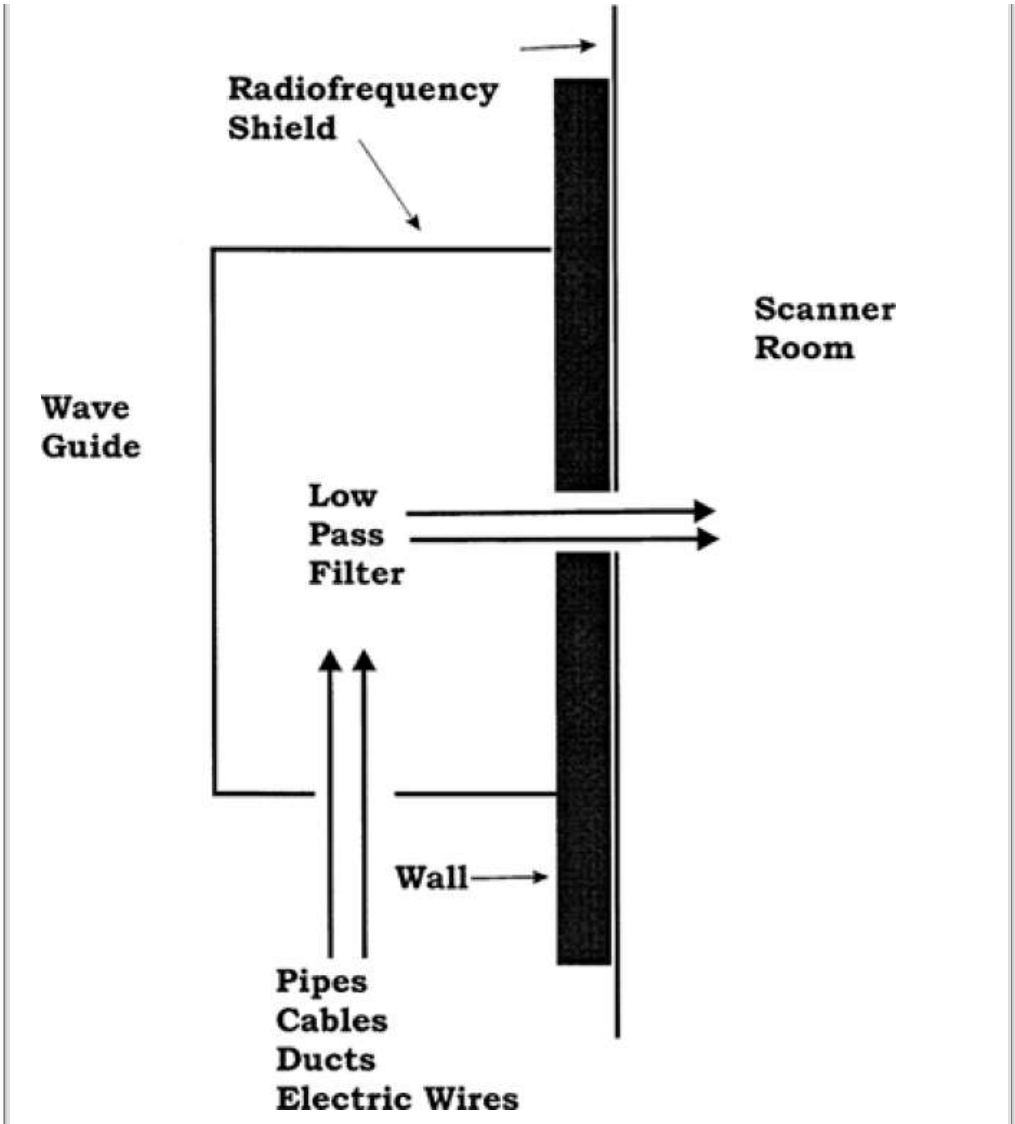

Figure 30.1 Wave guides are used to pass cables, tubings, sires, and the like through the wall while maintaining radio frequency shielding.

1. Both the monitors and the attendant are inside the magnet room. This allows direct observation of the patient. The attendant can both see and hear the monitors, but the attendant is subject to possible hazards (loud sounds,

magnetic forces, and possibly trace anesthetic gases or hypoxia). It may be necessary for the attendant to be in the room when there is an inability to see the patient, particularly if the patient has entered the scanner headfirst and/or the patient is a child (28).

2. The monitors are inside the room with the attendant outside. The patient and monitors can be viewed through a window or by using a television camera. Light-emitting diode (LED) displays are usually easier to read from a distance than liquid crystal displays (21). Remote auscultation using specially designed equipment can be used to monitor heart and respiratory sounds (29). A drawback is that monitor sounds and alarm signals may not be heard well by the attendant.
3. The third option is to have the monitors outside and the attendant inside the room. Most equipment can be kept outside the scanner room with cables and such running through wave guides (30,31). The attendant can observe the monitor through a window or a television screen but cannot hear monitor and alarm sounds well.
4. The last option is to have both the monitors and the attendant outside the room. The attendant can see the monitors and can hear the alarms and sounds but cannot observe the patient well.

If the attendant is outside the room, he may fail to detect dangerous situations in a timely manner (32). There is a report of a patient dying during an MRI procedure when the pneumatically-driven ventilator ran out of oxygen (33). MRI auditory alarm signals need to be much louder than those used in the operating room due to the significant scanner noise.

Problems

It is important to note that some devices that are stated to be

MR compatible have limitations or restrictions to their use in the MR environment, and if they are not used in accordance with these restrictions/limitations, they can pose the same types of hazards as devices that are not MR compatible (14,34).

Ferromagnetic Materials

All materials can be classified as either paramagnetic or diamagnetic (7,15,16,17,18,21,22,27,35,36,37,38,39,40,41,42). Paramagnetic materials are weakly attracted and diamagnetic materials are weakly repelled by magnetic fields. Ferromagnetism is an extreme form of paramagnetism exhibited by a small group of materials that are powerfully attracted to magnetic fields. Ferromagnetism is shown by devices containing iron, iron oxide, iron-containing alloys, nickel, and cobalt (43).

Depending on the configuration of the magnetic field and the shape and mass of the object and its position within the magnetic field, these forces can result in rotational (torque) and/or translational (attractive) motion of the object.

Ferromagnetic Materials External to the Patient

The attractive force exerted on a ferromagnetic object depends on the distance between the object and the center of the magnet, the mass and geometry of the object, the strength of the magnet, and factors that modify the field configuration such as magnetic shielding.

The attractive force increases rapidly as one nears the magnet and can be several times that of the earth's gravitational field by the time it reaches the center of the magnet. When free, ferromagnetic objects can move toward the magnet center with dangerous speed (Ĩ€missileĨ€ or Ĩ€projectileĨ€ effect). This can result in equipment damage as well as serious injury to patients and/or workers trying to restrain the equipment or trapped between the equipment and the magnet (14,44,45). Since the

magnet is continuously ON, it can attract ferromagnetic devices even when no imaging is occurring. In addition,

significant masses of ferromagnetic material in proximity to the magnet can disturb the homogeneity of the static magnetic field, resulting in distorted images.

Ferromagnetic parts may work loose over time, so precautions should be taken during product design to prevent the inclusion of components that could be pulled loose and attracted to the magnet bore (10). Removable equipment covers should use captive hardware (e.g., screws and fasteners).

There are hundreds of ferromagnetic objects that must be kept out of the MRI room. These include personal items (watches, scissors, keys, paper clips, nail clippers, hairpins, calculators, identification badges, cigarette lighters, steel-tipped/heeled shoes, pens, jewelry, clipboards, pagers, cell phones, firearms, etc.); patient items (strap buckles, safety pins, jewelry, zippers, metal gown fasteners, contraceptive diaphragms, cosmetics containing metallic particles (such as eye makeup), skin staples, superficial metallic sutures, RF tagging bracelets, metallic handcuffs or ankle cuffs, etc.), and medical devices (standard gas cylinders, hemostats, needles, vials, stethoscopes, chest tube stands, intravenous poles, stretchers, wheelchairs, mobile stands, carts, anesthesia machines, vaporizers, monitors, defibrillators, sandbags, traction weights, etc.) as well as mop buckets, vacuum cleaners, laundry carts, chairs, ladders, light fixtures, floor buffers, and parts of a forklift (12,38,39,40,46,47,48,49,50,51). Non-lithium batteries are strongly magnetic.

The presence or absence of ferromagnetism in a given object depends on a number of factors, including its composition and manufacture. Some objects that are ferromagnetic may still be safe because their mass is too small for the forces involved to be significant and/or because they are firmly anchored in position at a safe distance from the scanner. One method is to

anchor all devices that have ferrous material to a movable ceiling pendant system with a predetermined limited range of motion (24). Even with a reduced ferrous load, some delicate instruments are still ferromagnetic and subject to torque that can cause serious damage. Therefore, all equipment that is not required should be removed from the site.

Equipment may be positioned away from the magnet, in a room adjacent to the MRI room with tubings and wires used to connect to the patient. The safe distance from the center of the magnet depends on field strength and shielding. It is usually considered to be greater than the 5-gauss line (12). Equipment containing ferromagnetic components should not be allowed past the 5-gauss line unless it has been labeled MR safe for that specific MR environment.

All persons entering the scan room must be rigorously screened for internal and external ferromagnetic material. Prominent warning signs should be posted. MRI centers should keep registers of commonly used devices and whether they are safe to bring into the magnet room. The use of metal detectors in MR environments may help, but is not recommended by the American College of Radiology (49). Nonambulatory patients should be brought into the MR unit by using a nonmagnetic wheelchair or wheeled stretcher and transport equipment checked for magnetic objects (12).

Materials considered safe in the MRI scanner suite include aluminum, brass, nickel, plastic, titanium, copper, beryllium, silver, and gold (43,52). Certain types of stainless steels are considered safe, but others are strongly attracted in the magnetic field (11,38).

Battery-powered equipment should be tested at its intended location and maximum field strength to ensure that there is no significant attraction. A magnet can be used to test equipment going into the MRI room (53). Most institutions have a cardiac pacemaker ring magnet, and this can be used.

Ferromagnetic screening does not evaluate the potential for RF-related patient injury (53). Nonferromagnetic metals (e.g., aluminum or copper) that would yield a negative magnetic screen can absorb RF energy, resulting in MR image artifact or thermal injury to the patient.

Implanted or Inserted Ferromagnetic Objects

Ferromagnetic objects within the patient are subject to forces that try to bring them into alignment with the magnetic field. The extent of injury will be affected by the magnetic field strength, ferromagnetism of the object, the object's geometry and orientation, the location of the object in situ, and the length of time the object has been indwelling (fibrosis or granulation tissue can serve to stabilize the object). There are documented cases of death and blindness resulting from MR imaging of patients with ferromagnetic intracerebral aneurysm clips, cardiac pacemakers, and clinically occult metallic intraocular (39,54,55,56). MRI is contraindicated for a patient with shrapnel located in a biologically sensitive area. It could move and injure the patient (10). People in certain occupations, such as sheet metal workers, are at risk of having magnetic fragments in their bodies and in many cases are not aware of their presence (39). Now that MR imaging is a firmly established diagnostic modality, efforts are being made to use magnetically compatible substitutes for previously utilized ferromagnetic implants (39). For example, most new cerebral aneurysm clips are made of nonferrous material (52).

The Food and Drug Administration (FDA) requires that MR imagers be labeled to indicate that the device is contraindicated for patients who have electrical, magnetic, or mechanical implants because the energies produced by MRI systems may interfere with the operation of these devices (57). The composition of the device and its magnitude of magnetic deflection should be determined before these patients are scanned. These

devices include pacemakers, cardioverter-defibrillators, electromechanical infusion pumps, cochlear implants, neurostimulators, bone-growth stimulators, dental implants, bullets, magnetic sphincters, magnetic stoma plugs, magnetic ocular implants, tissue expanders with magnetic posts, and magnetic prosthetic appliances (57). Problems may also occur with magnetic objects that are attached to the patient's body (e.g., body piercing) (12).

Equipment Malfunction

Magnetic interference can cause computer or oscillometric images to be distorted (7,21,27,58,59). Devices with rechargeable batteries may switch off and blank their screens. MRI interference also causes transformers to become saturated and burn out. RF pulses are also capable of inducing electrical eddy currents and short circuiting electrical equipment. The magnetic field may cause damage or erase data on magnetic media such as digital tapes or floppy disks.

Equipment may contain pumps, electric motors, electronic circuitry, or analog gauges that are affected by the magnetic field (10). The magnets in motors may become saturated. This can result in lack or slowing of motor operation or increased operating current, which could ultimately burn the motor out.

There are two general methods to solve this problem: locate the equipment out of the magnetic field or make the equipment compatible with the magnetic fields.

One way to make equipment MRI compatible is to shield monitors and cables from RF currents. Cables can be wrapped with a thin layer of aluminum foil, and small copper boxes can be used to house electrical equipment. Using appropriate RF filters in the magnet shielding and isolated filtered alternating-current power circuits may permit effective monitoring (58).

Monitors specially designed for use in the MRI unit combine low

ferromagnetic content, shielding, and filters to minimize magnetic field interference. These devices may have some limitations to their use in the unit. It is important that prior to use, manufacturer declaration and/or clearance by a recognized body such as the FDA demonstrates MR compatibility.

Image Degradation

Equipment can degrade the quality of imaging in two ways (7,10,17,27,30,58,60). First, ferrous metal in monitors and other equipment can cause disturbances in the magnetic field. Second, the equipment may generate signals that interfere with the MRI signals.

Any RF energy within the bandwidth of the receiver, including stray radiation from outside RF sources, is amplified. Sources of RF noise include electrical machinery, motors, computer hardware, displays, television transmitters, beeper-paging systems, two-way radios, commercial radio stations, and other electrical equipment. It is common practice, therefore, to enclose the scanning area in an RF shield. Nonconductive devices can safely be passed through the shield, but wires that transgress the shield can act as aerials and feed noise from the external environment into the examination area. This can be overcome by filtering wires that run in and out of the shield. Care must be taken to match filters to specific monitors.

To prevent RF interference from degrading the MR image, appropriate measures to provide shielding, such as housing the display in a RF-tight enclosure or locating the unit outside the room, should be used. In either case, the connections between the display unit and the patient should pass through filters that attenuate frequencies around the imaging frequency. All electrically conductive material that is not required should be removed from the MRI system bore.

The distance from the magnetic core necessary to prevent RF interference varies with the strength of the magnet. Several

meters between the scanner and other equipment are usually necessary. This distance can make it difficult to read and interact with the equipment. Long spliced lines and tubings may disconnect, impose high resistance, or become obstructed.

Another solution is to adjust the frequency of the noise source so that it is outside the MRI-receiver system bandwidth. This can often be accomplished by adjusting the block that controls the operation of the microprocessor in the monitor.

Once the examination has started, the position of the monitoring equipment should not be changed, because repositioning of a large metallic mass may degrade magnetic field homogeneity.

Burns

Applying intermittent RF fields to metallic objects within the imaging area can cause heating and result in burns (7,10,16,26,48,57,59,61,62,63,64,65,66). Equipment of primary concern is that which may be positioned directly in the RF transmission field. This includes electrocardiogram (ECG) electrodes and leads, pulse pickup and pulse oximetry sensors and cables, halo devices, and surface coils as well as metallic components, connectors, and surface coils. These can provide a path for current flow through the patient or along the cable shield to ground. If this current is not limited, patient burns can result at the location of equipment or at body parts located next to an insufficiently insulated RF shield. Other devices that utilize a wire such as thermodilution Swan-Ganz catheters or epidural catheters can also subject the patient to electric shocks or dangerous heating (43).

Burns may also occur from contact with the scanner bore. High duty cycle sequences cause heat to build up

on the inside of the bore. Burns can be minimized by using the following measures:

1. Electrically-conductive leads should be replaced with nonconducting paths (e.g., fiberoptic cable or plastic tubing) or high-resistance paths (e.g., carbon ECG leads).
2. Electrically-conductive material (ECG leads, cables, etc.) that must remain within the MR system bore should be positioned to prevent ‘€cross points.‘€ A cross point is where a cable crosses another cable, loops across itself, or touches either the patient or sides of the magnetic bore more than once. When the patient is moved, wires may coil and form a loop, so it is important to check all wires each time the patient is moved.
3. Cables and sensors should be kept away from the bore (e.g., by placing a pulse oximeter sensor on the patient's toe when the head is being examined).
4. All sensors, wires, and cables should be checked to ensure that the electrical insulation around them is intact. A small towel should be placed between the patient and the wires or cable to avoid contact with the skin.
5. All unnecessary conductive materials such as unused wires, leads, sensors, cables, and surface coils should be removed from the MRI environment.
6. All electrically-conductive material that must remain in the MR system bore should be kept from directly contacting the patient by placing thermal and/or electrical insulation (including air) between the conductive material and the patient. Wires should not cross metallic prostheses.
7. Cables should be positioned so that they exit as close as possible to the center of the patient table of the MR system (63). It is also important to avoid cable contact with the skin or the MRI scanner.
8. Conscious patients should be instructed to call out if they experience uncomfortable heat levels so that the procedure can be immediately discontinued.

9. Any monitor that does not appear to be operating properly during the MR procedure should be removed.
10. A cold compress/ice pack should be placed along skin staples, superficial metallic sutures, and lead attachment sites, if this can be safely accomplished (49).

Hypothermia

Hypothermia can be a problem, especially with small children (27). Air is often circulated over the patient during the imaging sequence. Covering the patient, warming fluids, and using non-electrical heating pads and humidified inspired gases can help to prevent hypothermia (52). Heating blankets and radiant lights cannot be used because they interfere with imaging.

Other Patient Problems

Loud sounds in the MR environment may obscure cries for help from a patient in distress (9). The patient should be given a squeeze ball to sound a distress signal, but this is of limited usefulness in the sedated patient.

A major problem for anesthesia personnel is the relative inaccessibility of the patient. This creates problems with monitoring, airway management, intravenous access, patient visualization, and monitor application. Patients can only be directly observed from either end of the tunnel and can only be extricated by sliding them out.

Specific Equipment

A number of devices specially designed to be used in the MRI unit are available. It is important to demonstrate MR compatibility by preuse testing, manufacturer declaration, and/or clearance by a recognized body such as the FDA. For devices that do not carry such credentials, it is advisable to consult the manufacturer or biomedical personnel with expertise in MRI

before introducing them into the MRI room. It is important to read all of the instructions accompanying a piece of equipment, because some equipment may be MR safe or compatible only if installed a certain distance from the magnet (67).

MR is an evolving technology, and specifications and performance characteristics of specific MR systems continually change. Products should be tested under simulated or actual use conditions. Because upgrades to the MR system to achieve higher performance levels may affect the characteristics of the equipment, yesterday's device tests may not be sufficient to ensure the safety and effectiveness of a device with today's MR system (10). Since new equipment is continually being introduced, it is only possible to make generalizations about which equipment is MRI compatible. It is recommended that equipment intended for use within the magnet room be clearly labeled with the maximum field level within which it can operate effectively (10).

Monitors with multiple functions decrease the amount of equipment that must be transported, decreasing the risk of equipment damage and injury to the personnel responsible for transport.

Any equipment that has an alarm should have a visual alarm signal, because auditory signals may not be heard (5).

Anesthesia Machines

Standard anesthetic machines contain varying amounts of ferromagnetic substances and electronically controlled components, making them unsuitable for use in

proximity to an MRI magnet (68,69). Non-MRI compatible anesthesia machines have been used without problems by keeping them 20 to 30 feet away from the core of the magnet (26). Some anesthesia practitioners have used long tubings fed into the scanning room from an anesthesia machine placed

outside the scanning room or a standard anesthesia machine bolted to the wall (31,52). Replacing ferromagnetic components (e.g., support structures, castors, cylinders, and parts of cylinder supports) with nonferromagnetic materials and aluminum cylinders can make an anesthesia machine MRI compatible. A few ounces of magnetic material may prove negligible. MRI-compatible anesthesia machines are available (Fig. 30.2). Aluminum cylinders have been available for some time. Unfortunately, confusion about cylinder composition can arise (70).

Vaporizers

Most standard vaporizers perform accurately when used in the scanning room (36,68,69,71). However, a portable vaporizer may be dangerous due to ferromagnetism (51).

Anesthesia Breathing Systems

A number of breathing systems have been used successfully in the MRI environment. These include the circle and Mapleson systems (20,35,52,58,72,73). Long corrugated or fresh gas tubing will be required if the anesthesia machine is remote from the patient. Fortunately, most components of circle breathing systems used today are nonmetallic.

Figure 30.2 MRI-compatible anesthesia machine. (Picture courtesy of Ohmeda.)

Anesthesia Ventilators

Standard anesthesia ventilators usually contain ferromagnetic materials, pumps, electric motors, and analog gauges that can be affected by the magnetic field unless specifically adapted for the MRI. These may not function properly in a magnetic field or may degrade the image. A remote ventilator in the control room with circuit tubing fed into the scanning room can be used, or an incompatible ventilator can be attached to the wall (31,52).

Specially engineered MRI-compatible ventilators (both anesthesia and critical care) that have no electronic components are available (27,35,74,75,76,77). Fluidic ventilators work well in the MRI environment (75). Cur-rently available MRI-compatible anesthesia machines are equipped with ventilators. An MR-compatible positive end-expiratory pressure (PEEP) device is available (78).

Pulse Oximetry

Most of the early pulse oximeters were both susceptible to interference from the RF pulses and a source of interference to the MRI signal (10,15,17,21,79,80). Burns have been reported at both the sensor site and along the cable (17,22,61,62,81,82). Heavy insulation and shielding can be used to isolate the monitor signal (17,21). The monitor should be placed as far from the magnet as possible.

Components, including the probe, with a low ferromagnetic content are useful, as is minimizing the number of electrical connections and computer chips within the monitor. Most consoles have filters in the circuitry and some models have filters in the cable to help eliminate extraneous signals. These help to separate the signal from background noise (21).

A convenient method to eliminate ferromagnetic wire is to use a fiber-optic cable (79,83). If a standard ferromagnetic cable is

used, it should be wrapped with aluminum or copper foil to shield the metal and decrease RF interference (22,80,84).

A variety of MRI-compatible sensors, cables, and consoles are available. The sensor can be shielded to prevent noise from reaching the MR system. The digits can be protected with clear plastic coverings (27).

The sensor should be placed as far from the scan site as possible. This may require that it be placed on the foot or head, depending on the area to be imaged. The cable should be extended in a straight line away from the patient. The length of the cable should allow the oximeter to be far enough from the magnet to prevent image degradation.

Respiratory Gas Monitoring

There are a number of different technologies to measure respiratory gases. They are discussed in Chapter 22. Mainstream capnometry systems cause image interference. The sensor requires shielding from RF radiation. Sidestream monitors may be used during imaging as long as the monitoring device is outside the magnetic field (19,58,85). Multiple lengths of tubing may be connected to allow the monitor to be outside the magnetic field. The extra length of tubing between the patient and the monitor may degrade the capnogram and decrease the accuracy of the end-tidal reading, especially with small patients (22). However, even if end-tidal measurements are not accurate, the trends and respiratory pattern may still give useful information. If enough tubings are connected together, the resistance can become so high that the alarm for blocked tubing is activated (83).

MRI-compatible multigas monitors are available. This technology can be combined with other modalities such as pulse oximetry, electrocardiography, and noninvasive blood pressure monitoring (52). Such equipment can be positioned either inside or outside the magnet room.

Chemical detectors (Chapter 22) that change color in the presence of carbon dioxide are made of plastic and contain no metal parts. They must be placed close to the patient and may be difficult to see. They are qualitative devices and are only generally quantitative. This makes them more suited for checking tracheal tube placement than for long cases. Electrochemical oxygen analyzers are usually safe for use in the MRI suite as long as they are outside the magnetic field (20,22).

Noninvasive Blood Pressure Monitors

Automated blood pressure monitors are discussed in Chapter 27. The MRI does not affect monitors that use the oscillometric method as long as the electronic unit is either shielded or well away from the magnet core (18,19,20,26,27,36,85,86,87,88). It may be necessary to use extended tubings. Ferrous connections on the cuff should be replaced with plastic ones (83).

Manual sphygmomanometers have been adapted for use during MRI by replacing all ferromagnetic components with brass, aluminum, or plastic pieces (36). A plastic stethoscope can be used to monitor Korotkoff sounds. The magnetic field may affect the accuracy of analog gauges since the movement mechanism in some gauges uses a small magnet and a coil for operation. Blood pressure can be monitored outside the scanner by lengthening the tubing connected to the cuff (89). Ultrasonic Doppler units have been used to monitor systolic blood pressure (89,90).

Invasive Blood Pressure Monitors

Most intravascular lines are nonmagnetic and are not affected by the magnetic field (36). Direct pressure readings can be obtained if the lead from the pressure

transducer is passed through a RF filter or positioned away from the magnet (30,58). Fiber-optic MRI-compatible transducers are available (18,91).

Electrocardiographic Monitors

The ECG can cause patient burns and image degradation as well as function inaccurately in the MRI environment (15,17,21,27,35,52,58). ST-segment monitoring is impossible in the presence of the magnetic field using current technology (92).

The amount of RF interference that is coupled into the leads can be controlled by appropriate design measures (e.g., by selecting appropriate materials for the ECG leads and by filtering the amplifier circuitry input) (10). Special MRI-compatible electrocardiographic leads may be constructed by using high-resistance conductors that minimize induced RF currents (23).

A number of measures will minimize effects (7,21,27,35,58,93). Non-ferromagnetic fasteners, electrodes, leads, and cables are available. A filter can reduce artifacts in most leads (68,94). Good skin preparation is important to optimize the ECG signal. The skin should be shaved and cleansed with alcohol before the electrodes are placed (15). For best results, the skin should be dried or lightly abraded (27). Electrodes should be placed as close to the center of the magnet as possible because the RF power is changing least at this point. The limb electrodes should be as close together as possible and in the same plane. Using chest leads, V_5 and V_6 minimizes artifacts (95). Liquid crystal screens do not undergo distortion as do cathode ray tubes (58). The relative length of ECG leads may be critical in preventing gradient-induced artifact; therefore, many manufacturers advise against modifying ECG leads supplied with MR systems (58).

Telemetry may sound appealing because it reduces the wiring and cables needed, but it may interfere with the RF used for imaging. This interference is not seen with ultrahigh frequency units. These telemetry units are limited to QRS complex detection (27,88).

Temperature Monitors

Standard thermistor temperature probes can distort the magnetic field, causing localized image distortion if placed near the area of interest (96). They could also cause a localized concentration of RF power that would result in increased heating. Small wire probes have been used in the MRI without excessive heating (96).

Although temperature probes with filtered cables are available, they carry the same risks of signal interference and burns as other electronic monitors (97,98). A burn associated with temperature monitoring using a probe specially designed for use during MRI has been reported (98). A burn may be caused by inadvertent formation of a cable loop during patient movement.

Fluoroptic temperature probes that contain material that has temperature-dependent optical properties are not affected by high magnetic field strength and RF pulses and are therefore more suitable for use in the MRI environment (96). These probes are more expensive and more fragile than wire thermistors.

Liquid crystal temperature strips work well in the MRI room but may not be easy to observe (15).

Laryngoscopes

The standard laryngoscope (Chapter 18) is not ferromagnetic but can undergo a degree of torque in a magnetic field (58). Plastic laryngoscopes are available, but most batteries are magnetic. One solution is to modify the handle to operate from a non-battery-based power source (36,52). A remote fiberoptic light source can be used. MRI-compatible laryngoscopes are available. Most are powered by lithium batteries. A paper- or plastic-covered lithium battery can be used with a plastic laryngoscope (17,18,19,58,99).

If an MRI-compatible laryngoscope is not available, anesthesia can be induced and the airway intubated outside the magnet room using a conventional laryngoscope before the patient is moved into the scanner (19). If inadvertent extubation occurs

while the patient is in the scanner, an MRI-safe laryngoscope will be needed.

Tracheal Tubes

Tracheal tubes (Chapter 19) are most commonly made of polyvinyl chloride and are safe to use in the MRI environment. There are reports of signal interference from the spring in the cuff inflation check valve (60,100,101). A tracheal tube with a wire spiral cannot be used in the MRI room (35,102). Connectors should be plastic.

Supraglottic Airway Devices

The laryngeal mask (Chapter 17) is suitable for the MRI environment. It allows the light level of anesthesia that is possible, as there are no painful stimuli involved in the MRI process. Because some laryngeal inflation valves masks contain metallic material, it may be necessary to remove the valve and knot the pilot tube (103). Special laryngeal mask airways (LMAs) with valves that do not contain ferrous material are available (104). If the LMA-Flexible or LMA-ProSeal is used, the metal coil produces a large black hole in the image in the area surrounding the airway as well as deterioration of the image further out (105).

The LMA may not be suitable if magnetic resonance spectroscopy is performed because the resonance of some silicone-containing materials compromises interpretation of the scans (106).

Other supraglottic devices are for the most part made of polyvinyl chloride or silicone, which does not cause problems with the MRI. There are no reports of problems at the time of this writing.

Other

MRI-safe and -compatible suction regulators and nonmetallic precordial stethoscopes are available and should be used.

Some infusion pumps need to be located away from the magnet or shielded or they may perform inaccurately (17,36). MRI-safe infusion pumps are available. Extension tubing may be required. There is a report of a patient-controlled analgesia device that malfunctioned after exposure to the magnetic field (107,108). Some infusion pumps function correctly in the MRI environment (52,109,110,111).

It is possible to monitor intracranial pressure in this setting by using a nonferromagnetic subdural bolt or plastic catheter and a fiberoptic cable (21,53,112,113).

Electroencephalography and evoked potential monitoring, both of which use long conducting wires, will require technological advances before they can be used in magnetic fields (92).

Personnel Hazards

It is not possible at this time to determine without question if there are hazards to personnel who work in the MRI environment. This is largely due to the relatively short time for which this method of imaging has been in existence and the fact that this work is occasional for most practitioners. Future epidemiologic evidence may or may not demonstrate harmful effects of long-term exposure. Female staff should consider avoiding this area during the first 3 months of a pregnancy.

Noise

Noise is due to vibration of the switched gradient coils and is enhanced with higher strength gradient coils, shorter gradient duty cycles, and faster pulse repetition frequencies in the magnet (114). The trend toward upgraded imaging systems and stronger magnets would suggest that noise levels are likely to increase (31). Noise levels up to 106 ยฑ4 decibels with an average around 92 decibels have been demonstrated (31). These

are potentially damaging levels, and care must be taken to reduce these levels of exposure as much as possible. Ear plugs should be considered, although they may interfere with hearing auditory alarm signals (43,52).

Exposure to the Magnetic Field

With the increased use of MRI and magnets of increasing strength, anesthesia providers are experiencing increased exposure to static magnetic fields within MRI units. The static magnetic field extends beyond the confines of the magnet. The strength of this fringe field depends on the magnet configuration and shielding. It decreases rapidly as the distance from the magnet increases. The biologic effect of static magnetic fields is a controversial topic (38). There are no demonstrated oncogenic or teratogenic effects (52). It would seem prudent to take reasonable precautions against repetitive and avoidable exposure to intense magnetic fields.

Risks include danger from unrestrained ferromagnetic objects and from movement or malfunction of MR-incompatible implants within their bodies (31).

Trace Anesthetic Gases

Trace anesthetic gases and their risks to anesthesia personnel are discussed in Chapter 13. Scavenging systems and good ventilation with frequent air exchanges are not always available in the MRI unit (31). Some breathing systems such as the Mapleson systems (Chapter 8) are often used for pediatrics, and many of these are not scavenged.

Hypoxia

If liquid helium that surrounds the superconducting solenoid in the magnet escapes, it is possible that a hypoxic environment may be created (31). Oxygen sensors can be placed in the ceiling to warn of this problem.

[1]Most physicians refer to this type of imaging as MRI, while most physicists refer to it as nuclear magnetic resonance (NMR) (7). Both are accepted terms and refer to the same technology.

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Questions

For the following question, select the correct answer

1. The distance from the center of the magnet that is usually considered to be safe for ferromagnetic objects is

A. The 2-gauss line

B. The 3-gauss line

C. The 4-gauss line

D. The 5-gauss line

E. Beyond the 5-gauss line

View Answer

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. if D is correct

E. if A, B, C, and D are correct.

2. Which factors determine the attractive force on a ferromagnetic object in the MRI unit?

A. The strength of the magnet

B. The mass and geometry of the object

C. Magnetic shielding

D. The distance of the object from the outer field of the magnet

View Answer

3. Which of the following are considered to be safe in the MRI scanner?

A. Aluminum

B. Beryllium

C. Gold and silver

D. All types of stainless steel

View Answer

4. Which metals can cause a negative magnetic screen and absorb radio frequency energy that can result in an MRI artifact or thermal injury to the patient?

A. Aluminum

B. Gold

C. Copper

D. Silver

View Answer

5. Sources of radio frequency noise that can degrade the MRI image include

A. Commercial radio stations

B. Beepers

C. Motors

D. Liquid crystal displays

View Answer

6. Which items may cause a burn from radio frequency fields?

A. ECG electrodes

B. Epidural catheters

C. Pulse oximetry cables

D. Swan-Ganz catheters

View Answer

7. Methods to keep pediatric patients from developing hypothermia in the MRI unit include

A. Warm fluids

B. Radiant lights

C. Covering the patient

D. Electrical heating pads

View Answer

31

ature Control Equipment

ic Temperature Control

es have shown that significant temperature
ly occur in anesthetized patients (1). Inadvertent
by far the most common disturbance. Without
ntions, up to 90% of patients entering the
care unit (PACU) may be hypothermic (2). An
be patients undergoing magnetic resonance
n whom the absorption of radio frequency
artially offset heat loss.

P.885

etized patient, vasoconstriction maintains a
adient between the core and periphery of 2ยฐC to
ly temperature is normally maintained within a
f 37 ยฑ0.2ยฐC. When core body temperature goes
e, physiologic mechanisms are initiated to
norm. Anesthesia alters the response threshold,
dy to experience greater variations in temperature
ts to reestablish a 37ยฐC core temperature.
ltered temperatures are less effective under

der anesthesia usually follows a characteristic
Core body temperature usually decreases 0.5ยฐC
g the first hour (5,6,7) as vasodilatation causes
f body heat from the core to the periphery.
eral tissues before induction of anesthesia
ecreases the central-to-peripheral temperature
y minimizing the redistribution of heat from the
phery and reducing the initial decrease in core
9,10,11,12,13,14,15,16,17,18,19). This
annot be prevented by intraoperative skin surface

our, core temperature typically decreases at a
he body's heat loss exceeds the metabolic heat
s is followed by a thermal plateau during which
re no longer significantly decreases. At this time,
brates with heat production and vasoconstriction
bolic heat to the core compartment while allowing
es to continue to cool. Patients with neuropathies
ere hypothermia than other patients, possibly
set of vasoconstriction is delayed (20). A plateau
eached when regional anesthesia blocks
n (1).

ic patients, vasoconstriction decreases rewarming
reason, patients should be warmed during surgery
wed to cool and then be postoperatively ไ
arming may be accelerated by using certain drugs
a sympathetic block (23).

of Heat Loss

st via the skin surface. This loss is roughly
the skin-to-environment temperature gradient and
e area in contact with a lower temperature
ediatric patients have a high surface area to body
thus tend to cool more quickly than adults but
re quickly (24).

e major heat loss mechanism, accounting for 65%
ody's heat loss (6). This is the loss of
c energy through infrared rays from the warm body
s in the room that do not contact the body.
ss is a function of the difference in temperature
tient and objects in the operating room (OR) and
sivity (3). It is unaffected by air temperature, air
he distance between the surfaces.

n

jor mechanism of heat loss is convection. This is
heat to an air current. The magnitude of
exchange is determined by the temperature
en the body and the air as well as the velocity of
l drapes prevent convective heat loss during
f the heat lost by this mechanism occurs when
are exposed prior to surgical draping.

n

oss mechanism is conduction. Heat is lost
contact between the patient and colder objects
erating table, linens, surgical instruments and skin
gation, and intravenous (IV) fluids (25,26). The
portional to the temperature difference between
Thermal insulation between the surfaces will
nsfer. Wetness increases conductive heat loss
ittle heat is lost to objects such as the OR table
ost when cold preparatory and irrigation solutions
e used can reduce body temperature significantly.

on

loss mechanism is evaporation. Evaporation
om the skin, respiratory tract, open surgical
operitoneum, or wet towels and drapes that are in
ith the patient's body.

ors

ctors determine the severity of hypothermia. The
cal procedure, the greater the drop in
he site of surgery is another consideration, since
re subject to considerable heat loss from
ether open or laparoscopic techniques are used
1,32,33,34,35,36). Administering large quantities
igation fluids will further chill the patient.
e, cachexia, female sex, and low body mass are
inadvertent hypothermia.

Associated with Hypothermia

a potential cause of adverse patient outcomes
sociated with life-threatening complications
omplications are initiated intraoperatively,
re generally manifested

he recovery period. The consequences of
ll depend on the size and condition of the patient.
or those in weakened conditions will be more
he negative effects. Maintaining patient's
creases postoperative mortality and improves
,41,42,43).

Changes

olic changes include a leftward shift of the
dissociation curve, accumulation of metabolic
xacerbation of lactic acidosis (44,45,46).
uration may be higher with warming (47). Babies
vely warmed during cesarean delivery have a
vein pH (48).

and Thermal Discomfort

associated with postoperative shivering, which is
nd uncontrollable. It causes patient discomfort;
bolic demand and cardiorespiratory work;
ocular and intracranial pressures; and interferes
, especially pulse oximetry. Wound pain may be
shivering. Many patients recalled shivering and a
se cold as the most distressing memory of their
agement, even after relatively short procedures.
report the discomfort from shivering and the cold
e than the surgical pain (49,50). Skin temperature
ortance with core temperature in determining
(51).

Recovery Time and Length of

ave shown that intraoperative hypothermia causes
ng and longer time in the recovery room (even
ure is not a discharge criterion). Hypothermia may
ative confusion (52). Higher postanesthesia
extubation, and shorter PACU times are
normothermia
7,58,59,60,61,62,63,64,65). Mild hypothermia
g recovery in pediatric patients having peripheral
aintaining normothermia may shorten
(45).

Drug Tolerance

n is altered, drug metabolism is decreased, and
anesthetic drugs is altered. This often results in
ncentrations and prolonged duration of action

nia

n lead to fluid shifts from the vascular to the
ace and a relative hypovolemia. For every degree
ypothermia, 2.5% of the intravascular volume may
d-induced diuresis can occur, adding to the
e patient rewarms, vasodilatation may occur and
need to be given to accommodate the loss.
ypothermia have significantly greater fluid and
uirements (41,43,52).

oconstriction can make it more difficult to insert
us catheters. Active local warming facilitates IV
on (70).

cular System Effects

hances sympathetic activity. Catecholamine
may rise (71). Peripheral vasoconstriction, which
y's effort to conserve heat, can result in
l pressure and cardiac workload and
aphic changes (65,72,73). Risks include cardiac
le-creased contractility, myocardial ischemia and
cardiac arrest (74,75,76). Hypothermia can result
verse hemodynamic events and increased
r vasoactive drugs (41,77). Normothermia is
a reduction in the incidence of postoperative
events in patients with known risk factors for
disease (46,65,74,76,78). However, the effects
elatively young, generally healthy patients (55).

ing patients with profound hypothermia can result
redistribution of blood to the periphery as tissues

Coagulation

hibits platelet function and activation of the
cade (79). It may be associated with increased
higher transfusion requirements
1,82,83,84,85,86,87).

Resistance to Infection

thermia may delay healing and predispose
nd and other infections (45,88,89,90,91,92).
revent postoperative wound infection (93).
mothermia may attenuate protein breakdown after

ce with Monitoring

ry vasoconstriction decreases cutaneous blood
nterfere with pulse oximetry and other forms of
96).

Costs

tients have prolonged stays in the intensive care
care facility (41,87). Heart surgery patients have
ns of ventilatory support with normothermia. A
sts may result from active warming (53,97).

s may be found in association with infection.
ction and even gangrene may result (98). Cooling
ecrease in urine output (99). The agreement of
ipheral venous

riorates at lower temperatures (100). Increased
y may be associated with hypothermia (101).

Devices

ards on warming devices were published in 2002:
ng liquid and forced-air patient temperature
evices (102) and one for fluid warmers (103).

re in the standard for circulating liquid and forced

l-air devices, the maximum contact surface
re shall not exceed 48ยฐC, and the average
urface temperature shall not exceed 46ยฐC during
nditions.

ating liquid devices, the contact surface
re shall not exceed 43ยฐC, and the average
urface temperature shall not exceed 42ยฐC during
nditions.

ng standard requires that the device does not
bove 44ยฐC under normal conditions.

Methods

ccepted that no single technique alone is
bating hypothermia. The best results are likely to
combining methods. The costs, risks, and
ming should be specifically considered for each
g in preexisting medical conditions and the
ure.

Warming Devices

ming devices (convective warming devices, warm
rain ambient air through a microbial filter. The air
g an electric heater thermostatically controlled,
through a hose that is connected to an inflatable
Fig. 31.1). Some devices monitor the temperature
he warming unit. Some newer units monitor the
the end of the air delivery hose (104). Most offer
emperatures (Fig. 31.2).

vers, both disposable and reusable, are available.
ries of holes that allow the warm, filtered air to
Another design uses a fabric that allows the
ter through the entire patient side.

he cover varies (Figs. 31.1, 31.3,31.4,31.5). A
atric blankets are available. A U-shaped tubular
circles the patient may be useful in situations
c surgery, where much of the body cannot be

ver, it is less effective than a blanket placed over
2,105,106). It is possible to cut some covers and
of the cut to fit the patient (107,108). Patient and
vider gowns that can be connected

unit are available. Sleeves for warming an arm to
heter insertion are available.

1 Forced air-warming device with low body
cture courtesy of Arizant Healthcare, Eden
.)

2 Control unit on a forced air device. A selection of
es is provided.

Warming blanket for a small patient. Note the
r over the child. (Picture courtesy of Arizant
Eden Prairie, MN.)

et or sheet over the warming blanket will result in
transfer (109). Lower body warming is slightly
than upper body warming (110,111,112).
kets allow easy access to the patient (113).
are probably only useful for very small patients.

stitutions have used these units without the
t by placing the hose either under the surgical
een cotton blankets (free hosing) (114,115,116).
y result in heated air blowing directly onto only a
e patient's skin and cause burns (117,118).
practice is not recommended.

4 Over-the-body warming blanket with an
ter removed to allow surgical access.
urtesy of Arizant Healthcare, Eden Prairie,

es have shown that forced-air warming is
ntaining or increasing the patient's (including both
aby) temperature, decreasing the incidence of
ncreasing thermal comfort
9,62,105,110,119,120,121,122,123,124,125,126,127,128,129,130,131,132,133,134,135,136,137,138,139).

n when the available skin surface area to be
icted, as occurs during orthopedic, major
dominal operations (9,109). Forced-air warming is
onjunction with other warming methods (140).

6 Cardiac access blanket. This provided
arming to the legs while allowing access to

l-air warming is often effective in raising
perature, core temperature may not rise
3,144,145,146,147). This may be because of
nsfer between thermal compartments in
patients. In the patient with a neuraxial block,
may aid in heat transfer from the peripheral to
s.

ave found forced-air warming superior to older-
ulating mattresses, warmed or unwarmed
nt heat lamps, inhalation rewarming, passive
tric blankets, negative-pressure warming devices,
luids
7,57,109,127,128,139,144,145,147,148,149,150,151,152,153,154,155,156,157,158,159,160,161,162,163,164,165,166,167,168,169,170,171,172,173,174,175,176,177,1
rculating devices and resistive heating devices
ore efficient than forced-air warming devices
3,184,185,186,187,188). Some studies have
ming IV fluids was as effective as forced-air
ntaining normothermia (189,190).

mers are usually safe when properly used. There
ts of burns
94,195,196,197,198,199). Care should be
he hose does not come in contact with the
nd that the exit vents are positioned away from
the surgical field. Special care should be taken
t with ischemic areas (i.e., distal to a vascular

ming is simple, safe, effective, and inexpensive.
patient covers makes it adaptable to many
ons. Most nursing personnel and family members

hod to radiant heat. Forced-air warming provides
ost than other modalities
,202,203). Fiberoptic laryngoscopes can be
use with a forced-air warming device (204).
devices will prevent fogging when the device is
e mouth for intubation. It can be used to warm the
before the patient is transferred to it by placing
a sheet. It can also be used for cooling
ther use is to relieve claustrophobia (207). A
an be placed inside the hose from a forced-air
to heat IV fluid (Fig. 31.14). However, this is
t low fluid flow.

is that its electric power requirements make it
ield use (208). It is somewhat cumbersome to
up in a computed tomography (CT) scanner (190).
oved from the patient to expose covered areas.
antage is that many systems do not permit the
of multiple blankets (i.e., upper and lower body)
wo separate forced-air units.

Liquid-circulating device. The patient
can be wrapped around various parts of
Picture courtesy of Gaymar Industries, Inc.)

culating Devices

ting device consists of a heating/cooling unit and
device (mattress, pad, blanket, or wrap) that is
e heating/cooler unit by hoses (Fig. 31.6).
liquid circulates through the patient contact
back to the heating/cooling element. Some
upply more than one patient contact device.

may be attached to the liquid-circulating unit
can be heated by using a water mattress pad
ubing close to the patient (210).

laced either over or under the patient but is safer

tive when placed over the

1) (Fig. 31.7). Direct patient contact with the pad be avoided. Folds and creases in the pad should ese units may predispose patients to burns, so ust be assessed frequently (212,213,214).

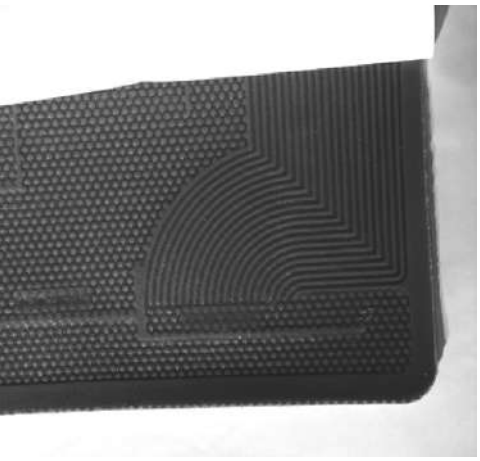
7 The pad from a liquid-circulating device ced over the patient. (Picture courtesy of Biomedical.)

8 Liquid-circulating device. The patient t adheres to the body surface. (Picture Kimberly-Clark.)

uid-circulating systems use a disposable thin pad rectly to the skin and is made of a material that conduction toward the patient. Different shapes vailable, allowing attachment to various body 86,215) (Figs. 31.8, 31.9). Most incorporate a that controls the flow and temperature and a ture sensor so that the liquid temperature can be

ntain the desired patient temperature. One
s under negative pressure so that if the pad is cut
ir will be pulled into the system rather than water
4).

id-circulating units are less effective than forced-
154,163,164,165,166,167,181,216,217,218). The
ts may be more effective than forced-air heating,
an cover a larger surface area
183,184,185,219,220,221,222).



Close-up of liquid-circulating device. The
emoved, revealing the sticky side of the pad
ched to the patient.

mattresses are heavy and cumbersome. It is
tain good contact with the stiff mattress and to
urface area (15). Their use can lead to burns,
pressure points where the patient contacts the
2,213,214,223,224,225). Placing them above the
crease the likelihood of burns. Care should be
ubing does not come into contact with the patient.

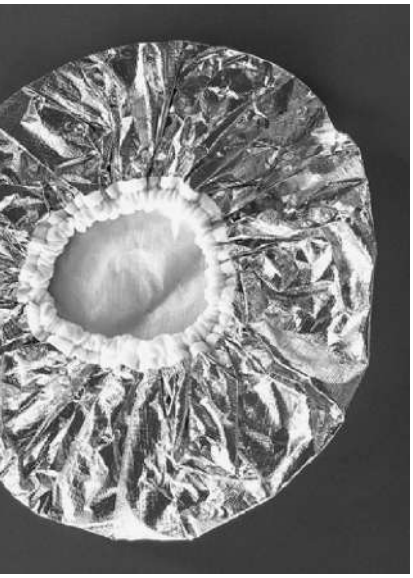
overings

e insulation can decrease heat loss from
iation, conduction, and evaporation. Cotton
cal drapes, towels and sheets, plastic sheeting,
nd specially designed reflective composites
s, space blankets, reflective blankets, metallized
or sheets, head coverings, blankets, socks,
are among the materials that have been used
29,230,231,232) (Fig. 31.10). There are minimal
ces among the various coverings
35,236,237). Warming the covers or adding
s of insulation further reduces heat loss only
not been found to be of benefit in preventing
239). These covers provide a transient sense of
ng as much surface area as possible is more
the type of covering or specific area covered.

nience should be major factors when choosing
The costs of laundering and replacing cotton
e taken into account. There are no published
nt injury caused by warmed hospital blankets

on will reduce cutaneous heat loss but will not
thermia
59,177,218,230,231,241,242,243,244,245,246,247,248,249).
ed cotton blankets to the patient has been a
in the PACU, but is ineffective (250). However,
n

e patient as soon as possible after the patient
OR will reduce initial heat loss and result in a
nperature when the patient enters the PACU



0 Thermal head covering.

ings have been found to be less effective than
ing for conserving body temperature
128,149,150,151,152,153,155,158,159,160,161,172,251).
ts were found to be inferior to radiant heat in
ering (248).

are convenient, easy to use, lightweight, and not
rical or mechanical failures. There is no burn
r, they may inhibit access to the patient. Most of
ustible and should be used with caution when a
on is present (252) (see Fires in Chapter 32).

Heating

ical heating devices generate heat by passing
rent through semiconductive wires or carbon-fiber

er results from penetrating the fabric. The system
erate normally because the current simply flows
nt fabric.

anket or mattress is thermostatically controlled by
naintain the contact surface at the set
his system can heat several fields independently.
attresses are available in a large number of
hat can be used in various combinations to
ating surface. They can be cleaned and
r use.

ng has been found to be as or more effective than
nologies, including forced-air warming
09,137,138,208,253,254,255,256,257). A reported
ost saving compared with forced-air warming
t is also quieter than forced air. Resistive heating
especially helpful for field treatment of
01,208). However, severe thermal injuries have
with an electrical warming mattress (258). A fire
electric blanket is folded and wires are broken.

eaters

rs use special incandescent bulbs or heated
erate infrared energy. The radiant heater can be
on a portable stand or a more elaborate panel
er comes as a portable unit or may be ceiling
cks (6,259,260).

vice is most effective when it heats areas high in
nastomoses such as the forehead, nose, ears,
(261). These can dilate in response to local
esthesia and allow applied heat energy to be
ctly to the core.

g can be used on exposed areas of the patient's
neter placement, skin preparation, and during the
ure, when feasible (6). It may be especially useful
60). The heat should shine on the patient's bare
through a thin sheet. If placed too close to the
result. The skin surface must be assessed
tect early signs of burns. Skin exposure may
g by convection currents, so it is important to
in the environment.

an provide faster rewarming and reduced
3,259,262,263,264,265,266). It is more effective
because of their relatively large body surface
eating has been found to be less effective than
ing but superior to electric, warmed, or reflective
49,154,178,180,248,260,267,268). It decreases
e skin washing but increases it during washing

mps enable the medical and nursing staff to have
d view of and access to the patient. There are no
d no patient contact. However, the equipment is
ewhat cumbersome. Exposure of the adult patient
ptable to the patient and family members (145). It
ns or hyperthermia if used for long periods of
ant heat source is close to the patient's skin, or if

em with the skin-temperature measurement
0). Because radiant warmers increase evaporative
may increase fluid requirements (271). Patients
neral circulation may be more difficult to heat. It
adjust the heater-skin distance if the operating

ered. Radiant warmers may interfere with imaging
RI unit (272).

d Humidifying Inspired or Gases

at loss from the airway can be prevented by using
ed gases (inhalation rewarming). Devices for
midifying inspired gases are discussed in Chapter
at transfer occurs with this method, which carries
mal injuries.

ave found that heating inspired gases is of
n rewarming, even when used in conjunction with
modalities (14,163,259,273,274). Other studies
ed humidification systems can reduce the
ivering and result in a more rapid return to
263,275). Airway heating and humidification may
ve in infants and children than in adults
but cutaneous warming is far more effective

midifying gases used for peritoneal insufflation
heat loss associated with this procedure (280).

Moisture Exchangers

ure exchangers (HMEs) are discussed in Chapter
le efficient humidification and work almost as well
difiers to prevent respiratory heat loss but cost
e filtration. However, the amount of heat
is method is small (281,282). Heat conservation
HMEs is comparable (38).

Gas Flows

gas flows reduces heat loss through the airways
, studies indicate that using low-flow anesthesia
maintaining intraoperative normothermia (158).

ming

are used to warm blood products, IV solutions,
ons, and insufflating gases (283,284). Since
usually well below body temperature, exposure
a significant source of heat loss when large
ed. Most fluid warmers have a temperature
alarm to alert the operator if the heater
temperature of the fluid is too high. Some alarm
mperature falls below a threshold.

will provide information about the maximum flow
sible for the particular system. This flow rate will
provide fluid at body temperature. If there is a
e manufacturer will also provide the flow rate that

d warmed to body temperature.

designed for use with dedicated disposable sets. sets are used in conjunction with a standard inistration set and extension tubing, while others as well as a patient line. Some offer a number of able sets designed for specific applications. ong these sets include the gauge and length of number of bag spikes, and the presence of a /or degassing mechanism.

can prevent the heat loss caused by infusion of generally cannot transfer enough heat to prevent restore normothermia expeditiously unless rewarming is used
157,162,189,210,274,285,286,287,288,289,290,291,292,293,294,295,296).
s improves the flow through the administration set viscosity (297,298).

nes about when these devices should be used ks include the expense and the time needed to pparatus. It is generally agreed that warming rmed during massive and/or rapid transfusion, in old agglutinins, and for exchange transfusions in t its use for routine procedures is controversial. should be considered include the rate of infusion, e to be used, the temperature of the fluid to be her patient warming techniques that are in use

etermining the Fluid Temperature ent

e Controller Set Point

set temperature of the warmer results in a higher l fluid temperature. The fluid may or may not oint, depending on the efficiency with which heat y the warmer and the speed that the fluid transits

id Temperature

ed at cold temperatures such as blood will require arm them than fluids stored at room temperature abinets.

Rate

t while hanging and while flowing to the patient. sually increases as the rate of infusion slows
03,304,305,306,307,308,309,310,311,312). This portant in pediatric patients where flow rates are ly low. However, if the flow is very rapid, it may ity of the fluid warmer to heat it adequately.

ubing between the Warmer and

bing between the warmer and the patient as short reduce heat loss
06,313,314,315,316,317). Heating the tubing may

ss. Placing the tubing under a warming blanket
ntain fluid temperature.

f Fluid Warming

ming

an blood products can be warmed in an OR
8). A maximum temperature of 43ยฐC is
319); some manufacturers recommend lower
This method

heat saline that is subsequently mixed with red
0,321). Dextrose-containing solutions should not
use the dextrose will be altered by heat.
uld be marked with the date that they were placed

or bag of IV fluid may be immersed in a bowl of
fore administration (44,322). However, this is slow
with technical problems (323). The bath water
the blood or IV solution. Placing the unit between
nay result in overheating (324).

blood and blood components have been warmed
in a microwave oven. This practice was
ause the nonuniform distribution of energy and
of penetration resulted in hot spots and
5,326,327,328,329). More recently, a microwave
ally designed for thawing fresh frozen plasma and
d red blood cells has become available (330).
the products are rotated within the device.

ontain fluid can be warmed by using a circulating
or forced-air warmer (323). Smaller syringes
dly than large ones. A โ€circle systemโ€ may be
the fluid in the heated tubing to act as a
which fluid can be withdrawn into syringes (331).

od or fluids is inexpensive and convenient. It is
with rapid transfusion. At slower flow rates or if
elayed, the fluid cools rapidly (301). Insulating
ner or tubing will reduce heat loss (300).

d bags or plastic containers of irrigation solutions
pplied to the patient's skin either as warming or
ces, because this has been associated with burns
ve (38,214,332).

ming

devices heat fluid as it passes from the source
or infusion device) to the patient. The warmer
d on a standard infusion pole, attached to a
system, or freestanding. A special disposable
set is usually used, but at least one unit warms
ventional IV tubing. Some devices have a means
nfusion rate and may display the infused volume
me allow the operator to set the temperature.
eans to administer a bolus of fluid.

ties include a low priming volume, large heat

ow pressure drop, and the ability to heat
flow rates (323,333).

of In-line Warmers

generally be used with red blood cells, whole
IV or irrigation fluids.

warmer is set up, new fluid bags can be
at once.

s must be punctured before warming, so warmed
not be mistakenly returned to the blood bank for
ther patients (44).

hat plasticizer does not leach into heated IV
ne drawback is that most devices can be used for
a time (44). Loss of body heat can be minimized
fluid flowing to one IV site while keeping veins
vailable sites. Multiple heating devices could be
e IV infusions.

-line Warmers

xchanger, the fluid passes through a tubing,
g that is placed around or within a heated block
,334) (Fig. 31.11). It may also be heated by a
tion heater (335,336) (Fig. 31.12). Infrared lamps
ed to heat the IV fluid (284). Some can be placed
sette on certain OR tables.

n the effectiveness of dry heat warmers at high
,312,334,337,338,339,340,341). Newer models
tter than older ones. Because the fluid is usually
long, constricted plastic tubes or channels, high
limit the flow rate (297,340). Current leakage has
with some units (342,343,344,345). Overheating
the plastic disposable tubing has been reported

icrowave warming devices were abandoned some
t studies show that in-line microwave blood
associated with significant damage to blood
47,348,349,350,351,352,353).

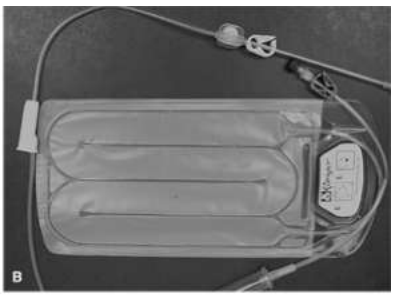
rowave warmer employs a disposable cartridge
short length of IV tubing coiled around a plastic
rature monitoring is carried out by microwave
ch measures the temperature within the lumen of
out direct contact with the fluid (350,436). The
owave power is then automatically adjusted until
emperature matches the target temperature.

ming units provide rapid heating and accurate
ntrol (298,346).

rsion

s warm a fluid as it passes through a bag or coils
sed in heated water (354). One or more IV
can be used in place of the coil or bag (355).
n warmers monitor and display only the water
re (44). Some units agitate the water to improve
this is done, it is important that injection ports
ntaminated and that the connections are secure.

hat these devices are inefficient at high flow rates
Some units take a long time to warm the water,
e turned ON sometime prior to use.



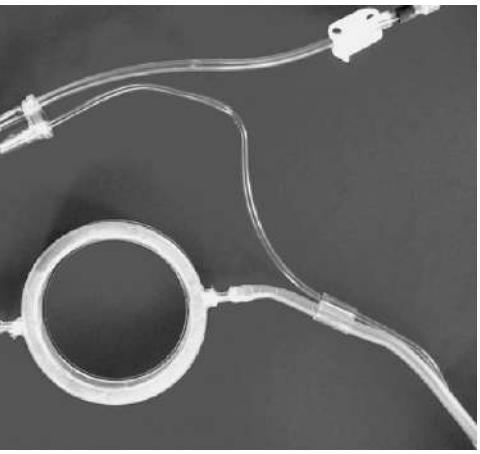
1 **A:** Dry heat warmer. A disposable cassette through which
s placed inside the device. **B:** Disposable cassette.

ated with water baths include leaking coils,
lysis resulting from overheating, leakage
epticemia secondary to contamination of the water
the IV tubing
60,361,362,363,364,365). The long tubing may
istance that could limit flow. A large priming
needed.

vice is impractical for field or ambulance use. It
re maintenance than other types of fluid warmers
IV fluid can leak into the water bath solution.

ent Heat Exchangers

heat exchangers use a countercurrent flow of
ith a tube containing the IV fluid inside
4,339,366,367,368). Single-channel and
untercurrent heat exchangers are available (353)



2 Disposable set from a magnetic induction

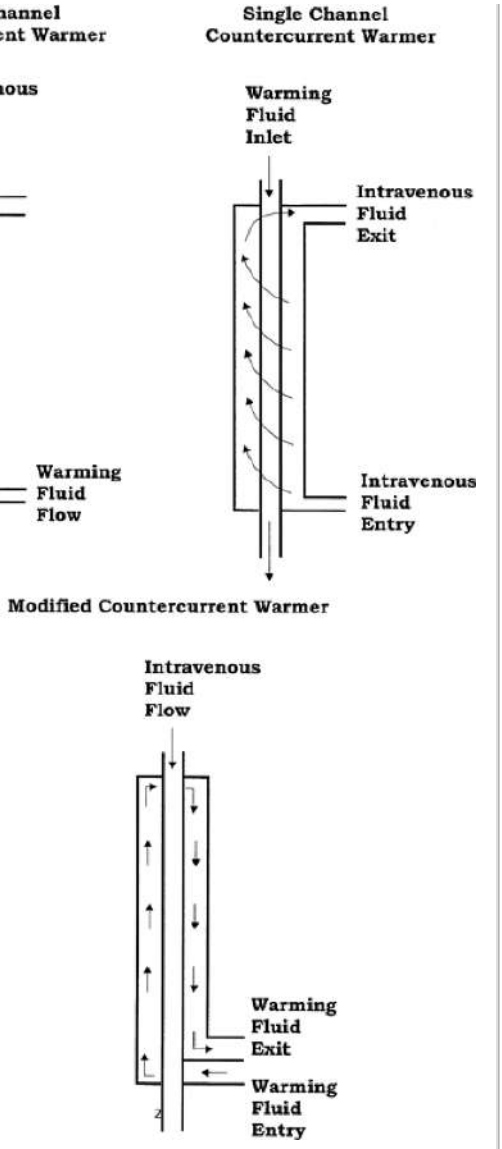
ers that use countercurrent technology heat more other fluid warmers
08,309,333,334,339,366,369), so they may be situations where rapid volume resuscitation is). However, their effectiveness may decrease as ses (306). Continual countercurrent warming of ing leading to the patient decreases the loss of e warmer. The resistance to flow may be lower bath warmers (305).

e placed inside the tubing between the patient e warming device (156,299,370,371). One manufacturer offers a special disposable coil with placed inside the hose that goes from the the blanket (Fig. 31.14). A folded water mattress lied to the tubing close to the patient (210). The n slows heat loss from tubing but is of limited 210,315,369). All of these warming methods result ess to the tubing for drug injection.

ressure Warming Devices

g. 31.15) consists of a thermal exchange chamber egative pressure when air is exhausted from the 372). A seal around where the wrist enters the es negative

is supplied by an electrical warming device.



3 Countercurrent heat exchangers.
rangements can be used for IV fluid and
id flow.

nd this device is that peripheral vasoconstriction
effectiveness of warming therapies applied to the
cutaneous vascular structure of the hand of a
dividual can be dilated by using subatmospheric
d to the skin, a thermal link between the skin and
would be created, allowing transfer of applied heat

ndicate that this may be a useful technique for
othermic individuals (373,374,375). Other studies
ind any significant benefits
78,379).

al Warming Devices

sists of a disposable double-lumen esophageal
e unit with water heater, circulating pump, and
nodule (380,381). Sterile distilled water is heated
ated through the esophageal tube.

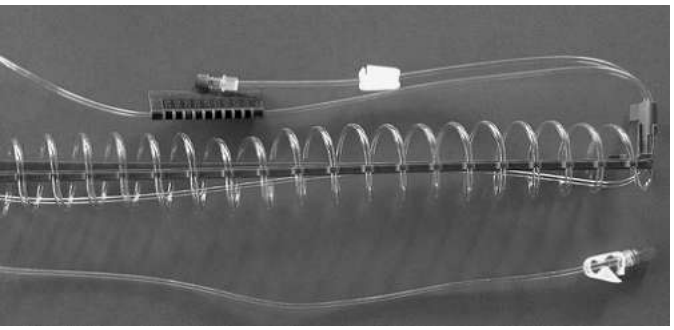
expensive and somewhat invasive. Most studies
be of limited effectiveness (131,266,382,383).

acks

en packs have been used to treat localized areas
ny burns have occurred with their use.

Containers

ers of irrigation or IV fluid are frequently kept in
ns near ORs, sometimes at quite elevated
211). It may be tempting to try to warm patients
hese containers in areas of high blood flow such
his practice, however, is both ineffective and
e lack of efficacy results because the surface area
ll (38). The danger is that burns may result from
e temperatures (214).



4 Disposable fluid-warming coil that fits inside the hose of a
warmer.

5 Negative-pressure warming device. The seal around not shown. (Picture courtesy of Dynatherm Medical,

Operating Room Temperature

ient temperature in the OR, especially while the prepped and draped for surgery, will decrease y heat by reducing the radiation and convection . The room can be cooled after the patient is ner means of temperature control are initiated. e can be raised again during emergence from n the surgery is finished (385). Systems are vill keep surgical personnel cool regardless of the the room.

ılar Devices

eriovenous rewarming uses percutaneously placed and venous catheters and the patient's own to create an arteriovenous fistula that diverts a ardiac output through a heparin-bonded heat . The heat exchanger consists of an inner h which hot water is pumped and an outer h which the patient's blood flows in a direction. These devices can increase core 1.5ยฐC to 2.5ยฐC per hour (386).

heat exchange catheters are discussed under the s section. These catheters can also be used for

they are highly effective, they are highly invasive

lder, or gastric lavage with warmed liquids can be

tiveness

f warming on perioperative costs depends on the ion, surgical procedure, and institutional factors accounting (59).

gative effects associated with the cold patient penses. Blood loss and transfusion requirements, on, the need for drugs, and the number of e length of stay in the PACU may be reduced ,388). The normothermic patient is more ly stable, requiring less intensive nursing care.

e different methods of providing warmth to determined that the old style of water mattress covers have the lowest return on a cost basis; IV ere more effective but not as economical as ers (47,200,201,202). Electric blankets may be tive than forced-air devices (57). If the blankets e reprocessing costs must be considered.

racheal Tubes

y a convective warming device has been shown vinyl chloride tracheal tube (389,390). This may more likely to kink and possibly obstruct (391).

of bacterial dissemination from forced-air devices ne to be uncomfortable with their use. contamination of the intensive care unit (ICU) is wever, studies indicate that there is no increased with forced-air warming devices (392). All forced- e filters that remove bacteria from the heated air. ns to avoid this problem include using a filter in ging the filter regularly, using only manufacturer- lankets, sterilizing the detachable hose, and not ts (393,394,395).

an act as a source of infection (358,396,397,398). ts and tubing connections should be kept out of The water should be discarded after use and the ed and disinfected.

ps in a countercurrent fluid warming system, may be infused into the patient (399). To avoid leak check should always be performed before line of the warming set to the patient. Since the IV line may

that in the water chamber, blood or fluid may

bath.

regional anesthesia have altered thermal
behavioral responses that may counter the action
gs. Warming may reverse this effect with resultant
99,400).

he American Association of Anesthesiologists
laims database showed 54 patient burns out of
ns (214). Eighteen burns were caused by bags or
been heated and placed next or close to the
Other cases of this type have been reported
he eight burns from electrically-powered warming
resulted from circulating-water mattresses. Other
from a warming light and a heated humidifier
one case was the heating device found to be
e are reports of burns with forced-air warming
94,195,196,197), radiant warmers in infants
stive warming mattresses (258,404).
burns are not usually recognized until after
en completed.

ent factor in many burns is poor cutaneous blood
e usually most severe in areas overlying bony
he risk of tissue injury is further increased when
e is combined with chemical irritation such as that
any skin-cleaning solutions, especially those
e (38). Age is another factor. The elderly often
ate skin that is especially susceptible to injury.
wborn patients has a reduced thickness compared
s diminishes protection against external noxious
atients with ischemic tissue or those who undergo
olving cardiopulmonary bypass are likely to be at
f thermal injury. Heating devices should not be
tourniquet or arterial clamp or during
y bypass.

g device is used for a patient with compromised
patient's skin condition should be monitored
the unit's maximum setting not used
Constant vigilance must be exercised to ensure
heating devices not meant for direct patient
s tubing for a water blanket or the hose of a
ess, do not come in contact with the patient
and blanket-warming cabinet temperature should
ยฐC (319,406).

ccurs, the pattern of the lesion can help to identify
). If a warming device has been used and the
to that device's edges but no other area of the
, then it is likely that the warming device caused

Transcutaneous Medication

transdermal drug uptake may occur when the skin

409). For this reason, transdermal medication
ed in a location that will not be warmed or should
during heating (410).

olyze if overheated (44,324,336,345,359).
ed cell integrity do not occur below a temperature
frank hemolysis does not occur until 48ยฐC
ked red blood cells remaining stationary within
ountercurrent heating cartridges may show
molysis (353). If water from a fluid-warming
to blood, hemolysis may result (399).

akage

dry heat exchangers must be well grounded.
electrical current into the fluid path (44).

sm

luid warmers is the possibility of infusing air into
ther as a result of bubbles created as the fluid is
ssing), air entrained through an infusion system,
air contained in the fluid source
14,415,416,417,418,419,420,421,422,423,424,425,426,427,428,429).
greatest with the use of pressure infusers; when
ed by a pump; and when rapid, high-volume fluid
s necessary.

acturers typically put 50 to 75 mL of air into each
ner (299,421). This should be removed from the
he tubing checked for bubbles before the start of
rtially emptied fluid bags should not be reattached
n (427,428).

provide a warning feature to alert the operator to
e, and traps that collect bubbles in the fluid are
o many disposable sets. If the trap is installed
ir may be transmitted to the patient (430). Many
cannot be easily vented; once the trap becomes
delivered to the patient. Some gas-eliminating
microporous membrane that allows the gas to
any user intervention (431). Another design uses
at stops the fluid flow when air is detected
Some systems allow fluid containing air to be
the reservoir chamber (310). However, no gas-
ce can reliably remove large amounts of air.
etection devices may fail (335,413,421,435,436).

ce with Bispectral Index

d bispectral index values have been reported in
ng forced-air warming around the head (437).
rruption of the warm air flow may be required to
adings.

d Infiltration

uid-warming system that pressurizes the fluid can

asation of fluid. A compartment syndrome could

evices

equire cooling for a variety of reasons, including
alignant hyperthermia and possible cerebral
ts during neurologic or cardiac surgery or
trauma or cardiac arrest.

travenous Fluids

n be induced by rapid infusion of chilled fluids or
m temperature (440,441,442,443). One liter of
mbient temperature or one unit of refrigerated
ered through a peripheral site reduces mean body
approximately 0.25ยฐC in adults (444).
he fluid centrally will decrease core temperature
42). This method is restricted by the volume that
tered without overloading the cardiovascular
help to compensate for anticipated diuresis and
n cerebral perfusion pressure. It is less effective
in ice water (206).

g Water Units

ng water units have been found to be effective for
r in neurologic patients (445,446). Older units
tive (447).

r Cooling

performed by using a forced-air unit. This needs
with other methods to achieve effective cooling
, most units have no feedback control. Personal
systems that attach to the medical air line are

n in Ice Water

duction may be less efficient than using forced air
ely to interfere with patient care (449,450).

enous Heat Exchange Catheters

ailable that have heat transfer elements that can
the central venous system (451,452,453,454).
ature is regulated through a closed-loop
se devices can lower core temperature rapidly
asiveness is a drawback in terms of ease of
risk of complications. The time lag before cooling
is a potential drawback.

lder, or gastric lavage with iced solutions can be
toneal lavage is invasive, and bladder lavage
al cooling.

s

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heat exchange catheters: a new method to
aintain hypothermia. Intensive Care Med
â€“943.

ns

g questions, select the correct answer

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ยท 1ยฐC

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ยท 0.2ยฐC

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ffective way(s) to utilize a water heating pad

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infusion

ing normothermia after surgery

Chapter 32

Operating Room Fires and Personnel Injuries Related to Sources of Ignition

Although flammable anesthetics have disappeared from operating rooms, perioperative fires continue to occur. They can have devastating consequences, precipitate legal action, and take a great psychological toll on everyone involved. They usually come as a complete surprise to the staff (1,2,3,4).

Most operating room fires are of little consequence and are not reported, making the actual incidence difficult to determine (2,5,6). Approximately 10% to 20% of reported fires result in serious patient injury (7,8). Fuels present in the operating room include plastics that produce dense black smoke when ignited. The smoke may contain toxins and may hinder safe evacuation of the patient and staff from the room. Sudden ignition can present secondary problems (9). It can cause a startle reflex, causing the surgeon's hand to jerk and potentially cut into unintended tissue or set other areas of the surgical site on fire.

The Fire Triangle

For a fire to occur, there must be three factors (fire triangle or triad) present: an ignition source, a fuel, and an oxidizer to support combustion together in the proper proportions and under the right conditions (Fig. 32.1).

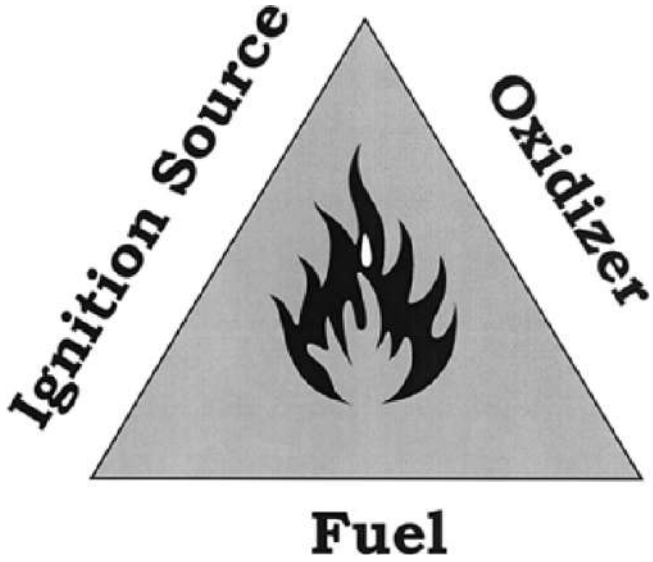

Figure 32.1 Three things are necessary for a fire to occur: an ignition source, fuel, and an oxidizer.

Ignition Source

There are a number of ignition sources in the operating room. Most are under the surgeon's control.

Lasers

The acronym *laser* (light amplification by stimulated emission of radiation) defines the process by which a form of energy is converted into light energy (10,11,12,13,14,15,16). The term can also refer to the device that produces the light or to the light itself.

Lasers use a colimated, coherent, monochromatic, intense beam of electromagnetic radiation to cut, coagulate, or vaporize tissue.

The rate that the laser energy is delivered is called *power* and is measured in watts. The wattage is equal to the amount of energy, measured in joules, divided by the duration of exposure measured in seconds. Laser power density is the amount of power distributed within an area and is indicated in watts per square centimeter.

Components of a Laser System

The basic components of a laser system are two parallel mirrors encompassing the laser medium and a power source (Fig. 32.2). In addition, there may be an aiming beam for delivering laser energy that is outside the visible range.

Laser Medium

The medium (head) holds the substance energized to produce laser light. The medium, which may be a solid, liquid, or gas, determines the wavelength of the emitted radiation. The laser is named for the material used as the medium.

Power Source

The power (pumping, pump, excitation) source supplies energy to the laser medium to create the light. When the power source is activated, energy is absorbed by electrons of the atoms in the laser medium, which are elevated to energy levels above their ground state. They then decay to lower energy levels and emit photons that are not in phase with one another and travel in all directions.

Optical Cavity

The optical (resonator) cavity provides the environment in which the laser medium is confined. Energy released from the medium travels in all directions. Mirrors are used to reflect and increase the energy of emission. One of the mirrors is not 100% reflective and allows a small portion of the light to escape.

Light Guide

A light guide (delivery system) directs the laser beam to the surgical site (Fig. 32.3). Fiber-optic bundles are a convenient flexible conduit for some wavelengths. Other lasers utilize a hollow tube with mirrors aligned to reflect the beam from its source through the focusing lens.

Aiming Beam

With certain lasers, it is necessary to use a low-powered visible beam as a marker. This is usually a helium-neon gas laser. It passes through the same optical path as the laser beam.

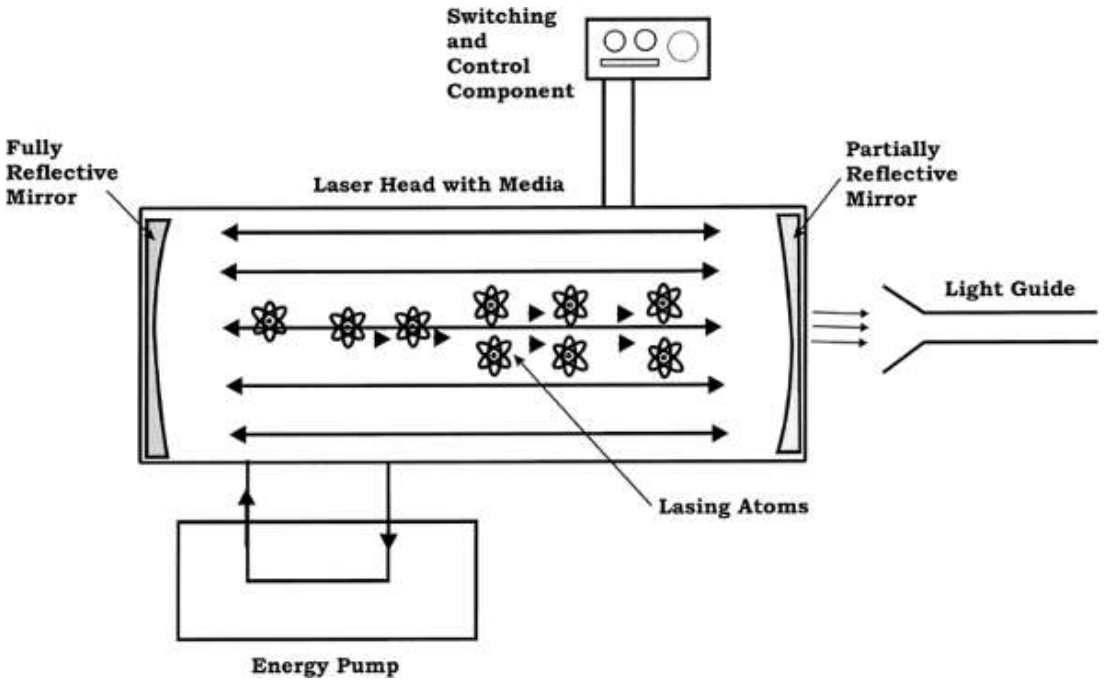

Figure 32.2 Components of a laser.

Laser Types

Types of medical lasers commonly used in surgery are shown in Table 32.1.

Laser Hazards

Lasers can cause significant damage to operating room personnel (including the anesthesia provider) and the patient. Hazards involving lasers include fires, atmospheric contamination, eye damage, organ or vessel perforation, and embolism (10). Figure 32.4 shows a sign used to warn personnel that a laser is in use.

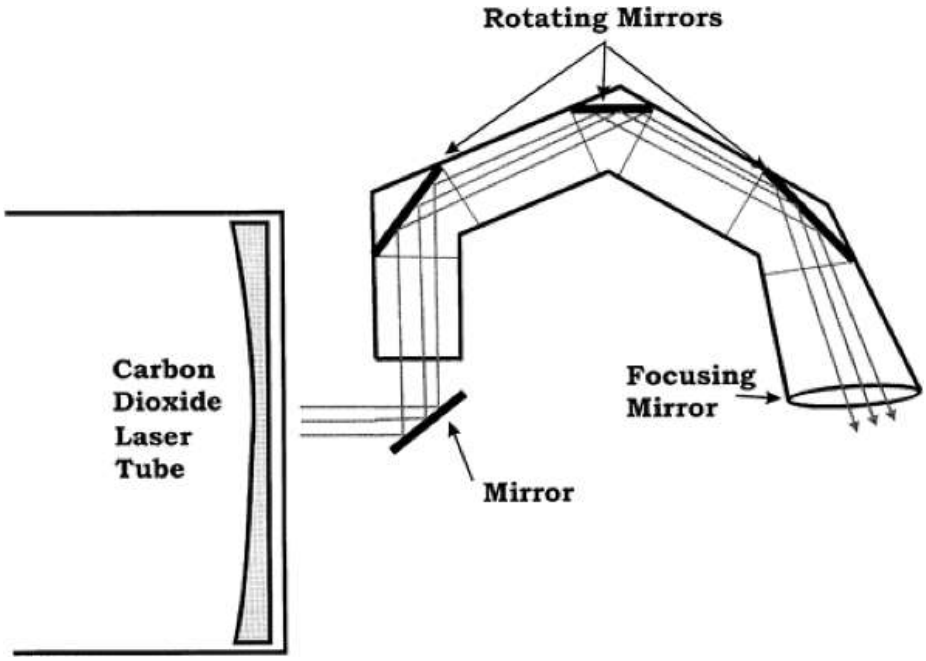

Figure 32.3 This is a schematic representation of a CO_2 laser guide as might be found in either an operating microscope or a handheld wand. The guide consists of hollow tubes with hinged, aligned mirrors that reflect the beam from its source through the focusing lens.

A recurrent problem with lasers is that they may be activated when not in use (22,23). Often, a foot switch accidentally activates the laser. The laser may be in a position where this is not noticed for some time. When the laser is not actually in use, it should be placed in the STAND-BY mode.

A fire may result when a laser beam hits a fuel or the laser fiber becomes damaged. Ignition can be almost instantaneous. While most ignition sources must be in contact with a material to cause ignition, a laser can supply heat to a fuel from a few centimeters to several meters away, so it can ignite material close to the tip, at some distance from the tip, or under several layers of other material. A surface drape can be penetrated by the laser but not ignite. Materials under the drape may then ignite and burn without being noticed for several minutes (24). The laser beam can be reflected from a metal surface, causing a burn or igniting material in a remote location.

Laser Risk Classification

A classification system reflecting laser risk to the patient and personnel has been developed (25,26,27). The higher the class, the more stringent the protection needed.

TABLE 32.1 Commonly Used Lasers and Associated Personnel Hazards

Laser Medium	*Features*	*Potential Hazards to the Eye*	*Special Considerations*
CO_2	Readily absorbed by all biologic materials, independent of pigmentation. Tissue destruction is proportional to its water content. Produces a very superficial tissue effect.	Injury to the eye will be confined to the cornea. There is no risk to the retina. Since the laser is absorbed by plastic and glass, ordinary eyeglasses with sideguards can be used for eye protection.	Fires involving both tracheal tubes and supraglottic devices have been reported with this laser.
Nd-YAG	Can be transmitted through fiber-optic fibers. Poorly absorbed by water but well absorbed by pigmented tissue (11).	Retinal damage can occur. Opaque green eyewear or eyewear with clear lenses with a special coating should be worn.	Because it is taken up by pigment, colored markings on tracheal tubes are more likely to be damaged than clear portions (12). Blood or mucus on or in the tracheal tube makes the tube less

			resistant to the laser beam. Fires have been reported from an Nd-YAG laser passed through the channel of a flexible bronchoscope (17,18). The rigid bronchoscope is recommended for use with this laser, although the flexible scope may be needed to treat hard-to-reach areas (19).
KTP	Passes through clear substances but is absorbed by hemoglobin and other pigments (11,20,22).	Retinal damage may occur. Special eyewear with red filter should be worn.	
Argon	Beam is selectively absorbed by red, orange, and yellow pigment and strongly absorbed by hemoglobin and melanin. Fiber-optic	Retinal damage may occur. Special opaque orange goggles/eyewear should be worn.	

	bundles can be used to transmit the laser beam.		

From Klarr P. Laser complications. In: Atlee J, ed. Complications in Anesthesia. Philadelphia: WB Saunders, 1999:588Ì€“590.

Class 1 Lasers

Lasers that are totally enclosed or that emit extremely low output fall into class 1. These are safe to view.

Class 2 Lasers

Low-risk lasers are in class 2. Their risk is approximately equivalent to staring at the sun or other bright lights that can cause central retinal injury. These are not hazardous unless someone overcomes their natural aversion response to bright light.

Class 3 Lasers

Class 3 lasers operate at a power level above 1 mW. This is a hazard even if viewed only momentarily. Class 3 lasers are subdivided into a and b subclasses. The 3a subclass consists of lasers in the 1 to 5 mw power range. These lasers pose a moderate ocular hazard. Class 3b includes lasers that emit between 5 and 500 mW of output power. Even momentary viewing of these lasers is potentially hazardous to the eye. They may also be a hazard to skin.

Figure 32.4 Note that the laser class is on the sign.

Class 4 Lasers

Any continuous wave laser with a power output above 500 mW is in class 4. These lasers pose serious skin, eye, and fire hazards.

Ignition risk is related to a number of factors beside the laser classification. Class 3b and 4 lasers are considered to be ignition hazards. The ignition risk of other classes of lasers will depend on how they are focused, the time of exposure, and the oxidizers and fuels that are present.

Metal instruments can become overheated with prolonged laser use and could cause a burn (28).

Electrosurgery Unit

Electrosurgery (radio frequency) apparatus is so widely used that there is often complacency about reading the instruction manual or following safe practices (29,30). Electrosurgery units are the most common ignition source in surgical fires (6). The instruction manual should be studied at the beginning of a training program and reviewed periodically. A brief set of operating instructions should be readily available on the instrument (31).

Terminology

The vocabulary concerning electrosurgery is somewhat confusing (32). This chapter will define electrosurgery devices as those that employ a high-frequency (radio frequency) electric current passing through tissues to cut, coagulate, or provide a blend of cutting and coagulation. Electrocautery utilizes a heated wire or blade, usually at the end of a probe for coagulation. Most electrocautery devices are battery-operated.

Physics

There are three modes available on modern electrosurgery devices.

Cutting Mode

The cutting mode uses a continuous sine wave. Heating is rapid and produces high temperatures that explode cells that come in contact with the electrode. This produces a cut in the tissue.

Coagulation Mode

The coagulation mode features short bursts of a dampened sine wave. Less heat is produced since the current is not continuous. Tissue desiccation occurs, and the ends of blood vessels are thermally sealed.

Blend Mode

The blend (cut-coagulation) mode employs a waveform and voltage between that of the cutting and coagulation cycle. The relative amount of cutting or coagulation depends on the lengths of the bursts of voltage. Several blend settings may be available on an electrosurgical unit (33).

Types

Monopolar

With monopolar (unipolar) electrosurgery units, electrons flow from the generator to the active electrode and through the patient to the dispersive (return, inactive) electrode, sometimes incorrectly called the *grounding pad* (Fig. 32.5). The current disperses from high density at the tip of the active electrode to a

lower density via the lowest impedance pathway that it can find.

Generator

The electrically powered generator (power unit) creates a radio frequency current that passes through the active electrode. The effect on tissue depends on the current intensity, the type of current employed, the duration of exposure to the current, the hand piece used, and the dispersive electrode (34). Coagulation requires longer contact with the probe than cutting. As electrical energy is applied to the tissue, char forms. Since char has higher impedance, more current dissipates directly to the dispersive electrode and the effect is reduced (34).

Active Electrode

The active electrode has a handle and is connected to the generator by a flexible wire. It directs current flow to the surgical site. The tip of the active electrode may be a blade, spatula, ball, lancet, loop, forceps, needle point, or suction tip. It may be disposable or reusable. The tip

configuration determines its ability to desiccate tissue. A needle-tip electrode concentrates more power on tissue contact than does a paddle or ball-shaped electrode (34). At a given electrode voltage, the paddle-shaped tip presents a higher power at the edge than on the flat portion. The electrode may be activated by a hand control or foot switch. The control may also be used to switch from one mode to another.

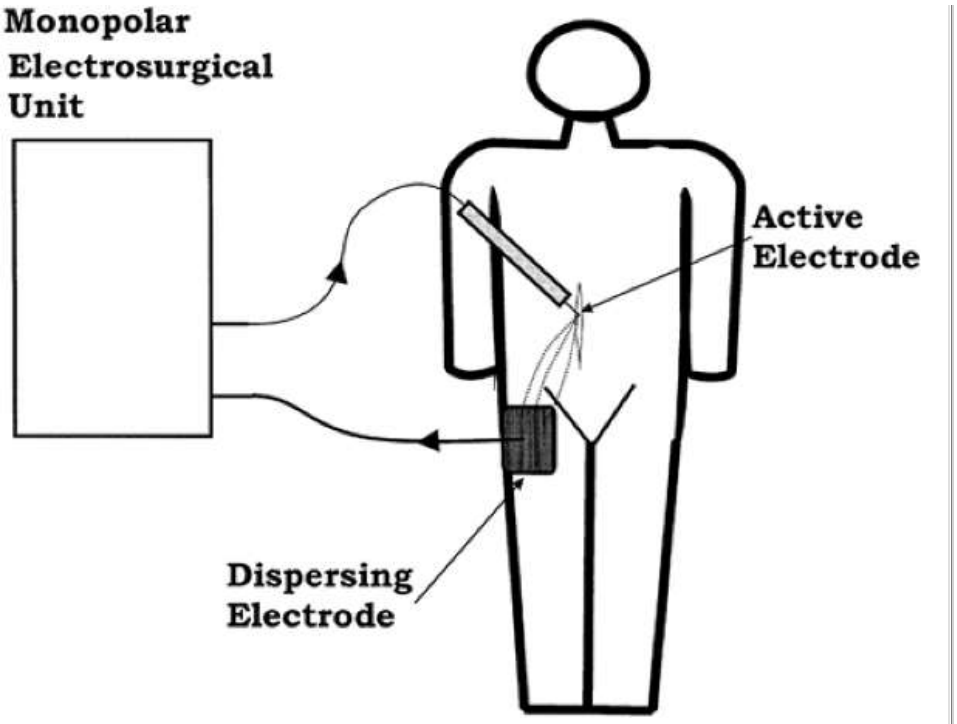

Figure 32.5 Monopolar electrosurgery unit.

Dispersive Electrode

The dispersive (inactive, return) electrode (grounding or ground electrode, plate, or pad) collects the current from the patient and returns it to the generator to complete the circuit. The large contact surface of the pad provides low impedance. Most pads presently in use are prejelled. Reusable metal plates used in conjunction with conductive gel are rarely used today. With some electrosurgery units, two dispersive electrodes should be used (35).

Safety System

Modern electrosurgical units possess a return electrode (contact quality) monitoring system. This ensures that the patient is connected to the return electrode (34,36). Current flowing to the active electrode is measured and compared with current returning from the dispersive electrode. If the currents are not balanced, the unit is deactivated. A more recent innovation is

active electrode monitoring (AEM) (37,38,39,40). This continuously monitors the electrical circuit and automatically shuts down the generator and sounds an alarm if dangerous electrical leakage occurs. Newer generators can sense dramatic changes in tissue impedance or temperature changes at the return electrode (33,41). Some modern electrosurgery machines are equipped with ‚€split pads‚€ (42). The unit will not function unless both halves of the pad are in contact with the patient.

Bipolar

The bipolar electrosurgery unit is composed of a generator and two electrodes located within millimeters of each other. The energy flow is between the two electrodes, and no current flows through the patient's body. This allows the energy to be localized more precisely. The current density in the tissues surrounding the active electrode is substantially less than that for monopolar electrodes, and deeper tissue layers are preserved with lower voltage and power requirements. This type of electrosurgery unit can coagulate even when the tip is immersed in blood. Bipolar units cannot be used for cutting.

Bipolar electrodes are produced in a variety of configurations: hooks, spatulas, scissors, forceps, and needles (29,43). Often, these devices are battery-operated.

There are reports that the ON-OFF switch on one of these devices did not always deactivate the device when it was set aside (44,45). The hot tip could then set drapes on fire. At least one device could be activated by another device's wireless remote-control unit or by fluorescent room lights (46).

Hazards Associated with Electrosurgery

Mishaps with the electrosurgery unit often involve faulty return electrodes, improper electrode placement, or alternate low-impedance outlets. Insufficient contact with the dispersive pad can result in patient burns and/or burns to others who are in contact with the patient. Among the low-impedance alternatives are electrocardiogram (ECG) monitoring electrodes, temperature probes, urinary catheters, metallic parts of surgical tables, heating pads, and oximeters (47).

About 68% of reported surgical fires involve electrosurgical equipment (48). Fires associated with the electrosurgery unit are

often associated with an oxidizer-enriched atmosphere. When the electrosurgery unit is used, heat vaporizes tissue or expels tissue embers from the tip. In room air, tissue vapors do not ignite, and embers are quickly extinguished. In an oxidizer-enriched atmosphere, the vapors can ignite into a brief flame, and embers can fly several inches and burn until they are consumed. A flare of evolved gases can directly ignite any convenient fuel. The electrical wires associated with the electrosurgery electrode may develop a short circuit, which could result in a fire (49).

During laparoscopic surgery, burns that are sometimes fatal can occur outside the surgeon's view when using an electrosurgery unit (14,29,33,38,40,50,51,52). These are usually caused by insulation failure, direct coupling, or capacitive coupling.

If a defect occurs in the active electrode's insulation, current can flow through the defect. Defects can result from improper handling or damage to both reusable and disposable electrodes. A number of devices are available to detect insulation defects (33,40,51). Active electrode monitoring continuously monitors the electrical circuit and automatically shuts down the generator and sounds an alarm if dangerous electrical leakage occurs (37,38,39,40).

Capacitative coupling occurs when the electrosurgical current induces stray currents on other nearby conductors. It can occur even through intact insulation. It occurs as a result of the active electrode contacting or coming into very close proximity to a non-insulated metal instrument (such as a laparoscope) in the surgical field. If the electrically-energized laparoscope has been placed through a metal cannula, the current will simply flow to the patient's abdominal wall. However, if the laparoscope has been placed through a nonconductive cannula, the current cannot flow to the abdominal wall. In this case, any piece of bowel or other internal tissue touching the laparoscope can be burned. Capacitative coupling is always present and cannot be totally eliminated.

Argon Beam Coagulator

The argon beam (enhanced) coagulator (ABC) is solely a coagulating instrument. Radio frequency monopolar current is delivered through a flow of ionized argon gas.

The flow is altered as the power is changed. The tip does not touch the tissue. If the tip is greater than 1 cm from the tissue surface, only a gentle stream of argon will flow. When the tip is 1 cm or less from the tissue surface, the active mode occurs. If the nozzle tip glows red, the tip is too close to the tissue or the power setting is too high.

Fiber-optic Illumination System

A fiber-optic illumination system consists of a light source and light-transmitting cable. The cable is connected to an endoscope or headlight. The term *cold light*, used to describe light from a fiber-optic source, is incorrectly assumed by many to mean that heat is not generated. Actually cold light refers to light in which the amount of infrared radiation has been reduced (53). These light sources can provide several hundred watts of visible, infrared, and ultraviolet light. Although some of these wavelengths can be filtered out, the power is typically focused into a fiber-optic cable of small diameter that can deliver a high-power density.

A number of fires have been ignited when the unprotected end of the fiber-optic cable was allowed to rest on a drape (6,49,53,54,55,56,57). The cable end can retain a significant amount of heat after being disconnected from the light source.

Defibrillator

When a defibrillator is activated, a spark may be generated if insufficient force is applied to the paddles; if the paddle pad is too small; if paddles are applied over an irregular surface or bony prominence or near an ECG electrode; when insufficient, excess or the wrong kind of gel is used; or if there is another conductive medium between the paddles (6,58,59). If disposable defibrillation pads are used to increase electrical conduction between the paddle and the patient, an arc can occur if the surface of the paddle is not completely on the pad, if the pad is smaller than the paddle, if there is a fold in the pad, or if the pad is dry.

Pressure Regulators

When gas is allowed to flow from a high-pressure to a low-

pressure chamber, recompression can cause a rapid rise in temperature. Materials that cannot withstand both 100% oxygen and high temperatures will ignite. This hazard is associated mostly with aluminum oxygen regulators (60,61,62,63,64,65,66,67,68).

Another cause of heat in a pressure regulator is particle impact from contaminants. Teflon tape, chips from seal materials, or hydrocarbon contaminants may be present (69).

Surgical Lights

Surgical lights can be a source of ignition. If the light does not have the proper mechanism to dissipate infrared radiation or if that mechanism fails, the patient or personnel environment can be exposed to energy levels high enough to cause burns or fires (70,71). The heat from a surgical light can contact and rupture a hose from the medical gas pipeline system (72).

Electrical Faults

An electrical fire can occur in any environment where there is electrical equipment. A short circuit can occur in an anesthesia machine (73,74,75). In one reported case, a short circuit in a laryngoscope with a rechargeable handle caused flames to shoot from the charging end of the handle (76). Electrical arcing in surgical booms has been reported to cause fires (77,78).

Other Ignition Sources

Other reported sources of ignition in operating room fires include resectoscopes, heat lamps, heated probes, pneumatic tourniquets, dental and orthopedic burs and drills, heated-wire breathing tubes, and humidifiers (1,79,80,81,82,83,84).

Fuels

Fuels abound in the operating room. A fuel is anything that can burn, including most things that come in contact with patients as well as the patients themselves.

Tracheal Tubes

The risk and characteristics of a tracheal tube fire will depend on the type of tube used. In most cases, ignition requires the tube

to be penetrated (85). The fire begins on the inside rim of the penetration area and then spreads both with and against the flow of oxidizing gas.

Polyvinyl Chloride Tubes

Polyvinyl chloride (PVC) tubes are combustible in an oxidizer-enriched atmosphere with a carbon dioxide (CO_2) laser. Once ignited and penetrated, a PVC tube can sustain a torchlike flame. PVC tubes without markings are relatively resistant to the Nd-YAG laser, but markings increase the risk (86). If there is blood, mucus, or saliva on the tube, the risk of fire is increased. The injuries associated with PVC tube fires are more severe than with other types of tubes (87,88).

Red Rubber Tubes

Red rubber tubes are combustible with the CO_2, potassium titanyl phosphate (KTP), and Nd-YAG lasers (86,87,88,89,90). A major problem is the inability to see through the tube. Should an intraluminal fire develop, it may go undetected for a longer period of time than with other tubes.

Damage to the tracheobronchial tree after an intraluminal fire may be less severe with a red rubber tube than a PVC tube (87). Red rubber tubes are less likely to soften, deform, or fragment if ignited than are other tubes. Another advantage is that they can be quickly

removed from the patient (91). The high pressure in the cuff causes it to deflate more quickly than is possible with a low-pressure cuff.

Silicone Tubes

A silicone tube is more resistant to penetration by a CO_2 laser than other tubes (87). If ignited, a silicone tube rapidly becomes a brittle ash that crumbles easily and may be aspirated, raising the possibility of future problems with silicosis (87,90,92,93). However, the acute injuries are less severe than with red rubber and PVC tubes (88).

Laser-resistant Tubes

A number of ready-to-use laser-resistant tubes and tube wraps are available and are described in Chapter 19. They should meet the requirements of International Standards Organization (ISO) 14408 (93). It is important to remember that laser-resistant does not mean laser-proof. Laser-resistant tubes can ignite, especially if manufacturer's warnings, precautions, or directions for use are not followed. If a laser tube is used with a laser other than that for which it was designed or a flammable part such as the cuff is exposed, it will catch fire (92,94). Laser-resistant tubes are usually not resistant to other heat sources such as an electrocautery pencil.

Supraglottic Airway Devices

The relative resistance of supraglottic airway devices depends on their composition. Those devices that are made of silicone rubber such as the LMA-Classic, LMA-Flexible, and LMA-ProSeal are significantly more resistant to the CO_2 laser than are PVC tracheal tubes (95). Many disposable supraglottic devices are made of PVC and are probably as susceptible to fires as tracheal tubes of the same composition.

Surgical Products

Surgical drapes, towels, and dressings are common fuels for operating room fires. Often, the drape is ignited from another fire (24). While many drapes are resistant to ignition in room air, the oxidizer-enriched atmosphere that is often present may cause them to burn with vigor (49,96,97,98,99,100,101,102,103,104).

Disposable drapes may be particularly difficult to deal with during a fire because they are water repellent. Addition of water may even spread the flame. Laser-resistant drapes are available. Some synthetic drapes will melt away from the laser rather than ignite (103).

There are numerous reports of surgical sponges, gauze pads, and swabs being ignited (49,105,106,107,108,109,110,111,112,113). Wet sponges may be used to protect a tracheal tube from a laser beam. However, if they are allowed to dry out, they become flammable.

Adhesive Substances

Adhesive tape can be the fuel for a fire (114). Collodion and

benzoin are flammable.

Skin Preparatory Solutions

Flammable volatile organic solutions are often used to prepare the skin prior to surgery. If the liquid or vapor is contacted by an ignition source, a flame can result (1,101,115,116,117,118,119,120,121). Alcohol-based solutions are especially flammable. They can also infiltrate and pool under the drapes. When this happens, they are slow to dissipate. Alcohol-based fires have a flame that is difficult to see. Often, the result of the flame is the first thing noticed.

Intestinal Gases

Gases that accumulate in the bowel (especially hydrogen, hydrogen sulfide, and methane) can be the fuel for a fire or explosion if an electrosurgery unit is used to open the bowel (105). Proper bowel preparation may prevent this (122). Sufficient oxygen to support combustion is normally not present in intestinal gas. However, nitrous oxide may diffuse into the intestinal lumen, creating a flammable mixture.

Oxygen Cannulas

Oxygen cannulas are made of plastic that can burn. They carry 100% oxygen. If touched by a hot electrosurgery probe or a laser beam, they burn readily. Even if not directly contacted, the area around them may be so oxygen-rich that a small spark can turn into a burning ember that can ignite the cannula.

Lubricants and Ointments

Petroleum-based ointments that are used in an oxidizer-enriched atmosphere will ignite when enough heat is present to cause vaporization (105,123,124). Water-based lubricants will not burn and can be used to coat hair to make it fire-resistant.

Body Hair

Body hair, including eyelashes, moustaches, and beards can be involved in a fire (105,106,125,126). Coating the hair with a water-based lubricant will decrease the risk.

Surface flame propagation occurs where there are fine surface

fibers of fabric or body hair (127). In the presence of an oxidizer, these fine fibers can be ignited. Often, the skin or underlying fabric is not burned. The surface fire races in the direction of the oxygen source, where the oxygen supply tubing may be ignited (58).

Other Combustible Substances

A number of articles used in or near the patient can serve as the flammable material. These include (but are not limited to) oxygen tubings, endoscopes, smoke evacuator hoses, esophageal stethoscopes, breathing tubes, reservoir bags, eye patches, stents, masks, nasogastric tubes, enteric feeding tubes, rubber and plastic nasopharyngeal airways, covers, paper products, blood pressure cuffs, aerosol adhesives, tourniquets, gloves, stethoscope tubing, throat packs, eggcrate foam

mattresses, bandages, stockinettes, dressings, pillows, glue, gowns, straps, caps and hoods, rubber electrosurgical unit probe sheaths, shoe covers, local anesthetic spray, and organic gas from a necrotic tumor (106,116,128,129,130,131,132,133,134,135,136,137).

Alcohol-based hand sanitizers (gels, foams, and liquids) are highly flammable (138). They should be stored in a cabinet that is designed for flammable materials. However, a study published in 2003 found no fires attributable to hand sanitizers, and the National Fire Protection Association now allows alcohol-based hand sanitizer dispensers in corridors and other public areas, provided certain restrictions are observed (139). If a dispenser is mounted in a hallway, the corridor must be at least 6 feet wide. The dispenser can project up to 6 inches from the wall and must be installed above handrail height.

Oxidizers

With an oxidizer-enriched atmosphere, a fire ignites easier, burns more vigorously, spreads more rapidly, and is more difficult to extinguish. The oxidizers of greatest interest are oxygen and nitrous oxide. Nitrous oxide supports combustion and in the process releases the energy of its formation, providing increased heat. Thus, any mixture of oxygen and nitrous oxide will support combustion. Air will also support combustion, because it contains oxygen.

Because oxygen is heavier than air, it collects in low-lying areas, including drape folds. Some materials such as drapes and towels absorb oxygen and retain it for some time (1,127). Tenting drapes will allow oxygen to drain off toward the floor and be diluted by air circulation.

Common Scenarios

Airway Fires

During airway surgery, all of the three necessary components are in close proximity: a combustible substance (tracheal tube, gauze, etc.), an ignition source (laser or electrosurgery apparatus), and gas to support combustion (oxygen with or without nitrous oxide). An airway fire is particularly serious because a considerable amount of heat is generated in a small area, and the smoke and gases from such fires can be blown deep into the patient's lungs.

Using Electrosurgery during Tracheostomy

Many airway fires have occurred while using the electrosurgery unit during tracheostomy (9,105,128,130,140,141,142,143,144,145,146,147,148,149,150,151,152,153,154). Often, the patient is being given 100% oxygen in anticipation of interrupted ventilation and/or because of the underlying clinical condition. If the tracheal tube or cuff is contacted, an oxidizer will be released. Currently, there is no tracheal tube that is safe for use with electrosurgical devices or electrocautery, although some are more resistant to ignition than others (155).

Using Electrosurgery in the Mouth

Using electrosurgery in the oral cavity may result in a fire (6,156,157,158,159,160,161,162). The tracheal tube is often the fuel, but other items such as sponges or patient tissue may be involved. Often, wet gauze is used in the throat to catch secretions or to protect the tracheal tube. If there is a leak around the tube, the gauze can becomes oxidizer-enriched and dry out more quickly.

Laser-induced Tracheal Tube Fires

The likelihood that a laser will contact the tracheal tube during

airway procedures is high (163). Cuffed tubes are more likely to be contacted than noncuffed tubes. The tube may be exposed to either the direct or reflected laser beam. Flaming tissue in close proximity to the tube may cause it to ignite (164).

In addition to local damage in the larynx, injury can occur to the lower airway and the parenchymal tissue in the lung. The products of combustion may be blown into the lungs.

The cuff is the most vulnerable part of the tracheal tube. It cannot be wrapped, and laser-resistant tubes do not have laser-resistant cuffs.

Wet cotton sponges are often used around the tube to protect the cuff from the laser beam. If these dry out, they can become fuel for a fire (165). Tape that is used to secure the tube can ignite.

During lower airway surgery using a laser, the cable may be passed through the inside of a tracheal tube. The tracheal tube should be placed just below the vocal cords so that the tip is as far away from the operative site as possible.

Other Head and Neck Fires

Head and neck fires can occur during local anesthesia procedures when electrosurgery apparatus is used (6,49,56,126,166,167,168,169,170,171,172,173). Often, oxygen is being administered, and it may diffuse into the surgical area. Any flammable item in the vicinity can catch fire.

Fires Involving Pressure Regulators

While not a frequent occurrence, a fire in a regulator can be disastrous (174). These fires may result from adiabatic compression or particle ignition in which debris is blown from the cylinder into the regulator with sufficient energy to cause ignition. Improper pressure regulator assembly may also cause a fire.

Regulators with aluminum components are more likely to burn than other regulators. The Food and Drug Administration (FDA) and the National Institute for Occupational Safety and Health (NIOSH) now recommend that aluminum regulators be replaced with ones with brass components (64,66). A number of aluminum

oxygen regulators have been recalled (67).

Intraperitoneal Fires

Several explosions have been reported during laparoscopy when nitrous oxide was used as the insufflating gas (122,175,176,177). Nitrous oxide in the inspired gases will diffuse into the peritoneal cavity and may reach a high enough concentration to support combustion (178,179). Fires have also resulted from inflating the peritoneal cavity with an oxygen-CO_2 mixture instead of pure CO_2 (180,181). The Pin Index Safety System (Chapter 1) will not prevent this error, because the index holes for tanks with 100% CO_2 are the same as for any tank with greater than 7% CO_2.

Fires during Defibrillation

Oxygen is always used during resuscitation, and the source is often disconnected and placed near the head (58,182,183). This may allow oxygen to flow over the defibrillation electrodes (184). A spark caused by placement of the defibrillator paddle or electrode close to an ECG electrode or poor contact between the patient's skin and the defibrillator paddle or electrode may ignite hair or other combustible materials in the area (183,185).

Fires in Canisters

Fires in CO_2 absorbent canisters have been reported (186,187,188,189,190,191,192,193). These are discussed in more detail in Chapter 9.

Personnel Risks

Smoke Hazards

Potentially hazardous airborne contaminants are formed from tissue vaporization when a laser is used. These by-products have the potential to be mutagenic, carcinogenic, teratogenic, or a vector for viral infection (10,194). Electrosurgery devices and bone saws also produce vaporized fragments that have the same hazards (25).

Inhaling potentially hazardous airborne contaminants can be kept to a minimum by scavenging the smoke. This will help to give the

surgeon a clearer view of the surgical field and removes offensive and irritating odors. Various smoke evacuators are available (103,195). To be most effective, the evacuator nozzle should be positioned as close as possible to the operative field and be functional before, during and for 30 seconds after tissue is vaporized (196).

Personnel masks should be removed and discarded as soon as possible after use (196). Standard surgical masks filter out particles down to about 3 microns in diameter. The laser plume has particles as small as 0.31 microns. High-efficiency masks can filter particles down to 0.30 microns, but they are difficult to breathe through and lose their efficiency when wet (10,103).

Ocular Injuries

The laser beam may be directed over some distance. The area of hazard may not be limited to the immediate surgical area and may present risk to operating room personnel (25). The surgeon is not highly susceptible to injury because of the safety devices built into the instrument. However, if the instrument is accidentally activated, he is exposed to the same hazards as other personnel.

The eye is especially vulnerable to injury. Because CO_2 laser beams are absorbed within the first 200 ยตm of tissue, they are a hazard to the cornea (197). Argon, KTP, and Nd-YAG lasers are more likely to cause damage to the retina. The extent of damage will depend on which part of the retina is affected. Permanent visual loss may result (25).

All personnel in the area where a laser is used should wear appropriate protective eyewear. This may include goggles, face shields, spectacles, or prescription eyewear using special materials or reflective coatings (or a combination of both), selected to reduce the potential ocular exposure. The safety eyewear should be marked according to the wavelength (laser type) (Fig. 32.6). It should be noted that laser safety eyewear is not designed for looking directly at a laser beam (16). The patient's eyes should be closed and covered with saline-soaked gauze or a nonshiny metal shield. Awake patients should wear goggles specific for the laser being used. Windows in the room should be covered and a warning sign placed

on the operating room door at eye level (Fig. 32.4). Spare eyeware should be available at all entrances.

Figure 32.6 All laser-protective eyewear should be clearly and permanently labeled.

Electrical Shock

Another concern is electrical shock from the electrosurgery device. A common practice among surgeons is to allow an assistant to touch the distal end of a forceps with the active electrode from the electrosurgery apparatus. This action makes the forceps the active electrode. A glove may not offer sufficient protection from the electrical circuit. Holes appear in as many as 15% of gloves.

There are ways to minimize the shock potential while using electrosurgery. The active electrode should be firmly in contact with the forceps before it is energized. The person holding the forceps should try to contact it in as large an area as possible to spread the concentration of the charge.

Fire Prevention

The best way to deal with fires is to prevent them from starting (127,198). Fires can be avoided by not allowing the three elements of the fire triangle to come together at the same time.

Controlling Ignition Sources

One way to reduce fires is to properly use equipment that might act as an ignition source. It is important to read instruction manuals and to alter techniques to fit these instructions.

Lasers

Personnel who use lasers should take a certified laser course (6,23,26,103). They should practice their technique on inanimate objects and gain experience at the hands of an experienced clinician. Specific personnel should be designated to monitor and prevent laser hazards.

A laser protocol should be developed and followed. Lasers should be test fired onto a safe surface before use to ensure that the beams are properly aligned. Lasers should always be kept in the standby mode except when needed. The lowest power density and shortest pulse duration that will do the job should be used. The laser should be activated only when the tip is under the surgeon's direct vision. The laser should be placed in standby mode before removing it from the surgical site.

Laser fibers should not be clipped to drapes because the fibers may be broken. The laser fiber should be carefully passed through an endoscope before introducing the scope into the patient to minimize the risk of fiber damage. The fiber's functionality should be verified before inserting the endoscope into the patient.

If a laser contact tip is used, the tip will remain hot for several seconds. Blind entry into cavities with this tip should be avoided (199). The risk of tracheal tube ignition will be lowered if the laser is activated during the expiratory pause (200).

Electrosurgery Unit

The electrosurgery unit should not be used during tracheostomy (31,34,50,111,171,201,202,203,204). Bleeding should not be treated with electrosurgery after flammable dressings have been applied.

A bipolar electrosurgery unit should be used whenever possible. This will reduce the current density in the tissues surrounding the active electrode and minimize the potential for direct coupling. Bipolar units work at lower voltages and are not associated with insulation failure.

Monopolar units should have a means to monitor the return electrode or active electrode. Using active electrode monitoring will minimize the risk of stray electrosurgical burns (38). Before each use, the electrosurgery unit and associated safety features should be inspected for signs of damage and tested to ensure that the unit is functioning correctly. If it is not working properly or is damaged, the electrosurgical apparatus should be immediately removed from service. The unit should be protected from spills. Unintentional activation may occur if fluids enter the generator. The alarm system should be checked prior to applying the dispersive electrode. The active electrode should have a tip that is secure, because a loose tip may cause a spark. Prejelled dispersive electrode pads should be checked for uniform gel distribution and absence of exposed wires before being applied to the patient. Outdated or previously opened but unused dispersive electrode pads should not be used, because the gel can undergo electrolysis and/or desiccation. If a dispersive electrode pad requiring gel is used, the pad should be checked carefully to identify any dry spots on its surface before it is placed on the patient.

After the patient has been positioned, the connection between the patient and the unit should be established by placing the dispersive electrode on a nonhairy area of clean, dry skin. The dispersive electrode should be the appropriate size for a patient (i.e., neonate, infant, pediatric, adult) and never be cut to reduce its size.

The dispersive electrode should be applied to clean, dry skin over a large, well-perfused muscle mass as close to the operative site as practical, avoiding bony prominences, scar tissue, skin over a metal prosthesis, or distal to a tourniquet. Excessive hair should be removed before applying the dispersive electrode, because hair will insulate the pad from the patient. The pad's entire surface area should maintain uniform body contact. There should not be any tenting, gaping, or moisture under the pad. This will interfere with adhesion to the skin and

decrease the contact surface. The dispersive electrode

should not be moved to another site after initial application. The status of the dispersive electrode should be checked if any tension is applied to the cord or if the patient is repositioned after the pad is applied. A used dispersive electrode should not be reapplied.

Electrocardiographic electrodes should be placed as far as possible from the operative site to minimize the alternate flow of current through the electrodes and monitor to ground.

If insulated electrosurgical electrode probes are required, only commercially available insulated probes should be used (9). Insulating sleeves cut from catheters or other materials should not be used to sheathe probes.

The lowest power settings that are effective for the surgical procedure, as determined by the surgeon in conjunction with the manufacturer's recommendation, should be used. The entire circuit should be checked if the operator requests higher power settings because of ineffectual results.

The electrosurgery unit should be activated only when the tip is under the surgeon's direct vision and only by the person using it. Cords should not be clamped with or wound around any objects. The electrosurgery probe should be kept clean to minimize the risk of adherent tissue incandescing or flaming. The electrosurgical pencil should be placed in a holster when it is not in active use. The electrosurgical unit should be placed in standby mode whenever it is not in active use. Unnecessary foot switches should be removed so that they are not accidentally activated.

During laparoscopic surgery, all-metal or all-plastic cannulas should be used and not a hybrid cannula system (i.e., a combination of plastic and metal cannulas) (37). Electrosurgery electrodes should not be used inside metal suction irrigators.

The electrosurgical unit should be deactivated before removing it from the surgical site. Even after deactivation, the probe tip may retain enough heat for a few seconds to melt plastics or ignite some fuels, so it should be placed inside a clean, well-insulated holder or broken off. In addition to protecting the tip, this makes it more difficult to accidentally activate the switch. The tip should

be broken, and a safety cover should be placed over the tip and activation switch before the device is discarded (205).

Argon-enhanced Coagulation

All safety measures observed for the electrosurgical unit should be observed for argon-enhanced coagulation (31). The electrode should not be placed in direct contact with tissue. The hand piece should be moved away from the patient's tissue after each activation. The argon gas flow and the argon coagulator should be activated simultaneously. The argon gas line should be purged of air before each procedure and by activating the system after moderate delays between activations.

Fiber-optic Light Sources

All connections should be made before the light source is activated, because the end of the cable can cause a fire (53). An active fiber-optic cable should not be placed on flammable material. The light source should be turned OFF before disconnecting the cable. The end of a fiber-optic cable can retain a significant amount of heat after being disconnected from the light source (206). Therefore, it is important to be careful where one places the end of a fiber-optic cord.

Heated Humidifiers

Only a breathing tube and heating circuit labeled for use with a specific humidifier should be used (207). Heated breathing circuits should not be covered with sheets, blankets, towels, clothing, or other material. They should not rest on surfaces such as the patient, operating table, blankets, or medical equipment. Instead, a boom arm or tube tree should be used to support them. A heated-wire breathing circuit should not be turned ON before flow has been initiated. If there is no flow (as during cardiopulmonary bypass), the heater should be turned OFF (208).

Defibrillators

When using a defibrillator, care should be taken to hold the paddles firmly and position them properly. Disposable conductive pads should be larger than the metal surface of the paddle and be within their expiration date. This will prevent arcing when the

paddles are activated (58). ECG electrodes should be applied as far as possible from the defibrillation pads.

Electrical Faults

All electrical cords should be regularly inspected for cuts and nicks in the insulation, frayed insulation, and loose connections at the plug or receptacle ends (209). All plugs should be pushed completely into the receptacles to prevent prong-to-prong arcing (210).

Managing Fuels

Tracheal Tubes

Non-intubation Techniques

Since the tracheal tube is often the fuel for the fire, anesthetic techniques that do not require a tracheal tube will eliminate one component of the fire triad (92). These include apnea, jet ventilation, and spontaneous breathing.

Apnea

With the apneic technique, the patient is ventilated by using a mask or tracheal tube, and these are withdrawn as the laser is used (92,93,211). After a period of time, ventilation is reinstated. This is repeated as long as needed to perform the surgery.

Insufflation

Patients may be allowed to spontaneously breathe a combination of oxygen and anesthetic agents while laser procedures are undertaken. The gases are administered through a catheter or hook in the

corner of the mouth that is well out of the way of the laser beam. The suction channel of a laryngoscope may be used to insufflate oxygen. Operating room pollution with anesthetic agents may be high with this technique. Oxidizers should be used as sparingly as possible since the insufflated gas could support combustion.

Jet Ventilation

Jet ventilation techniques either via a metal bronchoscope or a

catheter inserted through the cricothyroid membrane may be used (212). A high-velocity jet of oxygen or helium and oxygen can be directed into the airway above or below the glottis by using various apparatus (21,92,93,196,213,214).

There has been a fire reported with this technique (215). An errant laser strike ignited the surgeon's glove. The resultant burning vapors were entrained into the patient's airway. The patient's mustache was also ignited, and the patient suffered facial burns.

Filling the Cuff with Saline

The cuff is the most vulnerable part of the tracheal tube, regardless of the tube or cuff material. If a laser beam penetrates an air-filled cuff, gas can leak into the operative field, and if the oxygen concentration is high, the risk of fire is great.

Fluid in a cuff acts as a heat sink and makes the cuff less easy to perforate (216,217). Filling the tracheal tube cuff with a lidocaine jelly-plus-saline mixture not only prevents the cuff from being ignited but may plug small holes in the cuff resulting from a laser hit (218).

If the cuff is perforated, a jet of fluid may extinguish the fire. If perforated, fluid-filled cuffs retain their shape longer than air-filled cuffs. Care must be taken to remove all air from the cuff, because any remaining air will settle in the most superior part of the cuff, which is the part most likely to be hit by the laser beam. Addition of methylene blue or other biocompatible and highly visible dye to the saline will help the surgeon to recognize a perforated cuff. Some surgeons object to the addition of methylene blue because if the cuff is punctured, the color of the tissues is altered, making it difficult to recognize pathology.

Protective Wrappings

The tube can be covered with a protective wrapping. These are discussed in greater detail in Chapter 19.

Merocel wrap (Laser-Guard^{TM}) was found to be acceptable for surgical levels of CO_2, KTP, and Nd-YAG lasers (219,220,221,222). Merocel-wrapped tubes are not more combustible if they are coated with blood (223). Reflected laser beams have not been a problem with this wrap (224). This

product is easier to apply than metallic tapes (225).

Aluminum and copper tapes are effective for use with the CO_2 and Nd-YAG lasers if the tube is meticulously wrapped (226,227,228). However, a fire can occur if the laser contacts part of the tube that is not wrapped (229,230). A wrapped red rubber tube does not offer protection from the KTP laser (86). The adhesive backing or surface coating of some tapes can be ignited by laser beams (92). The presence of blood on the surface of foil-wrapped tubes makes combustion more likely to occur (223). Tape-wrapped tubes may unravel, leaving portions of the tube exposed. If the wrapping is dislodged, it could obstruct the airway. A wrapped tube may catch fire (231,232). Metallic tapes may reflect the laser to nontargeted areas (224). Spiral wrappings may cause the tube to kink. Any wrapping adds thickness to the tracheal tube, which could be a problem for the surgeon.

Protecting the Cuff with Wet Covers

As a further precaution, moist cottonoids, sponges, or pledgets can be placed on the cuff (92,233,234). Cotton gauze is a good choice because it stays wet longer than other covers and has low energy transmission (235). Wet gauze will also protect the shaft (236). These have been found to be especially helpful with the CO_2 laser (234). The Nd-YAG, KTP, and argon lasers may allow some energy to penetrate the pledget and rupture the cuff (235).

It is important that wet covers be kept moist. Laser beam hits may dry them, and if that happens, they lose their protective effect. Further hits can cause the cottonoids and/or cuff to ignite. All these must be retrieved after surgery.

Special Tracheal Tubes

Ready-to-use laser-resistant tubes are discussed in Chapter 19. *Laser resistant* means that the material can withstand limited laser energy with little or no damage. The use of a special laser tube does not necessarily prevent a fire during laser surgery (237). Even though the tube is labeled laser-resistant, the cuff will not be resistant, and special precautions need to be taken to protect it. A fire may occur if the protective wet gauze over the cuff dries or is displaced.

No laser-resistant tracheal tube is completely safe from all types of lasers under all conditions. All of these tubes can be damaged or ignited by lasers for which they are not intended or by high laser energies (238,239). Some are made more combustible by blood (223). Tubes sold for use with lasers should indicate the type of laser for which they are suited as well as the conditions (power, power density, spot size, oxygen concentration) under which the tube is safe to use. Strict adherence to manufacturer's warnings and directions is essential.

If the Nd-YAG laser is used through a fiber-optic bronchoscope passed through a tracheal tube, it is best to use an unmarked PVC tube (240). The tracheal tube should be placed just below the vocal cords so that the tip is as far away from the operative site as possible. It should be remembered that the cover on the fiber-optic endoscope is plastic and can burn.

Some laser-resistant tubes are more resistant to fire than conventional tracheal tubes when contacted by electrosurgical instruments (155).

When laser contact tips are used, there is an even greater opportunity for ignition. They can get hot enough to melt and burn plastics even when the laser is inactive (241).

Double-cuff tubes are not more resistant to leaks that will occur after cuff puncture but do allow a seal to be maintained if one cuff remains intact. The second cuff is still vulnerable to puncture (239).

There are disadvantages associated with laser-resistant tubes. They are more expensive than PVC and red rubber tubes. Since these tubes are often used for patients who have had previous laryngeal surgery, the anatomy may be distorted, making intubation difficult. Some laser-resistant tubes are so stiff that it is difficult to pass a stylet or use with a specialized laryngoscope such as the Bullard laryngoscope (Chapter 18). Therefore, a difficult intubation may become even more challenging when these tubes are needed.

Using Smaller Tracheal Tubes

Small-diameter tracheal tubes require higher power densities for ignition than large-diameter tubes because the higher gas flow

cools smaller tubes more quickly than larger tubes. Also, the smaller the tracheal tube, the less likely it is to be hit by an ignition source.

Making the Tracheal Tube Easy to Remove

The tube should be fixed so that it can be removed rapidly, if necessary. If the tube is to be removed, this should be done immediately after ignition to minimize damage to the airway and lungs. If the tube continues to burn, it may be very difficult to remove. Some tracheal tubes break apart as they burn. If the tube is wrapped, the wrapping may break into pieces that could lodge in the airway.

Some tubes are easier to remove than others (91). PVC tubes with saline-filled cuffs are more difficult to remove than red rubber tubes. The fastest way to deflate a fluid-filled cuff is to remove the contents with a syringe rather than cutting the pilot balloon. Unclamping the inflation tube on a red rubber tube will result in rapid release of the cuff contents.

Wetting Fuels

The use of wet towels, packers, or sponges around the surgical site can prevent ignition of materials near the site. Gauze or sponges used with uncuffed tracheal tubes to minimize gas leakage into the pharynx and sponges, gauze, and pledges (and their strings) used to protect the tracheal tube cuff should be moistened and not allowed to dry.

Hair that is near the operative site (e.g., eyebrows, beards, and moustaches) should be made nonflammable by coating it thoroughly with a water-soluble lubricating jelly.

Proper Preparation Practices

Water-based solutions should be used to decontaminate the skin prior to surgery whenever possible. If alcohol-containing solutions must be used, a minimum of the agent should be used and applied like paint, not in a thick, runny coat. The solution should not be applied in a manner that allows dripping, pooling, or wicking. If solution drips away from the surgical site, it should be immediately blotted with a gauze sponge before it can soak into any absorbent material. Any soaked materials should be removed. Daubing of prep pooled on skin (in the umbilicus or

cricoid notch) may be needed. Draping should be delayed to allow the solution to fully vaporize and become diluted in room air. This could take 10 minutes or longer (1,117). Incise (adhesive, occlusive) drapes should be used, if possible, to isolate head and neck incisions from oxygen-enriched atmospheres and from flammable vapors beneath the drapes (120). If the incise material does not adhere to the patient, the prep is likely still wet, and the patient should be redraped once the prep is fully dry.

Correct Product Choices

It is important to consider the fire potential when choosing equipment. The anesthesia provider should be aware of the circumstances under which a fire can occur and strive to use the product that will have the lowest flammability under conditions where it will be used.

Fire/laser-resistant drapes should be used when exposure to ignition is possible. It is important that the drape is tested with the type of ignition source that is to be used. A standard for testing drapes using the CO_2 laser has been published (242).

Laser-resistant anesthesia circuit protectors and drapes are available. These are aluminized to deflect the laser beam. There is still the possibility that the beam may be reflected onto a flammable surface and start a fire (243).

The use of a metallic Y-piece and elbow will ensure that tracheal tube combustion will not spread to the anesthesia breathing system (244).

Other Measures

A number of other measures may be beneficial in preventing a fire. The tracheal tube should be withdrawn to above the site of surgery during tracheotomy. The use of positive end-expiratory pressure (PEEP) may decrease the risk of airway fire in some cases (245,246). Nursing personnel can reduce the combustible load in the room by removing disposable paper wrappers and covers before the start of the case. Not only does this reduce the fuel in the room, but it also reduces the waste that must be disposed as ‾€red bag‾€ with its higher disposal costs (2).

Minimizing Oxidizer Concentrations

The fire risk can be reduced by removing or isolating the oxidizer from the surgical area or minimizing its concentration.

During defibrillation, all sources of oxygen should be completely removed from the area around the patient.

Oxygen should be administered only when indicated and in no higher concentration than is needed (as guided by oxygen saturation monitoring).

There are several ways of supplying a gas with an oxygen concentration greater than 21% but less than 100% to the patient. An oxygen and an air flowmeter can be connected by using a Y-piece (Fig. 32.7), or a blender can be used. If the machine has an air flowmeter, a mixture of oxygen in air can be set and delivered to common gas outlet (247). If the common gas outlet can be accessed, a nasal cannula can be mated to the outlet by using a 5-mm tracheal tube connector. If the common gas outlet cannot be accessed, a circle system can be attached to the machine, the adjustable pressure limiting (APL) valve closed, and the selector switch set to BAG. A nasal cannula can then be attached to the Y-piece. This arrangement may cause the continuous positive pressure alarm to be activated. A forced-air convection machine can be used to provide a high flow of air around the patient's head while a nasal cannula delivers a low flow of 100% oxygen to the patient.

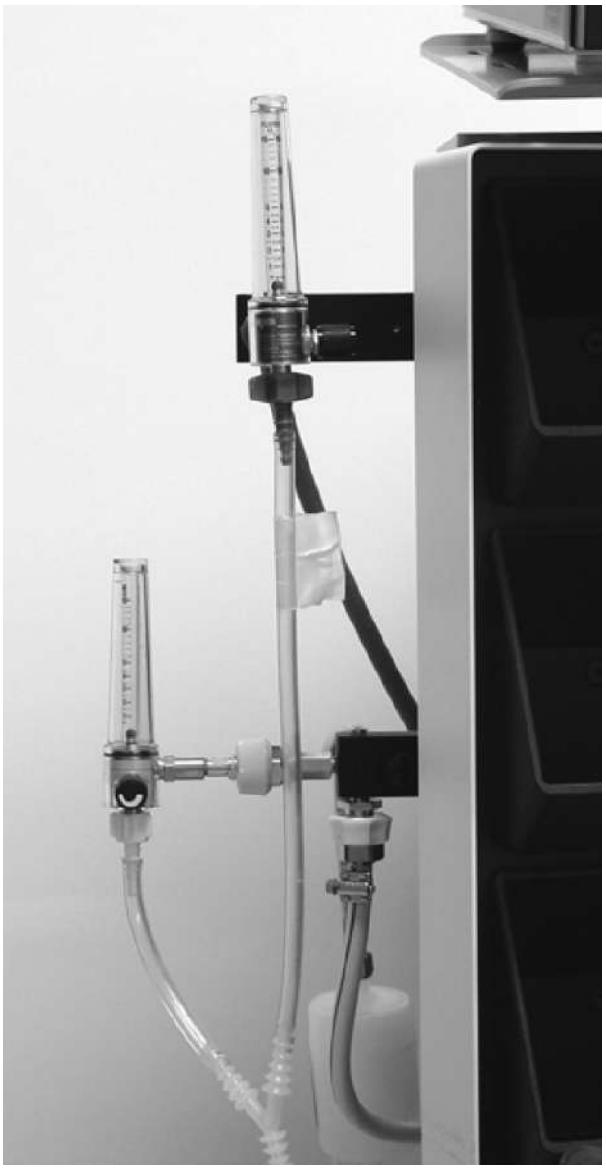

Figure 32.7 Gas from an oxygen flowmeter and an air flowmeter can be connected to produce a gas with an oxygen concentration of less than 100%.

If possible, the oxygen flow should be discontinued for at least 1 minute before heat-producing surgical instruments are used (248,249). When the heat source is no longer used and any tissue embers are extinguished, oxygen administration can be resumed.

During head and neck surgery, a barrier should be established between the oxygen-enriched atmosphere beneath the drapes and the surgical field, if possible. This can often be accomplished with an adhesive (incise, occlusive) drape (2,117). When gas is used to ventilate the area under the drapes and prevent CO_2 accumulation, the lowest acceptable concentration of oxygen should be used (250).

Forming an open tent with the drapes will prevent gases from collecting and allow oxygen to dissipate (56,170). Since oxygen is slightly heavier than room air as long as there is some way for the oxygen to get in and out of a space, it will tend to flow toward the floor. Actively scavenging the space beneath drapes with a suction device will lower oxygen concentrations significantly (251). Devices that combine oxygen delivery with suction to prevent oxygen buildup under the drape have been described (252,253). A fan can be used to blow the accumulated oxygen away from the patient. Directing the flow of nasal oxygen through a nasal airway will lower the oxygen concentration at the skin (254).

Health care institutions should consider purchasing anesthesia workstations that include internal pipelines and flowmeters for air (248). This makes it easy to switch patient ventilation beneath the drapes from oxygen to air before the use of heat-producing surgical instruments. An external flowmeter can be added to an anesthesia machine if piped air is available (Fig. 32.7).

Nitrogen, air, or helium may be used to reduce the inspired oxygen concentration to the lowest level that will provide acceptable patient oxygenation. Nitrous oxide supports combustion and should not be used as the diluent gas (255,256,257). Helium is a good heat conductor and may offer a slight protective effect with the CO_2 but not the KTP laser (258,259). The use of helium may decrease the resistance of the gases passing through the tracheal tube (260,261).

Nitrogen insufflation can significantly reduce the incidence of laser-induced tracheal tube cuff fires (262). This can be accomplished by attaching a catheter covered with a laser-resistant wrap to the tracheal tube. Nitrogen is then insufflated through the catheter. This technique should be undertaken with caution, as a hypoxic mixture may possibly be administered.

Although using lower inspired oxygen concentrations will reduce the risk of ignition, it will not totally prevent it. If there is a significant leak around the tracheal tube cuff, the anesthesia provider may fill the reservoir bag by pushing the oxygen flush. This will result in an elevated oxygen concentration. A more appropriate response would be to increase the fresh gas flow while maintaining the same inspired oxygen concentration or to replace the tracheal tube.

When electrosurgery is used in the oral cavity, the use of a cuffed tracheal tube will minimize the oxidizer level. Leaks around the tube may result in fires (161,263). If an uncuffed tube must be used, an occlusive pharyngeal pack moistened with a nonflammable liquid will reduce the gas flow into the oral cavity (264). Insufflating the mouth with gases such as helium, CO_2, or nitrogen will reduce the oxidizer concentration. The oropharynx can be scavenged with separate suction.

Pneumatic power tools should be operated with nitrogen or air. Inflatable tourniquets should be inflated with air or nitrogen but not oxygen or nitrous oxide (56,79,265). Nitrous oxide should not be used for insufflating the abdominal cavity during laparoscopy (266,267,268).

Preventing Pressure Regulator Fires

Fires in regulators can be minimized by not allowing them to become contaminated with oil, grease, or other combustible materials or cleaned with a flammable agent such as alcohol (122,269). Before a regulator is fitted to a cylinder, particles should be cleared from the cylinder outlet by removing the protective cap or seal and slowly and briefly opening (ĺ €crackingĺ€) the valve with the port pointed away from the user and any other persons. A cylinder valve should always be opened slowly to allow heat to be dissipated as the gas is recompressed. Consideration should be given to replacing aluminum regulators with those made from brass. Rules for handling cylinders are discussed in Chapter 1.

Fire Plan

Each health care facility should formulate a plan for dealing quickly with an operating room fire

(1,6,56,58,127,171,202,206,240,270,271,272,273,274). Surgical teams should be trained in and practice drills for keeping minor fires from getting out of control and managing fires that do get out of control. They should know the location and proper use of alarm boxes, gas shut-off valves, and fire extinguishers. Evacuation procedures should be reviewed periodically.

It is important to immediately call for help, decide who is going to fight the fire, when it will be appropriate to leave the room, and how to care for the patient during the fire.

Burning material on or in the patient often can be extinguished effectively and safely by hand or with a nonflammable liquid (e.g., saline from a basin on the scrub table) or wet cloth. With laser surgery in the airway, at least two syringes filled with sodium chloride should always be available to extinguish the fire (275). Larger areas can be smothered with a blanket or wet towel. Fire blankets are not recommended (8,276). If the drape is water-resistant, water poured on it will be ineffective (277). The fire will burn on the underside. The only effective technique is to pull the burning materials from the patient.

Fires that involve electrical components are best handled by disconnecting the device from its electric power supply and removing the device from the room.

The flow of oxygen, nitrous oxide, or air to any involved equipment should be turned OFF, if this can be accomplished without injury to personnel or the patient. Most patients can tolerate short periods of oxygen deprivation. The patient should be ventilated with air and intravenous agents used to maintain anesthesia until all possible sources of fire or reignition are suppressed. It may be necessary to close the oxygen and nitrous oxide shut-off valves to the affected room (58,278,279). Cylinder valves should be closed and all cylinders removed from the area. If supplemental oxygen is necessary to oxygenate the patient, the patient should be moved to the nearest area where oxygen can be safely used (56).

If an airway fire occurs, the breathing system should be disconnected from the tracheal tube to stop gas flow. If this site is not easily accessible or the operator may be burned in the process of disconnecting the tube, the breathing system can be disconnected at the absorber (280).

The tracheal tube should not be unduly secured so that it can be removed quickly. Although immediate removal of the tracheal tube and protective devices is usually recommended with an airway fire, this may not always be the best course of action (148,281). The risk:benefit ratio of extubation needs to be considered. A stylet or airway exchange catheter can be used to substitute a new tube the burned tube for. If the decision to remove the tube has been made, saline-filled cuffs on plastic tubes can be deflated faster by aspirating the fluid than by cutting the pilot tube (91). With red rubber tubes, unclamping the pilot tube is fastest.

The airway should be re-established and the patient ventilated with air until it is certain that nothing remains burning. Then, 100% oxygen should be administered. A search for fragments that remain in the trachea and assessment of damage to the larynx and tracheobronchial tree should be made.

Extinguishing a Fire

Although most operating rooms have a sprinkler system, sprinklers are frequently not effective with operating room fires (206). This is because the sprinklers are rarely located over the operating room table and are heat activated. Operating room fires tend to give off a lot of smoke and toxic products but not necessarily enough heat to immediately activate the sprinklers. Therefore, it is important the all operating room personnel are familiar with fire extinguishers.

Location

Strategically placed portable fire extinguishers are an important part of any fire protection program (1,282,283). They should be located in conspicuous, readily accessible locations that are known by all operating room staff (Fig. 32.8).

Hands-on experience with fire extinguishers is essential to a fire safety education program (284). Setting up real fires in a parking lot and providing practice with extinguishers can have valuable payoffs during an actual fire.

Use

Use of any fire extinguisher can be recalled by the acronym,

pass. Pull the pin. Aim the horn or nozzle at the base of the fire. Squeeze the trigger or handle while holding the extinguisher upright. Sweep the extinguisher from side to side, covering the area of the fire. Instructions are found on the fire extinguisher (Fig. 32.9). The pin and hose are shown in Figures 32.10 and 32.11.

Choice of Extinguisher

The choice of extinguisher should be based on the predicted fire risk for that location (282,285,286). Fires are classified according to their fuel. Class A fires include small masses of ordinary combustibles—cloth, paper, and most plastics. Fires involving flammable liquids or grease are in class B. Electrically energized fires are class C. Two standard sets of fire class labels exist: a traditional lettering system and a newer universal pictograph system that does not require the user to be familiar with the alphabet fire class codes (Fig. 32.9).

Figure 32.8 Fire extinguishers should be in conspicuous locations, well known to all operating room staff.

Halogenated Agents

Halogenated extinguishing agents are liquids that upon discharge under relatively high pressure surround a fire with a combination of vapor and liquid droplets (mist). Halogenated agents are ideally suited for fighting fires involving electronic equipment and fires in areas where electrical or electronic equipment is nearby.

Halon was the agent of choice for operating room fires for many years (202). It has the ability to penetrate burning material and to smother and cool the chemical reaction of the fire. While usually marked for class B and C fires, it is also effective against class A fires found in the operating room. Unfortunately, because of environmental concerns, halon extinguishers are no longer available. If present in an operating room, they may be used but cannot be recharged. The National Fire Protection Association requires that nonrechargeable

extinguishers be removed from service 12 years from the date of manufacture (287). In response to the prohibitions on the use of halon, a number of extinguishing agents have been developed to replace it (282,288,289) (Fig. 32.12).

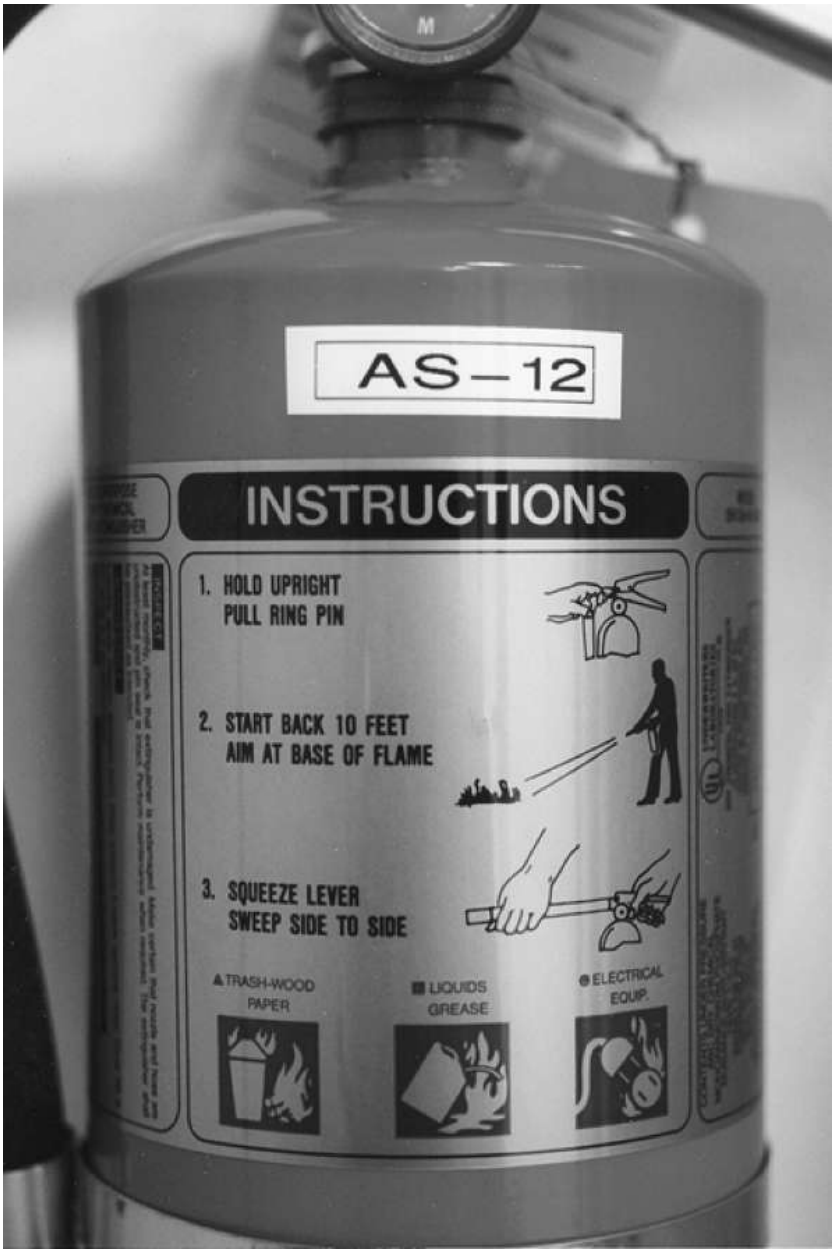

Figure 32.9 The instructions for using the fire extinguisher are printed on the extinguisher.

Figure 32.10 The pin that needs to be pulled to activate the extinguisher is in the handle at the top of the extinguisher. The hose is normally attached to the side of the extinguisher. This figure also shows the pressure gauge, which indicates that the extinguisher is usable, and the monthly checkout list, which shows that the extinguisher has been checked, the extinguisher and hose is undamaged, and the pressure is in the use range.

Figure 32.11 Close-up of pin and pressure gauge at top of extinguisher.

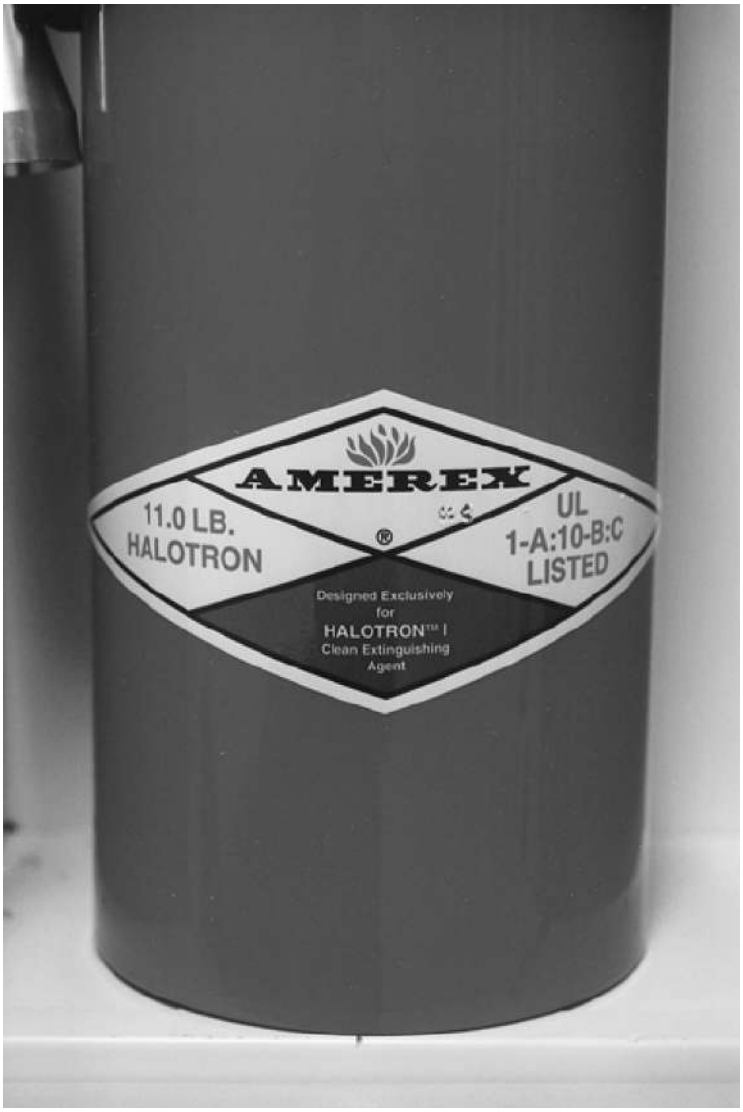

Figure 32.12 There are several substitutes for halon available.

Carbon Dioxide

CO_2 extinguishers emit a fog of CO_2 gas with liquid and solid particles that rapidly vaporize to cool and smother a fire. Although they carry a B and C rating, they can be used to extinguish small class A fires. CO_2 fire extinguishers are heavier and bulkier than halon-type devices. CO_2 extinguishers do not

leave a residue but do emit liquid and solid components that rapidly vaporize. This causes rapid cooling that might cause freezing if it comes into contact with exposed skin or internal organs (283,290).

Water

Pressurized-water extinguishers are chiefly effective against class A fires. They are more difficult to use than CO_2 and halon-type extinguishers. To put out fires on water-repellant drapes, a finger must be placed over the nozzle to produce a fine spray. A stream or splash of water could fan the fire (1). A non-magnetic water mist extinguisher is available for use in the MRI unit magnet room.

Figure 32.13 All operating room personnel must know where the fire alarm is located. The instructions for activating it are printed on the fire alarm.

If the fire starts to get out of control, the fire alarm (Fig. 32.13) should be sounded, and the fire department should be notified to give firefighters ample time to respond (1). Firefighters would

rather find that a small fire has been extinguished than see smoke billowing out of a buildingâ€”especially in a health care facility.

The patient and staff should be evacuated if the fire and smoke are excessive (210). In some situations, however, it may be more hazardous to move the patient than to attempt to extinguish or contain the fire. The attending physician must determine which would present the lesser hazard.

The doors should be closed to contain the smoke and isolate the fire. Wet sheets or towels can be stuffed under the doors to reduce the spread of smoke from the room.

Whatever steps are necessary should be taken to protect or evacuate patients in adjacent areas.

After the fire, involved materials and devices should remain in place for the fire department investigators. Notes should be made as soon as possible after the fire and an incident report completed.

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Questions

For the following questions, select the correct answer

1. The percentage of operating room fires that result in patient injury is

A. 10% to 20%

B. 20% to 30%

C. 30% to 40%

D. 40% to 50%

E. 50% to 75%

View Answer

2. Which of the following is most commonly involved in operating room fires?

A. Lasers

B. Electrosurgery equipment

C. Argon beam coagulators

D. Fiber-optic illumination systems

E. Defibrillators

View Answer

3. Which type of tracheal tube will cause the most severe damage to the tracheobronchial tree if it catches fire?

A. Red rubber

B. Silicone

C. Laser resistant

D. PVC

View Answer

4. In order to filter out potential airborne contaminants, the surgical mask must be able to filter particles of which size?

A. 30 microns

B. 3 microns

C. 0.3 microns

D. 0. 03 microns

E. 0.003 microns

View Answer

5. Wet cotton gauze will protect the shaft and cuff of a tube best with which laser?

A. Argon

B. KTP

C. Nd-YAG

D. CO_2

View Answer

6. A clear, unmarked PVC tube is relatively resistant to be used with which laser?

A. Argon

B. KTP

C. Nd-YAG

D. CO_2

View Answer

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. if D is correct

E. if A, B, C, and D are correct.

7. The factors necessary to start a fire include

A. Ignition source

B. Fuel

C. Oxidizers

D. Lasers

View Answer

8. The characteristics of laser light include

A. Coherency

B. Monochromaticity

C. Collimated

D. Ultraviolent

View Answer

9. Which factors determine the ignition risk with a laser?

A. Laser medium being used

B. How the laser is focused

C. Class of laser

D. Exposure time

View Answer

10. Common errors when using electrosurgical equipment include

A. Improper placement of dispersive electrode

B. Insufficient dispersive electrode contact

C. Faulty return electrode

D. Insulating the patient from the operating room table

View Answer

11. Measures to minimize the risk of a tracheal tube fire from a laser include

A. Filling the cuff with saline

B. Minimizing the laser power density and duration

C. Using a laser-resistant tube

D. Using low oxygen concentrations in the inspired gas

View Answer

12. Concerning laser-induced tracheal tube fires

A. The tube may be contacted by a reflected laser beam

B. The cuff is laser-resistant

C. Cotton sponges that protect the cuff may dry out

D. Use of an uncuffed tube increases the risk

View Answer

13. Which laser(s) is(are) likely to damage the retina?

A. KTP

B. Nd-YAG

C. Argon

D. CO_2

View Answer

14. Which laser(s) is(are) likely to damage only the cornea?

A. KTP

B. Nd-YAG

C. Argon

D. CO_2

View Answer

Chapter 33

Equipment Checkout and Maintenance

A checkout procedure is analogous to the preflight check for airline pilots and is intended to determine whether equipment is present, functioning properly, and ready for use. Failure to check equipment properly is a factor in many critical incidents (1,2,3,4,5,6,7,8,9,10,11,12). Properly checking equipment can reduce equipment-related morbidity and mortality, improve preventive maintenance, and educate the anesthesia provider about equipment (1,9,13,14,15,16,17). Defects may be found even just after preventive maintenance has been performed (18).

Failure to perform a proper check before use is common (4,19,20,21,22,23,24,25,26,27). Many anesthesia providers are unable to identify intentionally created faults (28,29,30,31,32,33). With intensive training, performance improves, but high rates of completion are not achieved (34).

User manuals that are provided by anesthesia machine manufacturers have detailed directions for checking. These should be read carefully. Unfortunately, these procedures are often overly complicated. When a procedure takes too long to perform, it is often abridged or skipped altogether.

The Food and Drug Administration (FDA), working with representatives of the anesthesia community and industry, developed a preuse checkout procedure, which was published in 1986 (35). Unfortunately, this list was too complicated for most users, and a simplified, more user-friendly version was published in 1993. This is shown in Table 33.1. The new version retained or added checks of components that fail more frequently than others and that can quickly injure the patient when they fail (36). Components that fail infrequently and that do not immediately jeopardize the patient when they do malfunction were not included in the 1993 version but must still be checked during routine preventive maintenance. Checklists have been published in other countries (16,17,37,38,39).

This chapter is constructed along the line of the 1993 FDA checkout procedure. One of the deficiencies of the 1993 FDA checkout was that while it said to check a certain item, it did not explain how. Many clinicians devised their own methods to fill that void but in fact were not correctly checking certain items. We have recommended a number of test methods to overcome this deficiency. When an alternate test method is given, an attempt will be made to point out the advantages and deficiencies of that method.

Since anesthesia machines from different manufacturers and different models from the same manufacturer vary, the user should study the manufacturer's suggested checking procedures and incorporate specific points into this generic checkout. Parts of the checkout procedure described in this chapter will not apply to machines with an electronic checkout. The user must determine which parts are checked automatically and add those that are not covered.

The FDA checkout is designed for workstations with a circle system, ventilator, capnograph, oxygen analyzer, respiratory volume meter, and airway pressure monitor. Clinicians who use equipment that does not conform to this configuration may need to modify the procedure to accommodate differences. For example, if a Mapleson system is to be used, the checking procedure should include this. Such modifications should have appropriate peer review. The manufacturer's user manual should be consulted for special procedures.

A copy of the checkout procedure should be kept in, on, or near the anesthesia machine. A record that the checklist was used should be made and kept. A printed checklist may present a more organized and systematic approach than if the anesthesia provider uses a mental checklist and may result in improved fault detection (9,33). A pictorial checkout may be easier to read and follow than a typewritten list (5).

Electronic checklists have been developed (40,41). Unlike the electronic checkout (see below), these only list what the anesthesia provider should do. An electronic checklist may be more extensive than a paper checklist.

Electronic Checking

Many of the newer anesthesia machines provide an electronic checking procedure (Fig. 33.1). When the machine

is turned ON, it reminds the user to start the checkout. Before an electronic checkout is performed, all components that are to be used for the anesthetic should be in place. If the breathing tubing is to be extended, it should be extended to the desired length prior to beginning the checkout. During the checking procedure, the machine may prompt the anesthesia provider to make certain adjustments such as opening or closing the adjustable pressure-limiting (APL) valve, occluding the Y-piece, or adjusting the gas flows.

TABLE 33.1 Anesthesia Apparatus Checkout Recommendations, 1993

This checkout, or a reasonable equivalent, should be conducted before administration of anesthesia. These recommendations are only valid for an anesthesia system that conforms to current and relevant standards and includes an ascending bellows ventilator and at least the following monitors: capnograph, pulse oximeter, oxygen analyzer, respiratory volume monitor (spirometer), and breathing system pressure monitor with high- and low-pressure alarms.

Emergency Ventilation Equipment

*1. *Verify that backup ventilation equipment is available and functioning.*

High-pressure System

*2. *Check the oxygen cylinder supply.*

a. Open the oxygen cylinder, and verify that it is at least half full (about 1000 psig).
b. Close the cylinder.

*3. *Check the central pipeline supplies.*
Check that the hoses are connected and pipeline gauges read about 50 psig.

Low-pressure System

*4. *Check the initial status of the low-pressure system.*

a. Close the flow control valves and turn vaporizers OFF.

b. Check the fill level and tighten vaporizers' filler caps.

*5. *Perform a leak check of the machine's low-pressure system.*

a. Verify that the machine master switch and flow control valves are OFF.
b. Attach a ‘€suction bulb‘€ to the common (fresh) gas outlet.
c. Squeeze the bulb repeatedly until fully collapsed.
d. Verify that the bulb stays *fully* collapsed for at least 10 seconds.
e. Open one vaporizer at a time, and repeat parts c and d above.
f. Remove the suction bulb, and reconnect the fresh gas hose.

*6. *Turn the machine master switch ON as well as all other necessary electrical equipment*
*7. *Test the flowmeters.*

a. Adjust the flow of all gases through their full range, checking for smooth operation of floats and undamaged flow tubes.
b. Attempt to create a hypoxic oxygen‘€“nitrous oxide mixture, and verify correct changes in flow and/or alarm.

Scavenging System
*8. *Adjust and check the scavenging system.*

a. Ensure proper connections between the scavenging system and both the APL (pop-off) valve and ventilator relief spill valve.
b. Adjust the waste gas vacuum flow, if possible.
c. Fully open the APL valve and occlude the Y-piece.
d. With minimum oxygen flow, allow the scavenger reservoir bag to collapse completely, and verify that the absorber pressure gauge reads about zero.
e. With the oxygen flush activated, allow the scavenger reservoir bag to distend fully and then verify that the absorber pressure gauge reads <10 cm H_2O.

Breathing System

*9. *Calibrate the oxygen monitor.*

a. Ensure that the monitor reads 21% in room air.
b. Verify that the low oxygen alarm is enabled and functioning.
c. Reinstall the sensor in the circuit, and flush the breathing system with oxygen.
d. Verify that the monitor now reads greater than 90%.

10. *Check the initial status of the breathing system.*

a. Set the selector switch to Bag mode.
b. Check that the breathing circuit is complete, undamaged, and unobstructed.
c. Verify that the carbon dioxide absorbent is adequate.
d. Install the breathing circuit accessory equipment (e.g., humidifier, PEEP valve) that is to be used during the case.

11. *Perform a leak check of the breathing system.*

a. Set all gas flows to zero (or minimum).
b. Close the APL (pop-off) valve, and occlude the Y-piece.
c. Pressurize the breathing system to about 30 cm H_2O with an oxygen flush.
d. Ensure that the pressure remains fixed for at least 10 seconds.
e. Open the APL (pop-off) valve, and ensure that the pressure decreases.

Manual and Automatic Ventilation Systems

12. *Test the ventilator systems and unidirectional valves.*

a. Place a second breathing bag on the Y-piece.
b. Set the appropriate ventilator parameters for the next patient.
c. Switch to the automatic ventilation (Ventilator) mode.
d. Turn the ventilator ON, and fill the bellows and breathing bag with and oxygen flush.
e. Set the oxygen flow to minimum and other

gas flows to zero.
f. Verify that during inspiration, the bellows delivers appropriate tidal volume and that during expiration, the bellows fills completely.
g. Set the fresh gas flow to about 5 L/minute.
h. Verify that the ventilator bellows and simulated lungs fill and empty appropriately without sustained pressure at end expiration.
i. Check for proper action of the unidirectional valves.
j. Exercise the breathing circuit accessories to ensure proper function.
k. Turn the ventilator OFF, and switch to manual ventilation (Bag/APL) mode.
l. Ventilate manually and assure inflation and deflation of artificial lungs and appropriate feel of system resistance and compliance.
m. Remove the second breathing bag from the Y-piece.

Monitors
13. *Check, calibrate, and/or set alarm limits of all monitors.*
Capnometer
Pulse oximeter
Oxygen analyzer
Respiratory volume monitor (spirometer)
Pressure monitor with high and low airway alarms
Final position
14. *Check the final status of the machine.*

a. Vaporizers OFF.
b. APL valve open.
c. Selector switch to Bag.
d. All flowmeters to zero.
e. Patient suction level adequate.
f. Breathing system ready to use.

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*If an anesthesia provider uses the same machine in successive cases, these steps do not need to be repeated or may be abbreviated after the initial checkout.

These electronic checking procedures test the electronic as well as some mechanical components of the anesthesia machine. In

addition, they may gather information about breathing system resistance and

compliance and leaks. They may also remind the user to check functions that are not included in the automatic checkout.

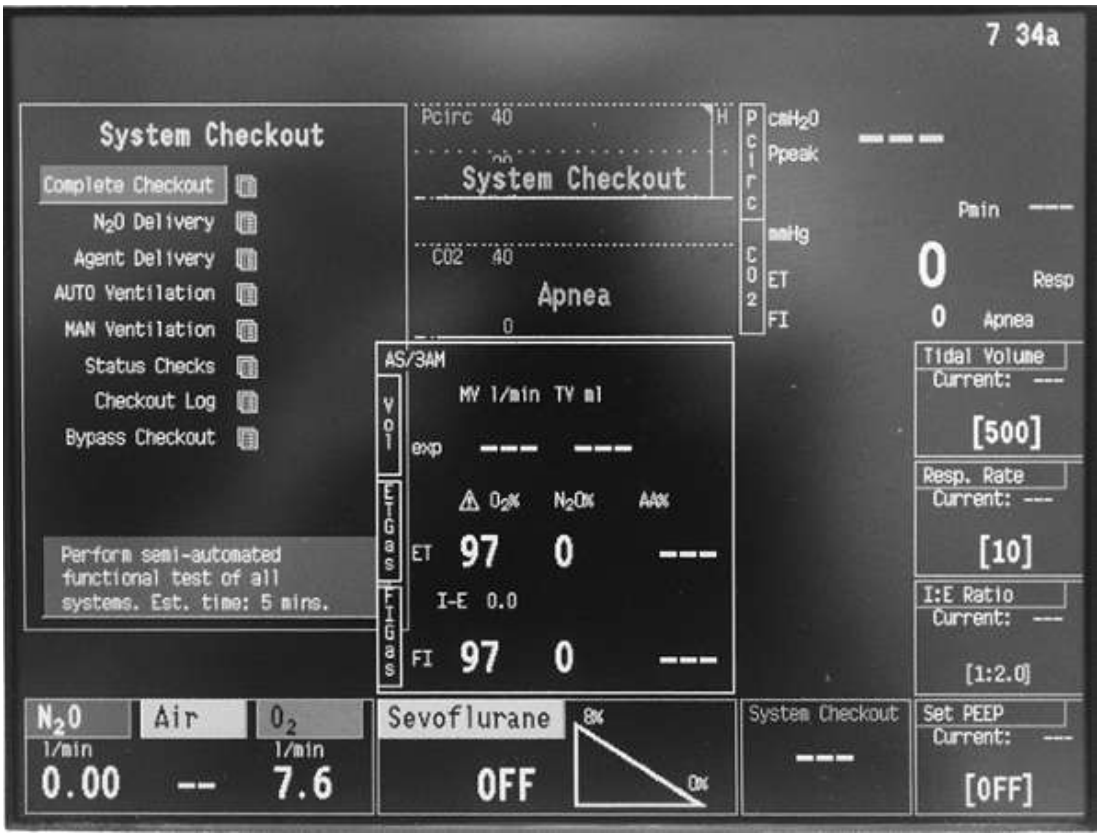

Figure 33.1 Electronic checkout procedure on a newer model anesthesia machine.

Most machines have a mechanism to limit or skip the electronic checkout. This is meant for emergency situations. Many clinicians routinely bypass the checkout (42,43,44). This is not good practice. The electronic check may provide a more comprehensive check than most people perform and may detect some problems that probably would not have been found otherwise. If an anesthesia machine has been held in a ready-to-use state for emergencies, it should be turned OFF at least daily

and restarted with a new checkout procedure.

Whether a full electronic check has been carried out or bypassed is automatically recorded in the machine's computer and can be accessed. If a problem should occur, failure to use the checkout may be cited as evidence of substandard care.

A problem with electronic checkouts is that some anesthesia providers feel that the electronic check is all that is needed. This is not true. The user manual should be considered as the final authority on what tasks need to be performed on each machine.

Since these electronic checkouts differ among manufacturers and different models from the same manufacturer and since they are subject to change, it is not feasible to discuss details of these in a text such as this. The Committee on Equipment and Facilities of the American Society of Anesthesiologists in conjunction with manufacturers, the American Association of Nurse Anesthetists, and the American Society of Anesthesia Technologists and Technicians is working to create a new checkout procedure that will include anesthesia machines with electronic checkouts (45). Anesthesia providers should follow this process closely.

Daily Checks before Beginning Anesthesia

Emergency Ventilation Equipment

Resuscitation Bag

Though rare, certain malfunctions can render the anesthesia machine inoperative (36,46,47). Sometimes, the problem cannot be diagnosed or quickly corrected. In this situation, a manual resuscitator (Chapter 10) will allow the user to provide positive-pressure ventilation while the problem is corrected or the machine replaced.

The patient port should be occluded and the bag squeezed (Fig. 33.2). Pressure should build up rapidly to a point at which the bag can no longer be compressed. If there is a pressure-limiting device, it can be checked by connecting a pressure manometer between the patient port and the bag, using a T-fitting. If there is an override mechanism on the pressure-limiting device, this should be checked.

The resuscitator should be inspected for signs of wear such as cracks or tears. A reservoir bag should be placed over the patient port (Fig. 33.3). Squeezing the resuscitation bag should cause the reservoir bag to inflate. After the reservoir bag is fully inflated and the resuscitation bag has been released, the reservoir bag should deflate easily. This tests both the inspiratory and exhalation paths for patency.

To check that the bag refill valve opens, the bag should be squeezed, then the patient port occluded, then the bag released. The bag should re-expand rapidly.

If the resuscitator has a closed reservoir, its function can be checked by performing several compression-release cycles with no oxygen flow into the reservoir. The reservoir should deflate, but the resuscitation bag should continue to expand. This checks that the air inlet valve functions with an empty reservoir.

Oxygen Source

A source of oxygen to connect to the resuscitation bag should be available. An oxygen flowmeter attached to the pipeline outlet (Fig. 33.4) or the courtesy flowmeter on the anesthesia machine (Chapter 5) will provide a source of oxygen.

Difficult Airway Equipment

If there is any indication that the patient's airway or tracheal intubation will be difficult, the difficult airway cart should be in the room. Emergency airway devices are discussed in Chapter 21. Whatever device expected to be used needs to be present and in working order.

Suction

The adequacy of suction can be checked by placing the end of the suction tubing on the underside of the thumb (Fig. 33.5). With the hand at waist height, the tubing

should stay attached without support. A rigid suction catheter (Yankauer) should be immediately available.

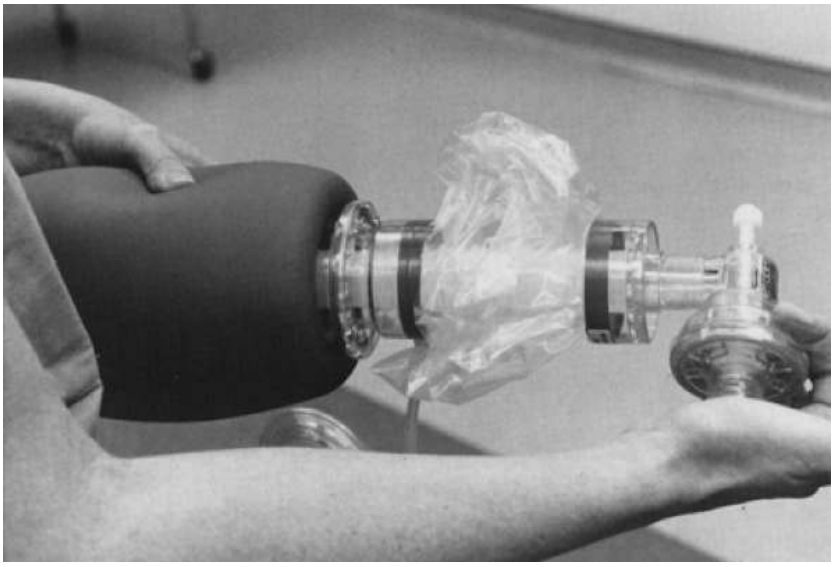

Figure 33.2 Squeezing the resuscitation bag with the patient port occluded.

Gas Supply

Cylinder Pressure

Oxygen cylinders should be checked for correct mounting. If there is a date-expired label on a cylinder it should be checked (48,49). Yokes should be scanned to make certain that any yoke not containing a cylinder is fitted with a yoke (blanking) plug (Chapter 5). All tags should indicate *full* or *in use*.

Before proceeding further, all flow control valves should be closed by turning them completely clockwise. Excessive torque should be avoided. Opening a cylinder or connecting a pipeline hose when a flow control valve

is open may cause the indicator to shoot up to the top of the tube and be damaged, stuck at the top, or not noticed.

Figure 33.3 The resuscitation bag is further checked by placing a reservoir bag over the patient port. Squeezing the resuscitation bag should cause the reservoir bag to inflate. The reservoir bag should then deflate easily when it is squeezed.

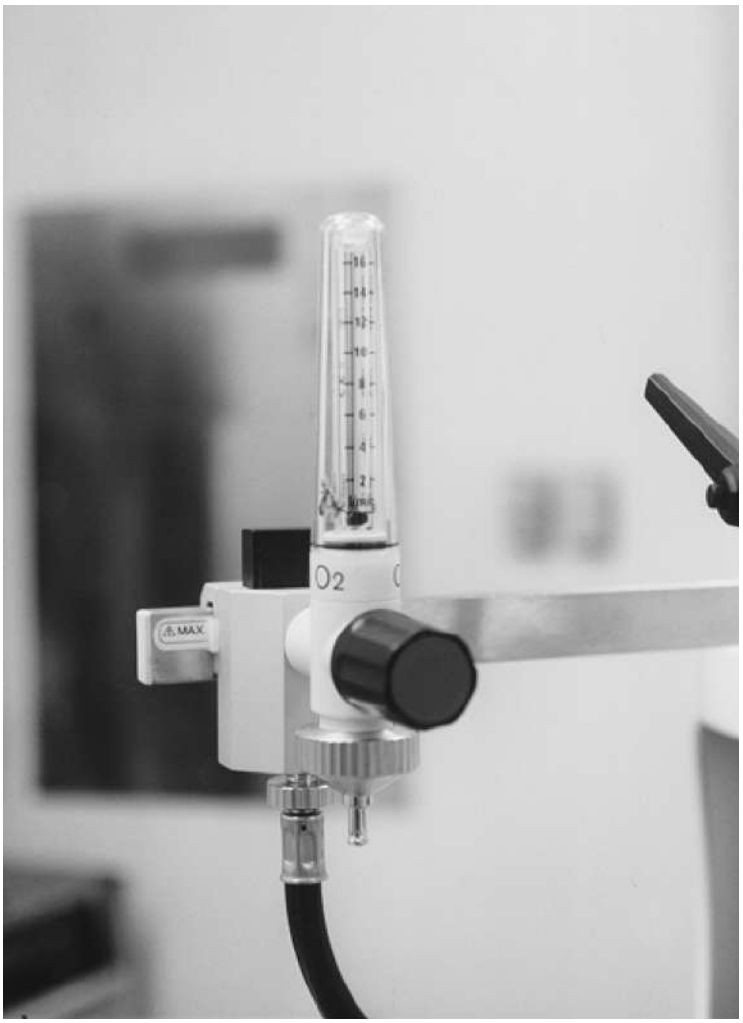

Figure 33.4 A flowmeter that is separate from the anesthesia machine can provide a source of oxygen in an emergency.

The pressure in an oxygen cylinder is checked by turning the valve slowly counterclockwise while observing the related pressure gauge (Fig. 33.6). If a hissing sound occurs, the cylinder should be tightened in the yoke. If tightening the cylinder fails to stop the sound, the washer should be checked for damage. If the hissing sound persists, the cylinder should be replaced.

The cylinder(s) should contain sufficient gas that in the event of a problem with the pipeline supply, life support can be

maintained until the pipeline problem can be corrected or more cylinders obtained. How low a pressure is acceptable will depend on whether additional cylinders are readily available, how low a fresh gas flow can be used, whether mechanical ventilation is necessary, and what type of ventilator is present. Some ventilators use oxygen to drive the bellows. Others use air or a mixture of air and oxygen as the driving gas. A piston ventilator will not require any oxygen to drive it. A full E cylinder will contain about 625 L of oxygen with a pressure of around 2000 psig. One full cylinder will last less than 3.5 hours at a flow of 3 L/minute.

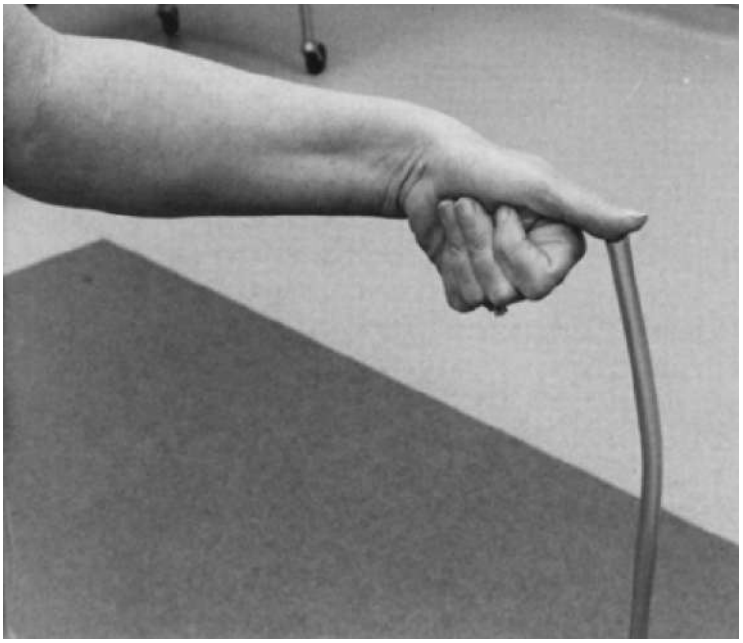

Figure 33.5 Check of suction. The strength of the vacuum is tested by determining that the weight of the suction tubing can be supported at waist height by the seal between the tubing and the underside of a finger. If the vacuum is unsatisfactory, the tubing will not remain in contact with the finger.

The FDA checklist recommends that the cylinder be at least half full (about 1,000 psig). If there are two cylinders and one is completely full, a lower pressure in the second cylinder may be acceptable. The authors believe that 500 psig in an oxygen

cylinder is adequate, provided cylinders will not be the primary oxygen supply (i.e., there is a pipeline supply) and the anesthesia provider is aware of the steps needed to conserve oxygen. Ventilators that use oxygen as the driving gas must be turned OFF and manual ventilation used. Even if there is only one cylinder and it is only 25% full, it would deliver oxygen at 1 L/minute for over 2 hours. Empty or near-empty cylinders should be labeled as empty and replaced with full cylinders (see Chapter 1).

Anesthesia machine cylinders are frequently checked and replaced by anesthesia technicians or other operating personnel. If anesthesia providers are not accustomed to checking and replacing cylinders, they will not react efficiently and effectively in the event of an oxygen supply failure (50).

It has been suggested that merely checking a cylinder for adequate pressure is not enough (38,51). The check valve that prevents cylinder gas from being used when the pipeline is connected may stick, preventing flow from the cylinder if the pipeline is not in use. To check this valve, the pipeline hoses should be disconnected and flow at the flowmeters demonstrated after the cylinder

is opened. This will also test the non-return valves in the pipeline hose inlet (see Chapter 5). Oxygen should not leak back through the disconnected pipeline hose (52).

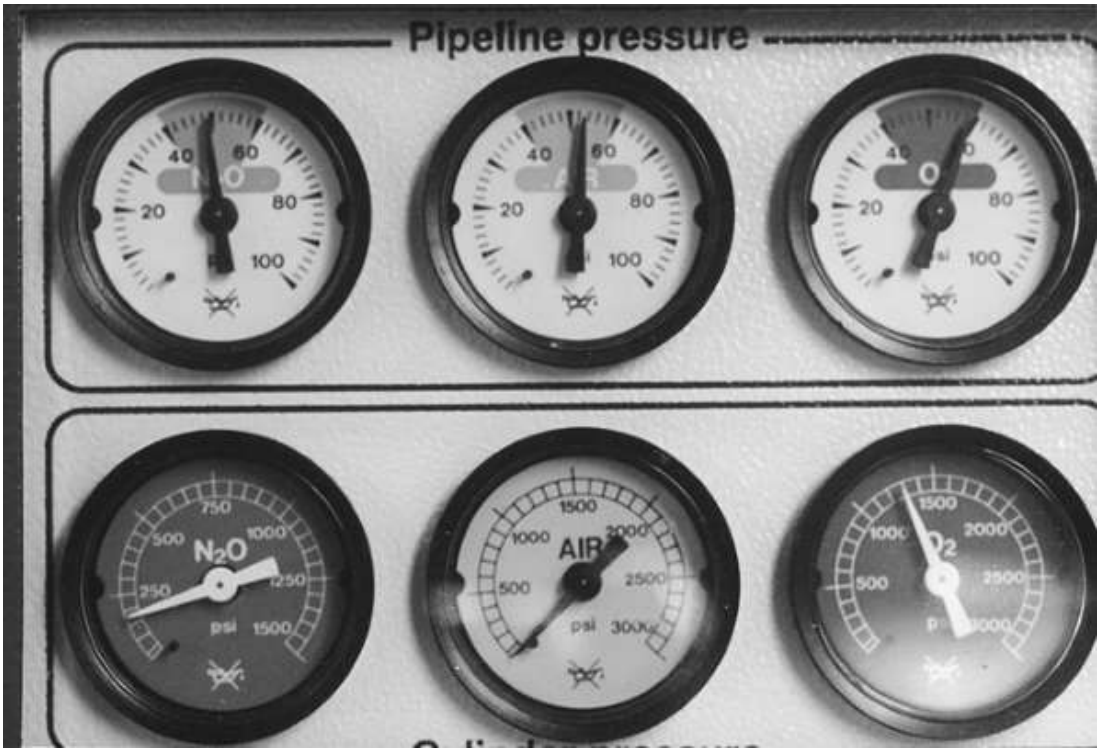

Figure 33.6 Top row: Pipeline pressure gauges. **Bottom row:** Cylinder pressure gauges.

The 1993 FDA recommendations do not mention checking cylinders containing gases other than oxygen, because these are not essential for life support. If it is planned to use one of these gases, it is reassuring to know that cylinder supplies are available on the machine. As discussed in Chapter 1, the contents of a nitrous oxide cylinder are not reflected by the pressure unless all of the liquid has evaporated and the cylinder is nearly empty. The pressure gauge will continue to read 745 psig until all the liquid has vaporized. If the pressure is less than 600 psig, the nitrous oxide cylinder is nearly empty and should probably be replaced.

After the pressures are checked, all cylinder valves should be closed, unless there is no pipeline supply for that gas. During use, there will be pressure fluctuations in the machine and the pipeline hoses, especially when a ventilator is in use. As the ventilator cycles, there will be a transient decrease in pressure in the machine. If the pressure falls below that supplied by the

regulator for the cylinder, gas can flow from the cylinder if the cylinder valve is open. This gas loss will at some point deplete the cylinder contents, and there will not be an emergency supply available.

When piped gases are not going to be used, there should be one full or nearly full cylinder of each gas to be used and the valve on one cylinder should be fully open after the pressure is checked.

Pipeline Pressure

Some institutions disconnect the pipeline hoses from the machine at night to allow the anesthesia machine to be moved for cleaning and reduce gas loss from leaks. If this is the case, the hoses need to be reconnected to the pipeline system. Fittings should hold firmly, no leaks should be audible, and the hoses should be arranged to prevent occlusion. The pipeline pressure indicators (Fig. 33.6) should read 345 to 380 kPa (50 to 55 psig).

As discussed in Chapter 5, a pipeline pressure gauge will register only pipeline pressure if it is positioned upstream of the check valve at the pipeline inlet, as required by the American Society for Testing and Materials (ASTM) workstation standard (53). If it is located downstream of the check valve, as it is on some older machines, the pressure registered will reflect the pressure in the machine, but not necessarily that in the pipeline (54).

Low-pressure System

The low pressure system is discussed in Chapter 5 and diagrammed in Figure 5.1.

Vaporizers

The low-pressure system check is begun by checking the liquid level in each vaporizer, adding more if needed. Filler caps and drain valves should be tight. Vaporizers should be checked to make certain that they are not tilted and cannot be lifted from their mountings.

Leaks

Leaks in the low-pressure part of the anesthesia machine can cause hypoxia or patient awareness (55,56). Profound hypercarbia can occur if a Mapleson system is in use (57).

Selecting an appropriate leak check can be confusing, because some anesthesia machines have a check valve either at the common gas outlet or just downstream of the vaporizers. This check valve prevents gas that is

under positive pressure in the breathing system from flowing back into the machine and through a leak.

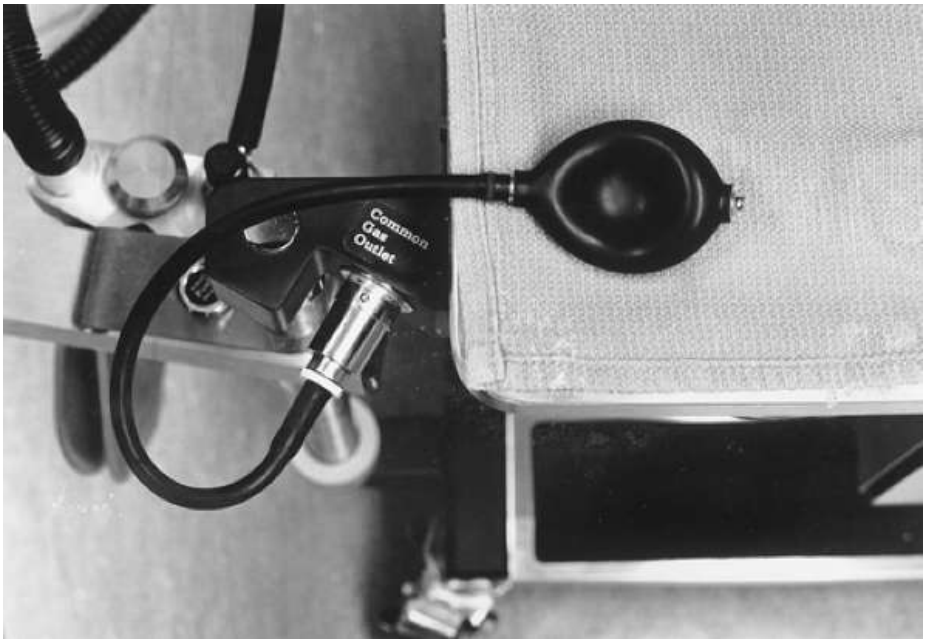

Figure 33.7 The suction bulb is attached to the common gas outlet and squeezed until it is collapsed. It should remain collapsed for at least 10 seconds. Following this, each vaporizer in turn should be turned ON and the maneuver repeated.

The minimum mandatory oxygen flow on most machines may decrease the ability to detect small leaks (58). The leak test should be performed without the basal flow. To eliminate this minimum mandatory flow, the machine needs to be turned OFF.

Irrespective of which test is used, the test should be repeated

with each vaporizer turned ON to its minimum setting. If this is not done, the machine will pass the test for leaks, but a leak associated with the vaporizer or its mounting will not be found (59).

Negative Pressure Test

The negative pressure test uses a suction bulb to create a negative pressure in the machine (55,60). The bulb is attached to a tubing with a 15-mm adaptor, which will fit the anesthesia machine common gas outlet on the other end (Fig. 33.7). This device is available commercially or can be constructed by taking a sphygmomanometer bulb, reversing the air inlet valve in the bulb, and connecting one end of a short tubing to the bulb and the other to a 15-mm tracheal tube adaptor. When reversed, the valve will pull air from the machine side of the bulb. Alternately, the device can be constructed from the bulb pump of a disposable intravenous blood administration set (61).

To perform the test, all flowmeters are turned OFF. If there is a minimum mandatory oxygen flow, the entire machine must be turned OFF. Squeezing the bulb until it is remains collapsed creates a negative pressure in the machine. If the bulb remains collapsed for 10 seconds, there is no significant leak present. If there is a leak, the bulb will inflate. This test should be repeated with each vaporizer turned ON. The suction bulb is then removed and the fresh gas hose reconnected.

This negative pressure leak test will work for all makes and models of machines, whether there is a check valve or not (55). For this reason, it is sometimes called the *universal leak test*. It differentiates between breathing system leaks and leaks in the machine. Studies comparing this with other leak tests found that it was the only one that identified all leaks and was the most sensitive at finding small leaks (55,56).

Unfortunately, it is not possible to use this test on some new anesthesia machines because the common gas outlet is not accessible to the user. An unintentional continuous gas flow will result in a false-positive test (56).

Positive Pressure Test

When performing a positive pressure leak test, care must be taken that the pressure does not increase beyond the prescribed

limits. There is little room for compression in the machine tubing, and no bag to buffer pressure increases. It is possible that the pressure could increase to a point where a flowmeter or other part of the machine could be damaged.

Pressure Gauge Test

A pressure gauge (the gauge from a standard sphygmomanometer will do) is attached to the common gas outlet (Fig. 33.8), and a flow control valve is slowly opened until the pressure on the gauge reaches 30 cm H_2O (22 mm Hg) (57,62). The flow is then lowered until that pressure is steady. The flow rate on the flowmeter is then equal to the leak rate in the machine at that pressure. It should be less than 50 mL/minute. This test cannot be performed if there is a minimum mandatory flow, because these flows are usually around 200 mL/minute.

Fresh Gas Line Occlusion Test

With this test, a flow of 50 mL/minute is set on the oxygen flowmeter and the fresh gas line kinked. The indicator in the flowmeter tube

should move downward. An advantage of this test is that it can be performed during a case (55). This test cannot be performed if there is a minimum mandatory flow, because these flows are usually around 200 mL/minute.

Figure 33.8 A pressure gauge from a blood pressure cuff is attached to the delivery hose from the machine. Sufficient flow is established on a flowmeter to maintain a pressure of 22 mm Hg on the pressure gauge. The flow that is required to maintain that pressure should be less than 50 mL/minute.

Combination Breathing System and Machine Leak Tests

The following tests can be used to check for leaks in the breathing system and parts of the machine downstream of the check valves.

Retrograde Fill Test

The APL valve is closed and the patient port occluded. The master control switch needs to be turned ON. The oxygen flush

or a high flow from the flowmeter is used to fill the reservoir bag. As the bag begins to distend, the pressure on the manometer in the breathing system is observed. As the pressure starts to rise, the flow on the flowmeter is adjusted so that a pressure of 30 cm H_2O is maintained in the breathing system. If this pressure is overshot, the APL valve should be opened briefly. The flow necessary to maintain a steady pressure should be no greater than 350 mL/minute. The pressure should be released by opening the APL valve rather than removing the occlusion from the patient port at the Y-piece.

The advantages of this test are that it can be performed quickly without accessory equipment and that it checks the breathing system as well as the low-pressure parts of the machine in those models that do not have a check valve (63). It also allows the continuous airway pressure alarm to be checked. Disadvantages are that it is relatively insensitive to small leaks, and it does not localize the source of the leak between the breathing system and the machine.

Squeeze Bulb Test

With the machine master switch and flow control valves turned OFF, the Y-piece is occluded and the APL valve closed. A suction bulb with a 22-mm connector is attached to the reservoir bag mount and squeezed repeatedly until the breathing system pressure gauge reads 50 cm H_2O. The gauge is observed. If a drop in pressure from 50 to 30 cm H_2O takes 30 seconds or longer, the leak rate is acceptable.

In-use Test

During use, a leak in the machine or breathing system can be quantified by lowering the fresh gas flow as low as possible (64). If the ventilator bellows or reservoir bag continues to fill, the leak rate is less than the fresh gas flow.

When a leak is suspected, a systematic search of the anesthesia machine and breathing system should be made, following the route of gas travel. A leak can sometimes be located by placing alcohol on the hands and moving the hands over components while gas flow is occurring. The leaking gas evaporates the alcohol and cools the skin.

When the machine leak test is complete, residual vapors should be flushed out of the machine by turning ON an oxygen flow at 1 L/minute for 1 minute with all vaporizers OFF (63). There should be no noticeable odor in the gas coming from the common gas outlet. Using the oxygen flush control will not flush vapors out of the machine, because its flow enters the fresh gas flow downstream from the vaporizers.

Turn the Machine's Master Switch and All Other Necessary Equipment ON

To continue the checkout, the machine master switch needs to be turned ON to enable the pneumatics and electronics. The machine should be allowed to complete its own diagnostic checks and any automated checking procedure. Any electrical equipment to be used during the anesthetic should be turned ON at this time with the exception of a diverting gas monitor, which should be turned ON after the breathing system is checked for leaks.

Flowmeter

Each flowmeter should be examined with the flow control valve closed to make certain the indicator is at the zero position (or at minimum flow if the machine is so equipped). Each flow control valve should be slowly opened and closed while observing the indicator. The float should move smoothly and respond to small flow

control valve adjustments. If the indicator is a rotameter or ball, it should rotate freely. An indicator that moves erratically or fails to return to zero may be displaying erroneous flow rates, and the machine should be taken out of service until the problem is corrected.

An attempt should be made to create a hypoxic mixture by adjusting the nitrous oxide flow up or the oxygen flow down while both nitrous oxide and oxygen are flowing. Turning the nitrous oxide flow up should cause the oxygen flow to increase. Similar results should occur if a high nitrous oxide flow is present and the oxygen flow is adjusted downward. Some anesthesia machines will not alter the oxygen flow but will limit the nitrous oxide flow. If the machine has a nitrous oxide : oxygen ratio alarm, it should be activated.

Adjustable Pressure-limiting Valve and Scavenging System

The APL valve and ventilator should be connected to the scavenging system interface. If an active disposal system is being used, the flow should be adjusted.

Adjustable Pressure-limiting Valve

The scavenging system and APL valve are checked by closing the APL valve, occluding the patient port, and filling the system by using the oxygen flush so that the breathing system pressure gauge reads 50 cm H_2O. The APL valve is then opened. There should be a gradual loss of pressure from the system. This establishes proper APL function and transfer tubing patency. If the scavenging system interface has a reservoir bag, it should inflate when the APL valve is opened and then deflate (65).

If the pressure is released by removing the occlusion at the patient port, the APL valve and scavenging system patency will not be checked. In addition, this could cause a cloud of absorbent dust to enter the breathing system (66,67).

Scavenging System

Closed System

Air Intake Valve (Negative Pressure Relief)

With minimal or no flow from the anesthesia machine, the APL valve should be fully opened and the patient port occluded. Scavenging suction should be turned ON. If there is a bag at the scavenging interface, it should collapse. The reservoir bag in the breathing system may also collapse. At this point, the breathing system pressure gauge should indicate a pressure of 0 to -2 cm H_2O.

Positive Pressure Relief

To test the positive pressure relief valve on the scavenging interface, the APL valve is fully opened and the breathing system patient port occluded. The oxygen flush is activated. The breathing system pressure indicator should read less than 10 cm

H_2O.

An alternate test can be used. The vacuum flow to the scavenging system is turned OFF and the APL valve fully opened. The reservoir bag and the scavenging system bags are fully inflated by using the oxygen flush. A flow of 2 L/minute is then set on the oxygen flowmeter. The pressure gauge in the breathing system should read not more than 3 cm H_2O.

Open System

Open scavenging systems do not have valves that need to be checked, as the system is open to atmosphere. The flow indicator on the scavenging interface should be checked to make certain that the flow is adequate.

Breathing System

Oxygen Monitor Calibration

Not all oxygen analyzers require a daily calibration check. The instruction manual should be consulted to determine what procedures are needed and how often they should be carried out.

If daily calibration is required, the sensor should be removed from the breathing system and moved well away from sources of gas that might change the ambient oxygen concentration. It should be calibrated to 21% and the low oxygen alarm checked by setting it above 21%. The sensor should then be placed securely in its mount in the breathing system and the breathing system flushed with oxygen. This should result in a reading of over 90%.

Initial Breathing System Status

The breathing system should be inspected to determine that no parts are damaged or missing and that all accessory equipment [e.g., humidifier, heat and moisture exchanger, filter, positive end-expiratory pressure (PEEP) valve] for the proposed anesthetic are in place. All connections should be made secure by ‘€push and twist.‘€ If a diverting gas monitor is to be used, the sampling line should be checked for kinks or occlusion and connected to the breathing system, but the monitor should not be

turned ON at this time. Transparent breathing tubes should be checked for foreign bodies (68). The bag-ventilator selector switch should be in the bag position. The pressure gauge should read zero. If the absorber is detachable, it should be checked to make sure that the attachment is secure.

The absorbent color should be noted. If there is any color change, the absorbent should be discarded and replaced with fresh absorbent. If there is a dual-chamber absorber, both chambers should be changed at the same time. If the machine is rarely used or if it has been sitting with gas flowing through it for an undetermined time, the absorbent should be changed even if there is no color change, unless an absorbent that does not cause

formation of carbon monoxide is being used. The effects of desiccated absorbent are discussed in Chapter 9. Accumulated absorbent dust and water should be removed from the absorber dust cup, taking care not to spill either.

Figure 33.9 Test for leaks in the breathing system. With all gas flows set to zero or minimum, the APL valve is closed and the patient port occluded. The reservoir bag is filled by using the oxygen flush until a pressure of 30 cm H_2O is shown on the gauge. With no additional gas flow, the

pressure should remain at this level for at least 10 seconds.

Leaks in the Circle Breathing System

If leaks in the circle system were checked for previously in combination with machine leaks, this test does not need to be performed.

To initiate the breathing system leak test, all gas flows should be at zero. The APL valve should be closed and the patient port occluded. The breathing system should be pressurized to 30 cm H_2O by using the oxygen flush (Fig. 33.9). If there is no leak, the pressure will remain near this level for at least 10 seconds. The APL valve is then opened. The pressure should decrease.

The leak can be quantified by adjusting the oxygen flowmeter to maintain a pressure of 30 cm H_2O in the breathing system (with the Y-piece occluded and the APL valve closed). The breathing system standard requires that this does not exceed 300 mL/minute (69).

Leak in a Mapleson Breathing System

A Mapleson breathing system should be connected to the fresh gas source with the APL valve closed. With the patient port occluded, the system should be pressurized using the oxygen flush. If there is no leak, the system will retain the pressure for at least 10 seconds. The pressure should be released by opening the APL valve.

The leak rate can be quantified by attaching a manometer to the patient port and determining the flow needed to sustain a certain pressure (70).

Bain System Inner Tube

The integrity of the Bain breathing system inner tube (Chapter 8) is essential to avoid excessive dead space. Profound rebreathing and hypercarbia can occur if the inner tube has a hole, is detached at the machine end, or does not extend to the patient end of the outer tubing. For this reason, it is essential that this is tested.

Inspection

The Bain system should first be inspected to determine if the center tube is properly connected to the absorber end of the tube. The inner tube must also be connected near the patient end. Any retraction or disconnection from either end should cause the system to be rejected.

Inner Tube Occlusion Test

NOTE: If the system has side holes or slots at the patient end of the inner tubing, this test *will not* work (75,76).

To perform this test, a 2 L/minute flow is set on one of the flowmeters (26,71,72,73,74). The plunger from a small syringe or a finger is inserted into the patient end of the outer tube, occluding the inner tube (Fig. 33.10). The flowmeter indicator should fall.

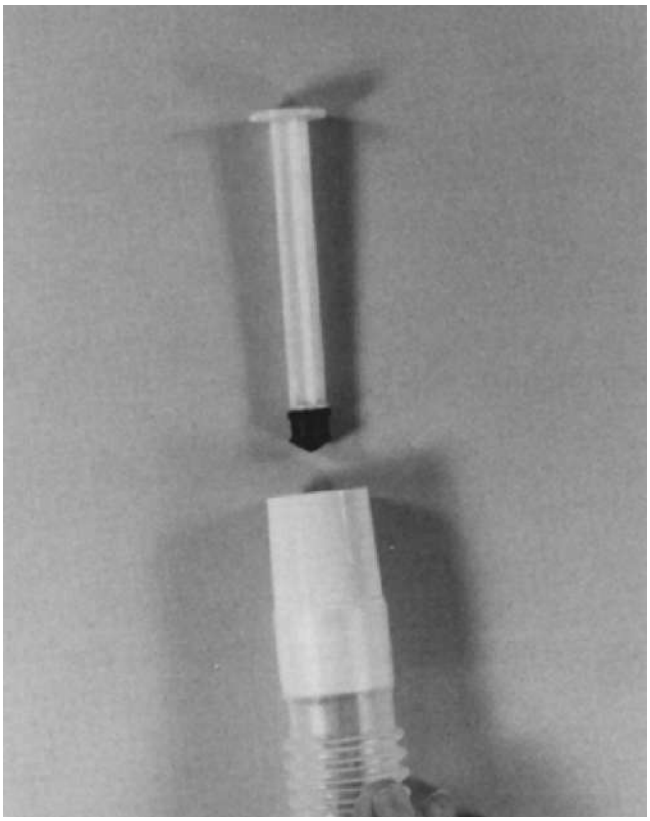

Figure 33.10 Bain system inner tube test. The plunger from a small syringe is inserted into the patient end of the system over the end of the inner fresh gas delivery tubing. The flowmeter indicator should drop.

A variation of this procedure is to attach a manometer to the end of the inner tube and determine the flow needed to cause a sustained pressure (70).

Oxygen Flush Test

To perform this test, the reservoir bag is filled (77). The patient port must be open to atmosphere. The oxygen flush valve on the machine is activated. The high gas flow through the inner tube will produce a Venturi effect, which lowers the pressure in the larger outer tube. If there are no problems with the inner tube, the bag should deflate. If the bag does not deflate or inflates, the inner tube should be checked. This test may fail to detect major faults that can be detected by the inner tube occlusion test (74,78,79,80).

Lack System Inner Tube

To test the integrity of the inner limb of the Lack system, a tracheal tube can be inserted into the inner tube at the patient end (81,82). Blowing down the tracheal tube with the APL valve closed will produce bag movement if there is leakage between the inner and outer limbs.

An alternative method is to occlude both the inner and outer limbs with the APL valve fully open (82). There should be no gas escape when applying pressure to the reservoir bag. If the inner limb is defective, gas will flow through the APL valve, and the bag will collapse.

A third test is to insert a tracheal tube into the inner tube at the patient end (83). The cuff is inflated to obstruct the opening between the outer and inner tubes. With the APL valve fully open, the reservoir bag should be filled using the oxygen flush. Squeezing the bag should cause the flowmeter indicator to drop, but no gas should be released through the APL valve.

Still another test uses a pressure manometer and inflating bulb

(62). A 7-mm nasal airway that is connected to the bulb and manometer is inserted into the inner tube with the APL valve closed. The inflating bulb is used to pressurize the inner tube to 30 cm H_2O. There should be minimal decline in pressure over 30 seconds. The APL valve is then opened. The pressure should fall immediately.

Coaxial Circle System

Hypercarbia related to a faulty coaxial circle system has been reported (84). This can be detected by having the anesthesia provider or patient breathe through the system with the APL valve open and observing the capnograph. If there is a connection between the two limbs, the capnograph baseline will be elevated.

Smell Test

Some authors recommend that the anesthesia provider smell the gas from the patient port with a 3 L/minute flow of oxygen set on the flowmeters. No odor indicates that a vaporizer is not leaking or left ON (85).

Manual and Automatic Ventilation Systems

A second reservoir bag should be placed on the patient port (Fig. 33.11). The oxygen flowmeter should be set at the minimum flow or 300 cc/minute if there is no minimum flow. The bag-ventilator selector switch should be in the bag position. As the reservoir bag on the bag mount in the breathing system is squeezed, the bag on the patient port should inflate (Fig. 33.11). The bag on the patient port should then be squeezed. The reservoir bag on the bag mount should inflate. System resistance and compliance should be evaluated during this test. This is useful to detect inadvertent PEEP or an obstruction in the system (86,87).

Ventilator parameters appropriate for the patient should be set and the bag-ventilator selector switch placed in the ventilator mode. The oxygen flowmeter should be set at the minimum flow or 300 cc/min if there is no minimun flow. The bellows and reservoir bag on the patient port should be filled by using the oxygen flush and the ventilator turned ON. The bag on the patient port should inflate and deflate (Fig. 33.12). The

appropriate tidal volume should be delivered and the bellows fill completely during expiration. If use of the PEEP valve is anticipated, it should be adjusted to different values and the breathing system pressure gauge observed to verify correct performance. The bag should be removed from the patient port and the ventilator allowed to continue cycling (88). The low airway pressure and tidal or minute volume alarms should annunciate after an appropriate delay.

Figure 33.11 Test of manual ventilation system. A reservoir bag is placed on the patient port. The bag-ventilator switch is turned to the bag position. As the reservoir bag in the breathing system is squeezed, the bag on the port should inflate. Squeezing the bag on the patient port should cause the reservoir bag in the breathing system to inflate.

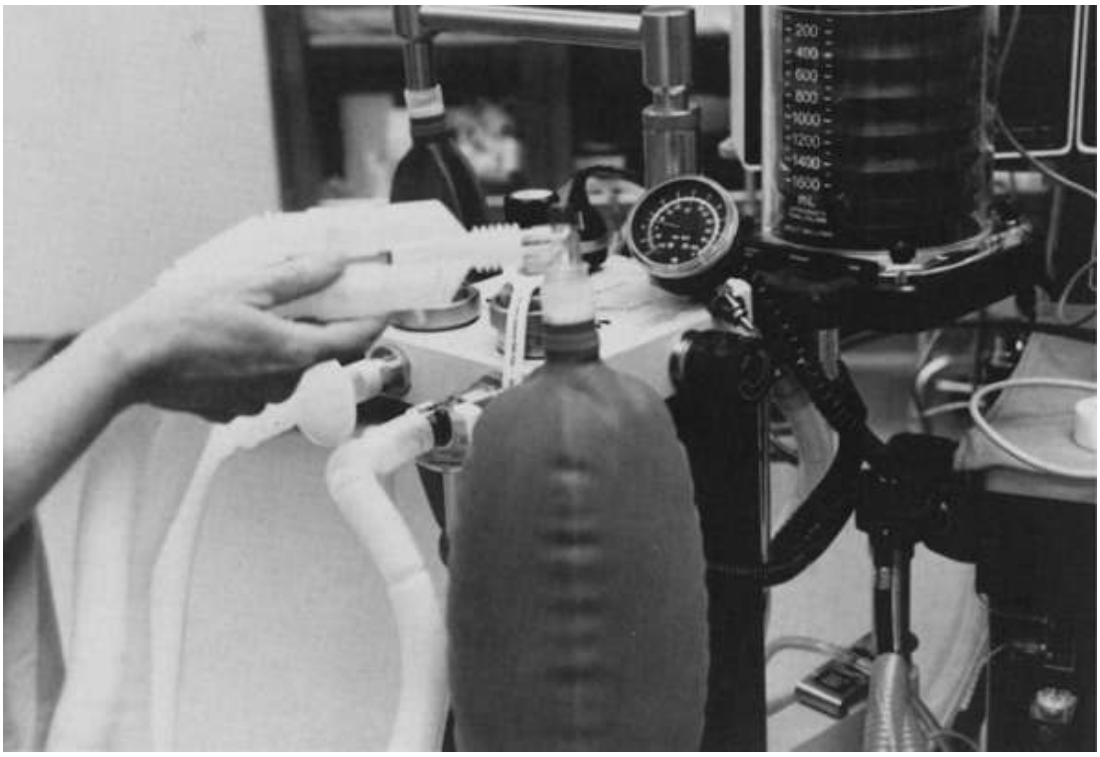

Figure 33.12 Test of ventilator. A reservoir bag is placed on the patient port. The oxygen flowmeter is set for a flow of 300 mL/minute. Ventilator parameters that are appropriate for the next patient are set. The bag-ventilator selector switch should be in the ventilator position. The bellows and reservoir bag are filled, and the ventilator is turned on. The bellows should move freely and fill completely as the ventilator cycles. The unidirectional valves should be observed to make certain that the discs open properly.

With the ventilator still cycling, the patient port should be occluded and the bellows filled using the oxygen flush. The breathing system pressure should rise no higher than that set on the high pressure safety relief pressure device. The high pressure alarm should sound.

To check for a leak in an upright bellows, the bellows should be occluded, the patient port occluded, and the flowmeters turned OFF. Alternately, the bag-ventilator selector switch can be set to bag. The bellows should stay inflated. If it falls, there is a leak.

To check for a leak in a ventilator with a hanging bellows (Fig.

33.13), all flowmeters should be turned OFF or to the minimum flow and the ventilator turned ON. When the bellows is fully contracted, the patient port is occluded (or the bag-ventilator selector switch is put in the bag position) and the ventilator switched OFF. The bellows should remain contracted at the top of the housing. If it expands downward, a leak is present. Another way of performing this test is to occlude the patient port (or put the bag-ventilator selector switch in the bag position) with the ventilator turned OFF and lower the bellows stop. The bellows should not expand downward.

Figure 33.13 Test for leak in ventilator with hanging bellows. The flowmeters should be turned off or at minimum flow. The APL valve is closed and the ventilator turned on. When the bellows is fully contracted against the head of the bellows assembly,

the patient port is occluded (or the bag-ventilator selector switch is put in the bag position), and the ventilator is turned off. The bellows should remain at the top of the housing for at least 10 seconds.

Unidirectional Valve Tests

The FDA checklist does not specify how the unidirectional valves are to be checked (89). Many practitioners feel that watching the inhalation valve disc rise during inhalation and the exhalation valve rise during exhalation while the ventilator is cycling is an adequate check. This verifies that they open but not that they close completely.

During use, incompetent unidirectional valves can be detected by an inspired carbon dioxide greater than zero when using a capnograph (Chapter 22). Some respirometers can detect reversed flow.

Unidirectional valves may be checked by several methods.

Breathing Method

With the APL valve closed, the inspiratory limb of the breathing system is detached from the absorber and occluded. Wearing a mask, the tester tries to breath through the Y-piece (Fig. 33.14A). It should be possible to exhale freely but not inhale. Next, the exhalation tube is detached and occluded. The tester should be able to inhale but not exhale (Fig. 33.14B).

Valve Tester

This method utilizes a device consisting of a bulb with a 22-mm female fitting that can attach to the inspiratory and exhalation ports (90,91). To test the inspiratory valve, the compressed bulb is attached to the inspiratory port. It should immediately reinflate. When the bulb is compressed, it should meet firm resistance (Fig. 33.15A).

To check the expiratory valve, the tester is attached with the bulb inflated. It should be possible to squeeze the bulb, and it should remain deflated (Fig. 33.15B).

Pressure Decline Method

To check the valves by this method, an extra reservoir is placed on the inspiratory port (92,93,94). The other bag remains on the bag mount. The fresh gas flow is set to a minimum and the APL valve is closed. The circle system is pressurized to 30 cm H_2O by using the oxygen flush. If the bag on the bag mount remains inflated, the expiratory valve is competent. Next, the APL valve is opened. If the reservoir bag on the inspiratory port does not deflate, the inspiratory valve is competent.

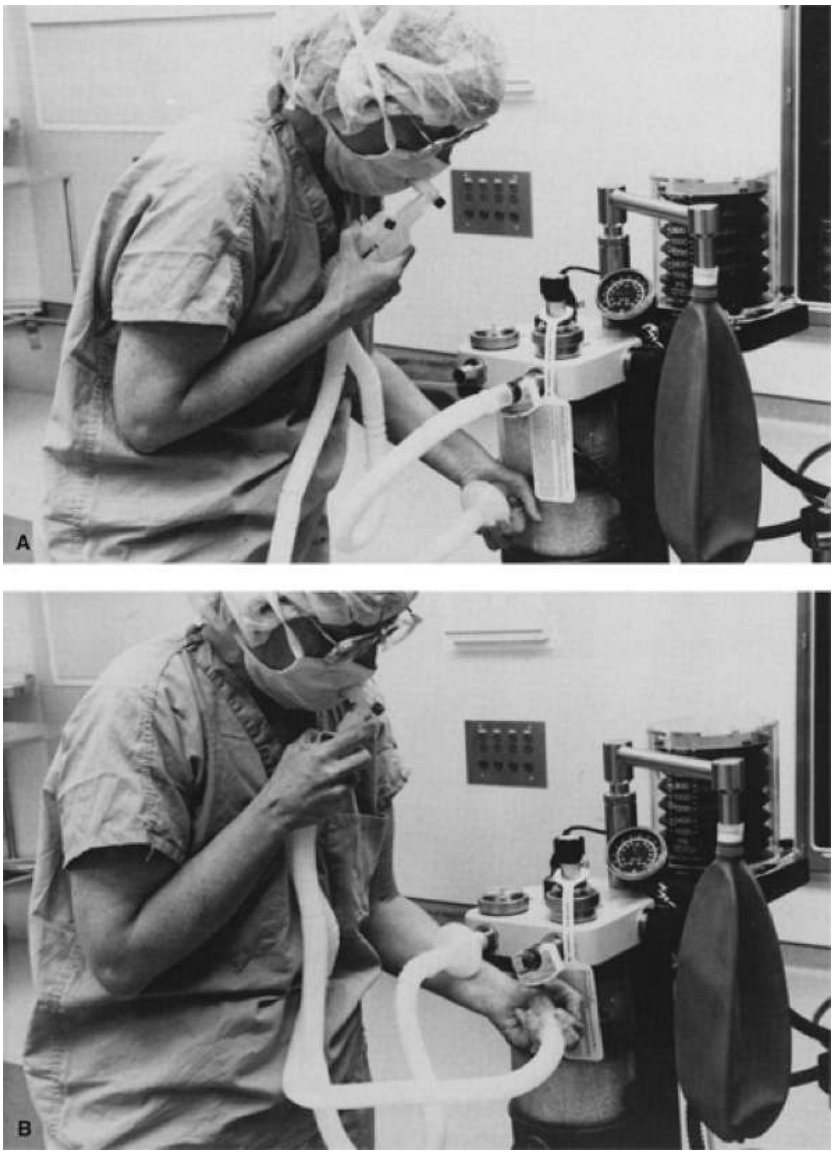

Figure 33.14 Checks for incompetent unidirectional valves. **A:** The inspiratory limb is detached and occluded. The tester tries to breathe through the Y-piece. It should be possible to exhale freely but not inhale. **B:** The exhalation tubing is detached and occluded. The tester should be able to inhale from the Y-piece but not exhale.

Final Configuration and Obstruction Check

At this point, breathing system accessory equipment (e.g., PEEP valve, heated humidifier) should be in place and turned ON. Obstructions in the breathing system can be detected by having the patient breathe 100% oxygen through a mask, provided a tight mask fit is achieved (95,96). This can also be done by the anesthesia provider wearing a mask (Fig. 33.16) (97). The reservoir bag should inflate and deflate, and the breathing system pressure indicator should show no PEEP. Negative pressure will reveal an obstruction in the inspiratory limb; positive pressure will reveal an obstruction in the expiratory limb (98). While this is being done, the capnogram should be checked to make certain that a normal waveform appears.

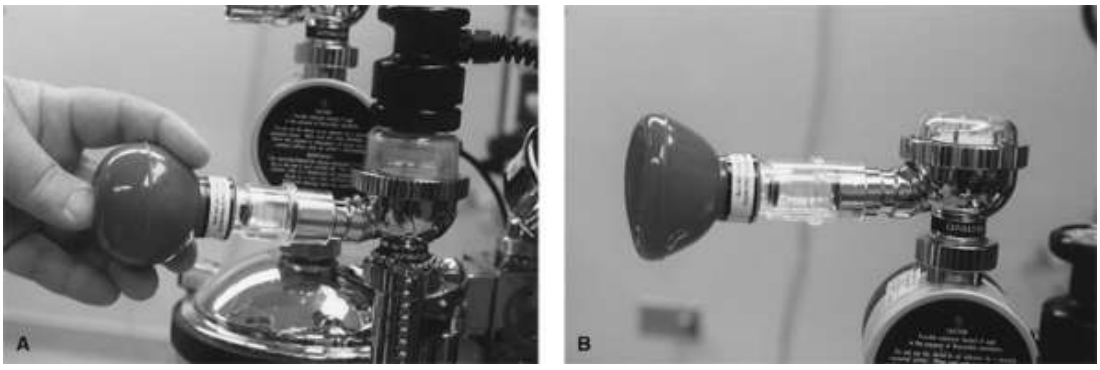

Figure 33.15 Checking the inspiratory unidirectional valve. The bulb should be compressed **(A)** and then attached to the inspiratory port. It should inflate. Then, it should not be possible to compress the bulb. **B:** Testing the expiratory unidirectional valve. The bulb should compress easily and remain compressed.

Monitors and Controls

All monitors should be turned ON (36). Alarms should be tested by simulating alarm conditions, and appropriate limits should be set.

The final status of all controls should be checked before the machine is put in use. This includes having all flow control valves closed, all flowmeters indicating zero flow, all vaporizers turned OFF, the bag-ventilator switch set to BAG, the PEEP valve OFF, and the APL valve open. The breathing system should be ready to use with all components connected by using a push and twist motion. The scavenging system vacuum should be ON.

Subsequent Checks on the Same Machine on the Same Day

If a thorough check is performed before the first case of the day, a less complete procedure can be used before subsequent cases. Those steps are indicated in

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Table 33.1 by an asterisk (*). The tests so marked may not be repeated or may be abbreviated if the machine is used by the same anesthesia provider for successive cases on the same day.

Figure 33.16 Breathing system patency can be confirmed by inhaling and exhaling through the patient port.

It is important for the breathing system to be checked before the next case begins (47). One of the most common alterations made between cases is changing of the carbon dioxide absorbent. The absorber may not be closed properly. This may cause a large leak and inability to ventilate.

Procedure at the End of the Case

At the conclusion of a case, flowmeters, vaporizers, and suction should be turned OFF. Monitors that would need recalibration if turned OFF should be left ON or put in a standby mode. The absorbent should be checked for signs of exhaustion and changed if indicated (Chapter 9).

Other Machine and Breathing System Checks

While the FDA checkout recommendations are adequate for daily use, other parts may need to be checked either daily or as the need arises. This is especially true after the machine has been altered or serviced.

Oxygen Pressure Failure Alarm

Most anesthesia machines are equipped with an oxygen pressure failure alarm, which is activated if there is no or low oxygen pressure in the machine. To test this alarm, the oxygen pipeline hose is disconnected and all oxygen cylinders closed. Any pressure remaining in the machine should be bled off by using the oxygen flush. The alarm should sound. This step was not included in the FDA checkout recommendations, because isolated failure of this component will not injure a patient (36). The Association of Anaesthetists of Great Britain and Ireland recommend that this alarm is tested on a weekly basis (39).

Leaks at the Yoke

If a cylinder is not properly tightened in a yoke, there will be a gas leak when the cylinder is turned ON. A large leak will be quite apparent by the sound. A small leak will not be heard but could cause significant gas loss. To check for a leak at the yoke, after the cylinder pressures have been checked and the valves closed, the cylinder pressure indicators should be observed for 2 to 5 minutes, with no flow on the flowmeters. A drop of more than 50 psig indicates significant leakage. If there is a minimum mandatory oxygen flow, the machine must be turned OFF. The minimum flow will mask any leaks in the high-pressure system.

Oxygen Failure Safety Valve

The oxygen failure safety valve was included as a routine test in the first edition of the FDA checkout but was not made part of the later version because it rarely fails, and there are many other methods of detecting oxygen pressure failure (36). This test can be performed by using either the pipelines or cylinders as the gas source. A cylinder of each gas on the machine is turned ON while the pipeline hoses are disconnected. Flows of 2 L/minute are established on the flowmeters for each gas. The oxygen cylinder is then turned OFF. As the oxygen pressure falls, the flows of all other gases except air in some machines, as indicated by their flowmeters, should decrease in proportion to the decrease in oxygen flow and eventually shut OFF. Restoring the oxygen pressure should cause the indicators to return to their previous positions.

To perform the test by using pipeline gases, all cylinder valves should be closed and the flow control valves opened until the cylinder pressure indicators register zero. The pipeline hoses are connected and flows established on all flowmeters. The oxygen hose is then disconnected. The indicators of the anesthetic gas flowmeters should fall just before the oxygen indicator.

Spare Components

Extra components of the breathing system should be immediately available (99). These include an additional disposable system or individual components of reusable systems (Y-piece, tubings, bag).

Electrical System

Tests of the electrical system vary with the different makes and models of machines. Most have a means to test the reserve battery. In addition, there is usually an indication that the machine is working on the battery power. To check this, the machine is disconnected from the mains power. The battery power indicator should be illuminated. Many electronic machines will have an indicator of the battery charge (see Chapter 5).

Vaporizer Exclusion System

Most anesthesia machines have a mechanism to allow only one vaporizer to be turned ON at a time (Chapter 6). To test the vaporizer exclusion system, one vaporizer should be turned ON and an attempt made to turn each of the other vaporizers ON, one at a time.

Other Equipment

Tracheal Tubes

Appropriate tracheal tubes of the sizes useful for the patient should be ready for use. Lumen patency should be checked. With clear tubes, simple observation will suffice. With other tubes, it is necessary to look in both ends or insert a stylet. The cuff should be held inflated for at least 1 minute to verify that there are no leaks. The cuff should inflate evenly and not stick to the tube wall or decrease the size of the lumen. One larger and

one smaller than the tracheal tube that is intended for use should be readily available.

Rigid Laryngoscopes

Laryngoscope malfunction is a frequent problem. At least two handles should be present, each fitted with the type of blade that the user anticipates will be best for the patient. The lights should be checked for adequate intensity. Blades of other sizes and shapes should be immediately available and checked for proper function.

Accessory Intubation Equipment

A stylet and bougie should be immediately available. If a rapid sequence intubation is planned, the stylet should be fitted to the tracheal tube. An intubating forceps should be immediately available. If a difficult intubation is anticipated, specialized equipment for difficult intubation described in Chapters 18 and 21 should be in the operating room and checked for completeness, defects, and proper assembly.

Masks and Airways

An assortment of masks and airways in a variety of sizes should be readily available.

Other Equipment

Special equipment that is required for particular cases, such as extension pipeline hoses, extension breathing hoses, patient warming equipment, and infusion devices, should be present and checked before use.

Procedures at the End of the Day

Following the last case, the pipeline hoses should be disconnected at the wall or ceiling (not at the back of the machine) and coiled over the machine. If the hoses are disconnected at the back of the machine, they will continue to be pressurized, and gas may be lost into the room through leaks. If a flow control valve is open and the pipeline supply is connected, dry gas can desiccate the absorbent, promoting the formation of carbon monoxide (Chapter 9). Cylinder valves should be closed. Each flow control valve should be opened until

the cylinder and pipeline pressure gauges read zero, then closed. If the flow control valve is left open, restoration of the gas supply may forcibly raise the indicator to the top of the tube, causing damage.

Vaporizers should be filled at the conclusion of the day after most operating room personnel have vacated the room. This will decrease personnel exposure to anesthetic agents.

Checking New or Modified Equipment

Each new anesthesia machine, ventilator, or other complex piece of equipment should be checked for proper functioning before being put into use. This is best performed by a manufacturer's representative, who may give in-service instructions. A document certifying that the equipment has been checked for proper assembly and function should be obtained and kept.

A manual that contains assembly and installation instructions, maintenance requirements, checking procedures, and instructions for use is supplied with each piece of equipment. This must be read carefully and reviewed periodically. A copy should be kept in the central equipment files and with the equipment itself.

Preventive Maintenance

Many items in an anesthesia machine and ventilator deteriorate with time and use. Preventive maintenance is designed to anticipate predictable failures and replace weakened components before they fail. In some cases, an improved part has become available and can be substituted. The recommended frequency of preventive maintenance (usually every 4 to 6 months) is determined by the manufacturer and will be stated in the operator's instruction manual.

Proper preventive maintenance has been shown to be effective in preventing equipment failure (100). One study determined that an adequately maintained anesthesia machine that was 10 years old had no more failures than new machines. Lack of a preventive maintenance program may lead to an unacceptably high rate of breakdowns, premature replacement of major equipment, and unnecessary risks. There are a number of ways that equipment can be serviced.

Equipment Manufacturer Service Contract

With a service contract, the manufacturer's service representative comes to the health care facility. Different levels of service are available. The cost will depend on the number of parts covered, the frequency of the visits, and the necessary response time.

Independent Service Company

Independent companies that are not associated with a particular manufacturer may perform service on certain equipment on a contractual basis. It may be difficult for the anesthesia provider to determine the qualifications of an independent service provider. Some manufacturers certify independent providers to service their equipment. To become certified, they must satisfactorily complete the same courses as the company's own service technicians. It may not be possible for an independent company to procure manufacturer-approved parts unless the service technician has been certified by the manufacturer. Alternately, the facility may be able to purchase parts from the manufacturer.

Laws enacted in at least one state (New Jersey) require that the credentials of each servicing person are approved by the machine manufacturer or determined by the physician director of the anesthesia department to be equivalent to the credentials of the manufacturer's service person (101).

In-house Biomedical Services

In-house biomedical services may be a satisfactory option for much equipment, especially in institutions where there are a large number of similar machines. Biomedical technicians can attend courses and become certified to service specific equipment. Often, a combination of an outside service agency and in-house biomedical services is used. The in-house biomedical technicians do intermediate checks and respond to immediate problems between services from the outside service agency (102).

Advantages of in-house biomedical maintenance include minimal response time and the ability to observe problems while the

equipment is in use. The service intensity from outside sources and down time for equipment can be reduced. The biomedical technicians can assist with clinical education, provide liaison between users and manufacturers, help with equipment selection, and keep abreast of modifications and service bulletins issued by manufacturers.

The question of liability exposure must be addressed when considering in-house service (103). If a problem occurs as a result of the actions of a biomedical technician, the facility will likely have liability.

Record Keeping

Record keeping on equipment has frequently been neglected in the past. Often, it is assumed that the service representative who does periodic preventive maintenance will take care of this task. Experience does not support this assumption. Record keeping is important for several reasons.

1. *It provides proof that an effort has been made to keep the equipment in proper working order*. This could have medicolegal or Joint Commission for Accreditation of Healthcare Organizations (JCAHO) significance.

   The state of New Jersey requires that records be maintained of all service and maintenance performed on all anesthesia machines, ventilators, and vaporizers. The record must include machine identification, servicing agent, work performed, and date of the work. The maintenance must conform to that required by the machine manufacturer. The servicing agent's credentials must be determined to be equivalent to the credentials of the manufacturer's service agents. New York has similar requirements (101).

   JCAHO requires that an equipment management program designed to assess and control the clinical physical risks of equipment for treatment, care, and patient monitoring be in place. Written criteria must include the characteristics of equipment function, maintenance, and incident history (101).

2. *It provides a means of communication with the service representative*. Representatives frequently come in the late

afternoon or evening, after anesthesia personnel have left. If there is no written record of problems that have occurred with the equipment, the service representative may not perform the indicated repair(s).

3. *It provides a complete, up-to-date record for each piece of equipment*. If one piece of equipment malfunctions more frequently than others, consideration should be given to replacing it.

4. *It provides a written record that maintenance by a service representative was performed and shows what was done*. Service representatives may present only a bill for service and parts and no record of what was actually done to which machine.

5. *It provides a check on the service rendered by the representative*. After equipment is serviced, it should perform well. If a machine develops a problem soon after servicing or if there is an increased frequency of repairs that can be traced to a change in service representatives, one may wish to question that representative's abilities.

6. *With pieces of equipment such as vaporizers that need to be sent to the manufacturer periodically for servicing or oxygen analyzers that need to have certain*

components replaced at intervals, records serve to remind the user when the equipment needs to be serviced or a component replaced. After a vaporizer is serviced, it may be held in reserve before being put into use. This would extend the time before servicing would be due. This can be noted on the form by recording the time when a vaporizer is received from the manufacturer and when it is actually put into service on a machine.

7. *Recording equipment problems may be useful for improving quality by analyzing causative factors and suggesting preventative strategies* (104).

A record should be kept for each piece of complex equipment such as an anesthesia machine, ventilator, vaporizer, or monitor. This should include identification information; date of purchase; instructions for servicing; and the name, address, and telephone

number of the service representative. If a problem with the equipment arises, the date, problem, and corrective action should be recorded. When routine servicing is performed, this should be noted, along with any problems or parts replaced. Each entry should be signed by the person making the entry. Laws recently enacted in at least one state stipulate that records must be kept for each machine, including the name of the service person, work performed, and date the work was performed. The amount of time needed to retain these records varies with the health care facility's policies. Certainly, the records need to be kept beyond the statute of limitations for possible litigation in the state where the equipment is located (105).

Accident Investigation

Any time a patient has an unexplained problem, equipment malfunction or misuse should be suspected and the apparatus not used again until this has been disproved (106,107,108,109,110).

When there has been an injury to a patient, the health care facility safety officer (or risk manager) should be contacted at once to supervise investigation of the incident. An established protocol should be followed so that all important areas are covered systematically. All individuals involved in the incident should document their observations soon after the event, while details are still fresh in their minds. This should be a simple statement of facts, without judgments about causality or responsibility.

The following questions need to be asked:

1. What was the date and time of the problem?
2. In what area did the problem occur?
3. What monitors were being used?
4. What were the set alarm limits?
5. What was the first indication that there was a problem?
6. At what time did this occur?
7. Who first noted the problem?

8. What changes attracted attention? Were any alarms activated?
9. What signs or symptoms did the patient exhibit?
10. Had there been any recent modifications to the electrical system or gas pipelines in that area?
11. Was anything altered shortly before the incident?
12. Was this the first case performed in that area that day?
13. Were there any problems during previous cases performed in that area on that day or the previous day?
14. Were there any unusual occurrences in other areas on that day or the previous day?
15. Had any equipment been moved into that area recently? Were there any problems noted in the room where it was previously used?
16. What preuse checks were made of the anesthesia equipment?
17. Who last filled the vaporizers on the anesthesia machine?
18. If a vaporizer was recently attached to the machine, were precautions taken to prevent liquid from being spilled into the outflow tract?
19. After the initial indication of a problem, what was the sequence of events that occurred?

An important step involves construction of a time line, on which all events are listed in chronological order (81). This will help to sort out events and may lead to identification of missing data.

Numerous photographs should be taken of the area from various angles, with all equipment situated where it was at the time of the incident. Each piece of equipment should be photographed separately.

After pictures have been taken, all supplies and equipment associated with the case should be saved and sequestered in a secure location and labeled ĺ€DO NOT DISTURB.ĺ€ Settings should not be changed. Relevant identifying information such as the manufacturer and lot and/or serial numbers should be recorded.

If after all this has been accomplished it appears possible that the equipment may be implicated in causing the problem, a thorough inspection of the equipment by an uninvolved third party in the presence of the primary anesthesia personnel, insurance carrier, health care facility safety officer, patient representative, or equipment manufacturers should be conducted. The investigation should consist of an in-depth examination of the equipment similar to the checking procedures described earlier in this chapter. Vaporizers should be calibrated and checked to determine if vapor is delivered in the OFF position. An analysis should be made of the

vaporizers' contents, if necessary. Following the investigation, a report should be made that details all facts, analyses, and conclusions.

If a problem with the equipment is found, an attempt should be made to reconstruct the accident if this can be done without danger to anyone, and the equipment should again be locked up until any litigation is settled. If the investigation reveals no problems, the equipment can be returned to service with the consent of all parties.

The Safe Medical Devices Act of 1990 requires medical device user facilities to report incidents that reasonably suggest there is a probability that a medical device has caused or contributed to the death, serious injury, or serious illness of a patient (87). The report is due as soon as possible but no later than 10 working days after the user facility becomes aware of the incident.

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Questions

For the following questions, answer

A. if A, B, and C are correct

B. if A and C are correct

C. if B and D are correct

D. if D is correct

E. if A, B, C, and D are correct.

1. What actions are required by the Safe Medical Devices Act?

A. Problems which must be reported include death of a patient

B. Reporting is done by the clinician who experienced the problem

C. Serious injury resulting from equipment must be reported

D. Incidents must be reported within 20 working days

View Answer

2. If there is a loss of pipeline oxygen, which steps should be taken to conserve oxygen from the cylinder?

A. Discontinue using nitrous oxide

B. Use air and intravenous agents

C. Discontinue using a piston ventilator

D. Use a low oxygen flow

View Answer

3. Which are important points to remember when checking the gas cylinders?

A. The pressure in the oxygen cylinder should be at least 500 psig

B. The cylinder valve should remain open to supply gas if the pipeline fails

C. The valve is turned counterclockwise to open the cylinder

D. The pressure in the nitrous oxide cylinder reflects

contents in the cylinder

View Answer

4. How can the low-pressure system in all anesthesia machines be checked for leaks?

A. Positive pressure from the breathing system test

B. Elapsed time pressure test

C. Fresh gas line occlusion test

D. A negative pressure test

View Answer

5. What actions should be taken if a piece of equipment is suspected to have caused harm to a patient?

A. Document the circumstances surrounding the time the problem first occurred

B. Determine if similar problems occurred in other operating rooms at the same time

C. Isolate the equipment until the problem can be investigated

D. Have the company service representative service the equipment

View Answer

6. Concerning calibration of the oxygen analyzer

A. It should read 21% when the sensor is exposed to room air

B. The sensor should first be removed from the breathing system

C. Repeated oxygen flushing with the sensor in the breathing system should cause the analyzer to read over 90%

D. All oxygen analyzers need to be calibrated daily

View Answer

7. Concerning testing the inner tube on the Bain System.

A. The inner tube can be occluded with a plunger

B. If there are holes in the inner tube at the patient end, the inner tube occlusion test will not work

C. The bag should be open to atmosphere when the oxygen flush is used

D. using the oxygen flush should cause the bag to inflate if the tubing is intact

View Answer

8. Leaks in the ventilator bellows and transfer tubing can be detected by which of the following tests?

A. Isolating these parts with the bag-ventilator selector switch

B. Verifying that a hanging bellows remains fully contracted after the bag-ventilator switch is put in the bag position.

C. Using a minimum flow from the oxygen flowmeter and observing the bellows return to the fully inflated position

D. Observing the excursion of the bellows during inspiration

View Answer

9. How should the unidirectional valves be checked?

A. Observing the motion of the leaflet as the ventilator cycles

B. Occluding the inspiratory tubing and not being able to inhale through the expiratory tube

C. Removing the valve leaflet to inspect for damage to the leaflet or its seat

D. Occluding the expiratory tubing and not being able to exhale through the inspiratory tube

View Answer

ter 34

ning and Sterilization

nesia practitioners should be concerned with the
s of their equipment, both to prevent spread of
between patients and to ensure that they themselves do
act an infection. Nosocomial infections continue to be a
t drain on human and economic resources, producing
and higher health care costs. Infection control has
n important focus of the Joint Commission on
tion of Healthcare Organizations (JCAHO).

tions (1,2,3)

microbial: A chemical or material capable of destroying
nhibiting the growth of microorganisms.

septic: A chemical germicide that has antimicrobial
vity and that can be safely applied to living tissue.
septics are regulated as drugs.

psis: A scheme or process that prevents contact with
oorganisms.

teria: Microscopic unicellular organisms.

tericide: A chemical agent or compound that kills
teria.

teriostat: An agent that will prevent bacterial growth but
s not necessarily kill the bacteria. Bacteriostatic action
eversible; when the agent is removed, the bacteria will
me normal growth.

burden (Bioload, Microbial Load): The number and types
able organisms contaminating an object. The level of
urden is related to the anatomic site where the device
used.

ogical Indicator: A sterilization-process monitoring
ce consisting of a standardized, viable population of
oorganisms (usually bacterial spores) that are known to
esistant to the mode of sterilization being monitored.
sequent growth or failure of the microorganisms to grow
er suitable conditions indicates whether or not
ditions were adequate to achieve sterility.

ing Value: Concentration of an airborne contaminant
ve which a person should not be exposed even
nentarily.

*mical Indicator (chemical monitor, sterilizer control,
mical control device, sterilization-process monitoring
ce*): A sterilization-process monitoring device designed
espond with a characteristic and visible chemical or
sical change to one or more parameters of a
ilization process.

mical Integrator: Chemical indicator that reacts to a

ety of sterilization parameters.

mosterilizer (chemical sterilant): Chemical used for the ose of destroying all forms of microbiological life, uding bacterial spores. The same chemical used for ter exposure periods and/or at a lower concentration be used for disinfection.

ning: Removal of foreign material from an item.

tamination: State of actually or potentially having been ontact with microorganisms.

cal Item: Item that penetrates the skin or mucous nbranes or is in contact with normally sterile areas of body.

ontamination: A process that renders contaminated imate items safe for handling by personnel who are not ring protective attire (i.e., reasonably free of the ability of transmitting infection) (2,3,4). ontamination can range from simple cleaning to ilization.

nfectant: Chemical germicide formulated to be used on imate objects.

nfection: Process capable of destroying most oorganisms but, as ordinarily used, not bacterial es. A disinfectant is usually a chemical agent, but e processes (such as pasteurization) are disinfecting. Centers for Disease Control and Prevention (CDC) has oted a classification that includes three levels of nfection.

-level Disinfection: A procedure that kills all organisms the exception of bacterial spores and certain species, as the Creutzfeldt-Jakob prion. Most high-level nfectants can produce sterilization with sufficient act time.

rmediate-level Disinfection: A procedure that kills etative bacteria, including *Mycobacterium tuberculosis*, t fungi, and viruses but not bacterial spores (5).

-level Disinfection: A procedure that kills most etative bacteria (but not *M. tuberculosis*), some fungi, viruses but no spores (5).

posable: Intended for use on one patient during a single cedure.

gicide: An agent or process that kills fungi.

micide: An agent that destroys microorganisms.

hanical Monitor (*physical monitor, physical indicator*): ilizer component that gauges and records time, perature, humidity, or pressure during a sterilization e.

critical Item: An item that does not ordinarily touch the ent or only touches intact skin but not mucous nbranes (5).

ocomial: Pertaining to a health care facility. A ocomial infection is one acquired in a health care ity.

missible Exposure Limit (PEL): The time-weighted rage maximum concentration of an air contaminant to ch a worker can be exposed according to Occupational ety and Health Administration (OSHA) standards.

ns: Proteinaceous infectious agents with no associated eic acids.

cessing: All of the steps performed to make a aminated device ready for patient use.

udoinfection: A positive culture without clinical ction.

ogens: Substances that can produce fever.

rocessing: Decontamination and repackaging of a ce that has been used for its intended purpose and is led for single use (6).

terilization: Sterilization of an Ĩ€unopenedĨ€ (i.e., inner o still intact, and therefore, the device is presumably Ĩ usedĨ€) sterile device or an unused wrapped sterile ce that is past the expiration date.

sable: Intended for repeated use either on the same or rent patients, with appropriate reprocessing between s.

itization: Process of reducing the number of microbial aminants to a relatively safe level. In general, tation is used for noncritical surfaces or for ications in which stronger microbial agents may cause ce materials to deteriorate (4).

itizer: A low-level disinfectant.

ncritical Item: A device that is intended to come in act with mucous membranes or intact skin but will not mally come into contact with sterile tissues.

rt-term Exposure Limit (STEL): A 15-minute time-ghted average exposure that should not be exceeded at time during a work day.

re: The normal resting stage in the life cycle of certain eria.

ricide: An agent that kills spores.

ndard Precautions: Policies promulgated by the Centers Disease Control and Prevention (CDC) in 1996 that ude universal precautions, airborne precautions, droplet cautions, and contact precautions. Standard precautions y to all patients, regardless of their diagnosis or known resumed infection status.

ilant/Disinfectant: Term applied by the Environmental ection Agency (EPA) to a germicide that is capable of ilization or high-level disinfection.

ile/Sterility: State of being free from all living

oorganisms. In practice, sterility is usually described in
s of the sterility assurance level.

ility Assurance Level (SAL): Probability that
oorganisms will survive after a terminal sterilization
ess. Before a manufacturer can label a product as
le, it must have a sterility assurance level of 10^{-6},
h means that the possibility that microorganisms have
ived on the item exists but is no greater than 1 ÷ 10^{-6}
1 in 1,000,000.

ilization: Process capable of removing or destroying all
le forms of microbial life, including bacterial spores, to
cceptable sterility assurance level.

minal Sterilization: Sterilization process that is carried
after an item has been placed in its final packaging.

eshold Limit Value Ceiling: Concentration of an air
aminant to which it is believed that nearly all workers
be repeatedly exposed day after day without adverse
ct.

e-weighted Average (TWA): Integration of all the
centrations of a chemical to which a worker has been
osed during a sampling period, reported as an average.

nsmission-based Precautions: Recommendations by the
for patients with known or suspected infection or
nization with highly transmissible or epidemiologically
ortant pathogens that can be transmitted by airborne or
let transmission or by contact with dry skin or
aminated surfaces.

erculocide: An agent or process that kills tubercle
lli.

versal Precautions: Recommendations made by the CDC
health care workers consider blood and certain body
s to be potentially infectious for bloodborne pathogens
use protective barriers and workplace practices to
ce the risk of exposure. In 1996, universal precautions
incorporated into standard precautions, which
anded the coverage to any body fluid that may contain
agious microorganisms.

etative: Active growth phase of a microorganism.

cide: Agent that inactivates viruses.

s: Submicroscopic, noncellular particle composed of a
ein shell and a nucleic acid core, and, in complex
s, a surrounding envelope. In broad terms, viruses are
er lipophilic (enveloped) or hydrophilic (naked) (7).

f the Federal Government and sional Associations

registers and regulates chemical germicides (8,9). It
manufacturers to test formulations of chemical
s for microbicidal potency (efficacy), stability, and
also approves sterilization devices.

and Drug Administration (FDA) regulates medical
nd considers liquid chemical germicides used to
medical instruments as accessories to medical
The FDA requires that the manufacturer of a device
as reusable provide the user with adequate instructions
ng and disinfecting or sterilizing the item.

he FDA and EPA signed a memorandum of
ding that states that the agencies will divide the
clearance of germicides so that the FDA would clear
mical sterilants and the EPA would register general-
isinfectants before marketing (9A).

ulates occupational exposure to chemical disinfectants
izers.

does not approve, regulate, or test germicides or
. Rather, it recommends broad strategies to prevent
ion of infections in the health care environment.

and procedures to reprocess reusable devices have
lished by several professional organizations, including
can Society of Anesthesiologists (ASA), the American
on of Nurse Anesthetists (AANA), and the Association
ng Room Nurses (AORN) (2,10,11).

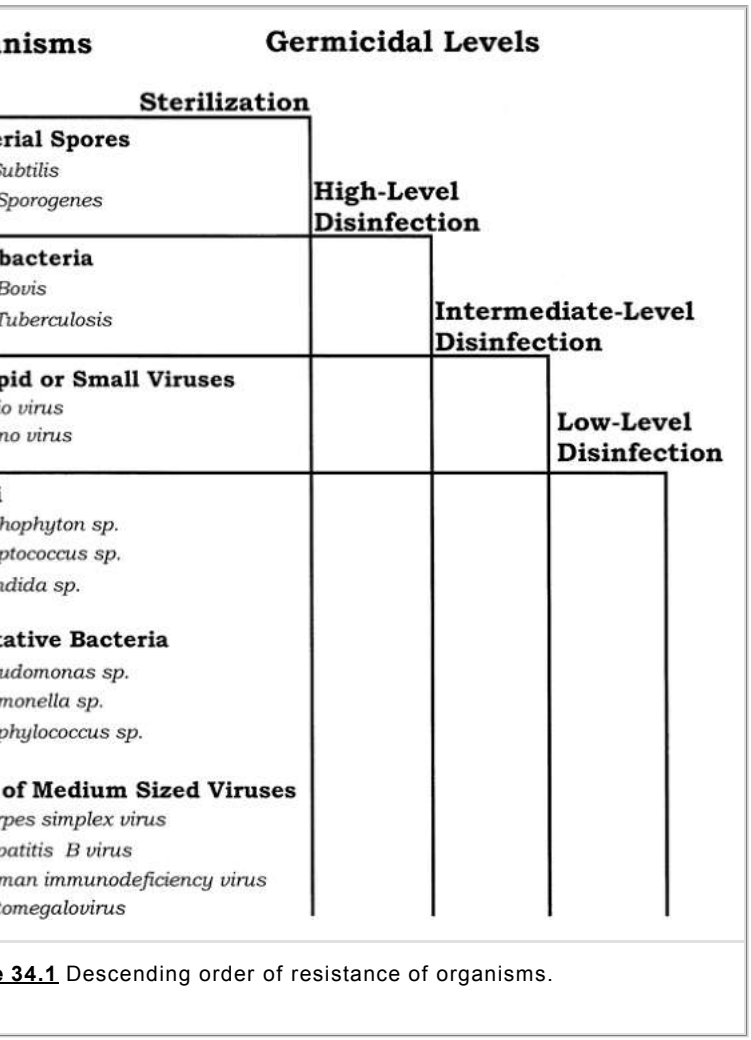
ance of Microorganisms to ection and Sterilization

nisms can be categorized into groups according to their
sistance to a spectrum of physical processes or
germicidal agents. Figure 34.1 shows a general
g order of microbial resistance levels. Resistance to
on and sterilization is not equivalent to resistance to
s. For example, antibiotic-resistant strains of
occi do not appear to be more resistant to chemical
s than nonresistant bacteria (8).

ng

and most important step in decontamination is thorough
(12,13,14). In some cases, cleaning may be sufficient
an item suitable for reuse. If an article is not clean,
salts and organic soil could inactivate chemical
s or protect microorganisms during the disinfection or
on process. Even if the item is rendered sterile,
may interfere with the device's function or cause a
n a patient.

rtant to prevent blood or other body fluids from drying
s. Enzymatic foam sprays that prevent drying, break
od and protein, and inhibit bacterial growth are
Flushing lumens with enzymatic cleaner will break up
ems that can be immersed should be soaked in water
nzyme presoak with or without detergent for at least 3
15). Stainless steel or other metal devices should not
d in saline or sodium hypochlorite solutions, because
de ions in these two substances will cause the metal to
13). A closed container should be used to move
ated devices to the decontamination area.



e 34.1 Descending order of resistance of organisms.

should be performed in a designated location that is from other parts of the facility to minimize inadvertent exposure or exposure of other items to contaminants. should be restricted to authorized personnel as much le. It should be away from traffic, patients, and clean- ge. The floors, walls, ceiling, and work surface should of non-porous materials that will not support the growth These surfaces should be washed frequently. The area ve adequate lighting with no shadowed or dark areas. should be designed to prevent slipping but be easy to rizontal work surfaces should be cleaned and d daily. Fluid spills should be cleaned up quickly to ips and falls. If the spilled material was contaminated , the spill area should be treated after it has been p with a tuberculocidal germicide.

ng, ventilation, and air-conditioning systems should be to minimize spreading contaminants to adjacent he air pressure within the decontamination space negative relative to the surrounding spaces so that air flow out of the area. There should be a minimum of 6 to

ir exchanges each hour with 100% fresh air. Air from should be exhausted to the outside without on or to a filtered partial recirculating system.

should be divided into dirty and clean areas. Signs where dirty equipment is to be placed should be ly displayed. Sinks should be big enough to contain ruments, and there should be enough sinks to date concurrent soaking, washing, and rinsing. Sinks ve attached counters or adjacent work surfaces on place soiled and clean items separately. Hand-washing should be conveniently located in or near the ination area. Personnel should wear a full complement ive attire (hair covering, fluid-resistant mask, eyewear, f gown or apron, appropriate gloves, and waterproof boots with nonskid soles) (13,16). Personnel should be ot to injure themselves with contaminated instruments.

ce manufacturer's instructions should be consulted to the appropriate cleaning methods and agents to oil without damaging the device. Tape should be and adhesive residue dissolved by using an appropriate

step is disassembly (if not done at the source). An er rinse or soaking with a specialized product (e.g., a ssolving solution) can prevent blood coagulation on the d remove gross debris. The water temperature should d 45ยฐC, because higher temperatures cause eous soil to coagulate (17). An alternative is to use a precleaner to help dissolve the soil (12).

equipment has soaked long enough to loosen organic should be thoroughly scrubbed inside and out. attention should be paid to lumens, crevices, corners, and knurled or textured surfaces. It is important to have of brushes (18). Brushes and other cleaning ts should be disposable or should be cleaned and or undergo high-level disinfection at least daily.

e devices cleaned under water to prevent ation of microorganisms. A cloth soaked in detergent can be used to clean items that cannot be immersed. s should be low sudsing and rinse off without leaving a Detergent residues can lead to staining and may with the action of some chemical disinfectants (13).

may be accomplished manually, mechanically, or by a on of both. Using mechanical equipment may increase ty, improve cleaning effectiveness, and offer greater for the worker.

of washing machines are available (12,19). They are omated, usually with microprocessor control. Washer- are designed to wash, rinse, and then steam sterilize 3). Washer-decontaminators/disinfectors use hot water ge of 60ยฐC to 95ยฐC. They are designed to wash, l dry the same items as a washer-sterilizer but can tems that would be deteriorated by the high temperature team sterilization.

uipment that has joints, crevices, lumens, and other each areas can be treated in an ultrasonic cleaning ter gross soil has been removed. In an ultrasonic igh-frequency sound waves passing through a solvent ubmicroscopic bubbles. These bubbles collapse on es, generating tiny shock waves that knock debris off A detergent is often added to the ultrasonic liquid. The y be heated. Ultrasonic cleaning tanks are available in of sizes and configurations. The equipment to be s placed in a basket or tray and into the ultrasonic tank et period of timeâ€”usually 3 to 6 minutes. Ultrasonic monitors are available (20). Some manufacturers of nstruments, including laryngoscopes, recommend that e subjected to ultrasonic cleaning because the process en fine screws and adversely affect alignment (21).

ning, rinsing should be performed to remove soil and detergent and to keep it from resettling on the t. Lumens and channels should be well flushed during e. Inadequate rinsing can cause irritation and burns in 22). Some items (such as those undergoing plasma on) should be rinsed with alcohol or distilled or ized water.

ed item should be thoroughly dried. Even if an item is o no further processing, drying is important because a vironment may encourage the growth of certain s. If a liquid chemical agent is to be used, water on the t will dilute the agent and make it less effective. If plets remain on equipment that is to be gas sterilized, oxide (EO) will dissolve in the water and form ethylene hich is both toxic and difficult to remove. Most items owel- or air-dried. Air-drying cabinets and hot-air ovens able (Fig. 34.2). If an item is to undergo EO on, unheated air should be used.

ning, each item should be inspected to verify s and tested for functionality (23). All accessible should be examined under normal lighting. Swab tests ing residual protein on surfaces are available. bled devices must be reassembled to perform ity testing. After functionality is verified, some devices n be disassembled to ensure that the sterilant can l the surfaces.

ection and Sterilization Methods

urization

eurization (hot water disinfection), the equipment is in water at an elevated temperature (but below for a specified time. The time and temperature vary. A quence is 30 minutes at a temperature of 70ยฐC. me is inversely related to temperature, that is, for t microbial kill, a longer exposure time is required when erature is reduced. CDC guidelines refer to ation as a high-level disinfection process, although it is intermediate-level (13,24).

ing machines come in different sizes (Fig. 34.3). Many the equipment. They are simple to load and operate.

ryers that are equipped with filters are available.

ation has been used for breathing tubes, reservoir
cheal tubes, face masks, airways, laryngoscope blades,
te blocks, Y-pieces, elbows, adaptors, and ventilator

dvantage of pasteurization is that the lower
ure is less damaging to equipment than the higher
ures employed during autoclaving. There are no toxic
residues. It is simple,

ve, and reliable. This technology may result in
ble savings compared with throwing equipment away.
disadvantage is that the treated equipment is wet and
be dried and packaged, during which time it may again
ontaminated. The heat may damage some materials.

e 34.2 Forced-air drying cabin for equipment.
e courtesy of Olympic Medical.)

Sterilization

erilization (autoclaving) utilizes saturated steam under (19,25,26,27,28,29). It is the most widely used and ve of the sterilization techniques.

vel, water boils at 100ยฐC. When it is boiled within a ssel at increased pressure, the temperature at which it that of the steam it forms will exceed 100ยฐC. The n temperature depends on the pressure within the Pressure per se has little or no sterilizing effect. It is heat at a suitable temperature, as regulated by the in the chamber, that brings about sterilization.

g the temperature dramatically reduces the time needed e sterilization. The minimum time for sterilization by 121ยฐC is 15 minutes. If the temperature is 126ยฐC, s reduced to 10 minutes.

inutes at 134ยฐC and only a few seconds at 150ยฐC.

e 34.3 Pasteurization machine. (Picture courtesy mpic Medical.)

g the temperature dramatically reduces the time needed e sterilization. The minimum time for sterilization by 121ยฐC is 15 min. If the temperature is 126ยฐC, the

duced to 10 min. It is 3.5 min at 134ยฐC and only a few at 150ยฐC.

ng is effective because the steam transfers heat to rapidly on contact. Microbial destruction will be most at locations where saturated steam can contact the nisms. At locations inaccessible to steam penetration occur with complex devices, improperly packaged ncorrect load configurations), some microbial n may occur, but dry heat is not as efficient at as saturated steam.

t to be sterilized is cleaned, and then may be packaged rial easily penetrated by steam. After sterilization, the material prevents recontamination during subsequent and storage.

ave Design

sterilizer can range from a small, manually-operated terilizer to a large, computer-controlled, floor-loading 6,28,29,30,31). Sterilizers are described by the method oval, temperature and the time the chamber is held at ied temperature (e.g., vacuum, 130ยฐC, 4 minutes)

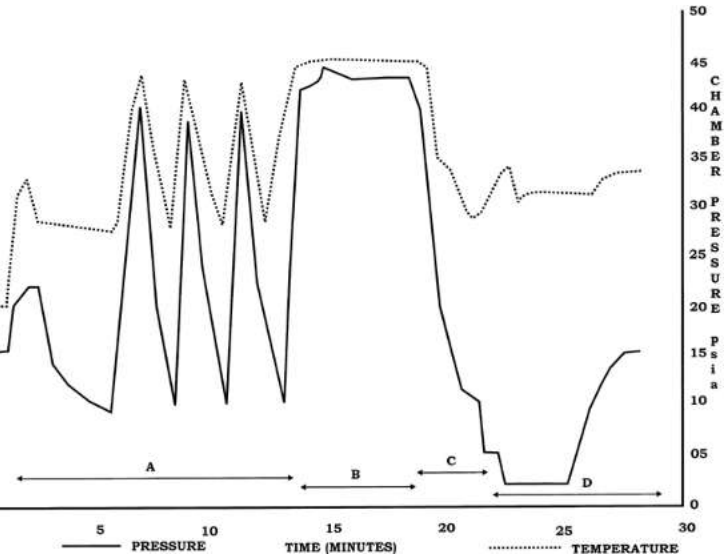
ber (pressure vessel) is where materials to be are placed and through which steam is circulated. It constructed to withstand the high pressures required to steam up to the temperatures required and fitted with a ve to prevent development of excessive pressure. size varies from less than 1.5 cubic feet in small terilizers to more than 70 cubic feet in large floor- odels (28). The jacket is the portion surrounding the It functions to maintain the temperature in the

izer may be equipped with one or two doors. Doors may or sliding and are opened and closed manually or by ectric, pneumatic or hydraulic). Items are placed on a he chamber, and the door closed and secured.

be displaced from the chamber. This is called the ng or heat-up phase (Figure 34.4). Its length varies, g on the load. In the gravity-displacement type of the incoming steam displaces the air through a port or r near the bottom of the chamber. The sterilizer drain remains open until the temperature in the drain is as the temperature of the steam entering the chamber, that the air has been removed. The pre-vacuum depends on one or more pressure and vacuum s to remove air. The steam-flush pressure-pulse uses a repeated sequence of a steam flush and a pulse. No vacuum is required. A pre-vacuum or steam- ssure-pulse sterilizer results in shorter cycles because oved more rapidly.

vity-displacement type of sterilizer, the incoming steam the air through a port or drain in or near the bottom of ber. The sterilizer

drain remains open until the temperature in the drain is as the temperature of the steam entering the chamber, that the air has been removed. The pre-vacuum depends on one or more pressure and vacuum s to remove air. The steam-flush pressure-pulse uses a repeated sequence of a steam flush and a pulse (Fig. 34.4). No vacuum is required. A prevacuum flush pressure-pulse sterilizer results in shorter cycles he air is removed more rapidly.



e 34.4 Typical steam sterilization cycle. Conditioning phase (*A*); tation phase (*B*); exhaust phase (*C*); dry phase (*D*). (Redrawn from e in Young JH. Steam sterilization: scientific principles. In: ert M, Young JH, eds. Sterilization Technology for the Health Care y. 2nd ed. Gaithersburg, MD: Aspen Publishers, Inc., 1997:124โ)

enters the chamber, it enters the load to be sterilized up its latent heat. Once the intended temperature is the sterilization time is set. This is called the *exposure ation phase*. By convention, sterilization cycles in re settings have been standardized at a few re-time relationships (29). The lowest temperature for r is 121ยฐC (250ยฐF). Cycles may also be programmed C (270ยฐF), 134ยฐC (275ยฐF), or 145ยฐC (285ยฐF), g on the sterilizer. In general, wrapped items should be for 30 minutes and unwrapped items for 20 minutes at 32).

sterilization phase, items must be dried before being from the sterilizer. This is called the *postexposure dry*) phase and consists of exhausting the chamber to re followed by circulating filtered air through the or by drawing a deep vacuum (27). Some tabletop s require that the door be cracked, but newer models closed-door drying (33,34).

rilization allows items to be steam sterilized for
e use (35,36). The items to be processed are usually
d. The time and temperature will depend on the
and the configuration of the load. The processed items
erred immediately from the autoclave to the point of
lly the sterile field in an ongoing surgical procedure.

ms with Steam Sterilization

ms with the Steam

ality or saturation refers to the percentage of liquid in
urrent standards call for a steam quality greater than
s than 3% liquid water). Variations in steam pressure
t the time needed to attain the proper temperature and
re uniformity within the chamber. Clogged filters,
gineered piping, or excessive demands on the steam
ay cause pressure variations. Steam is saturated when
proper balance of pressure and temperature. If the
is too high, the steam will change to liquid, causing
become wet; if the pressure is too low, the steam will
eated. Superheated steam is less able to transfer its
gy to the cooler items being sterilized than saturated
d will interfere with achieving a uniform temperature in
ber.

the Autoclave Chamber

nce of air in the chamber will impair sterilization. Air
heat poorly and retards steam penetration. The
evacuates much of the air at the beginning of the cycle
). All of the air does not have to be removed, but all
requiring sterilization must be exposed to adequate
(27). Improper sterilizer loading and incorrectly
individual packages can affect the ability of the
to remove air from the load (37).

oclaves have a built-in vacuum leak test (37). Such
are capable of running a special cycle that pauses
maximum vacuum is achieved. For others, the efficacy
removal process can be tested by a Bowie-Dick test.
n with a single test pack in the chamber. This should
ch day before the first sterilization cycle (20,38). Air
devices may be added to the sterilizer plumbing and
stem.

ment Malfunction

of equipment malfunction include out-of-calibration
re or pressure gauges and controllers, incorrect steam
essure, faulty or maladjusted control valves, leaks,
ent lines or drain screens, faulty vacuum pumps,
steam traps, and malfunctioning cycle sequence
s.

nnel Errors

errors include inadequate cleaning, incorrect pack
on or packaging methods, and poor loading techniques
s in the sterilizer must be positioned so that air cannot

d. Items should not be crowded or stuffed into the
. Crowding may interfere with both air elimination and
the shape of an item would allow water to collect in any
item should be positioned on its side or upside down
e water can run out. If water can pool, then air could
d against the surface.

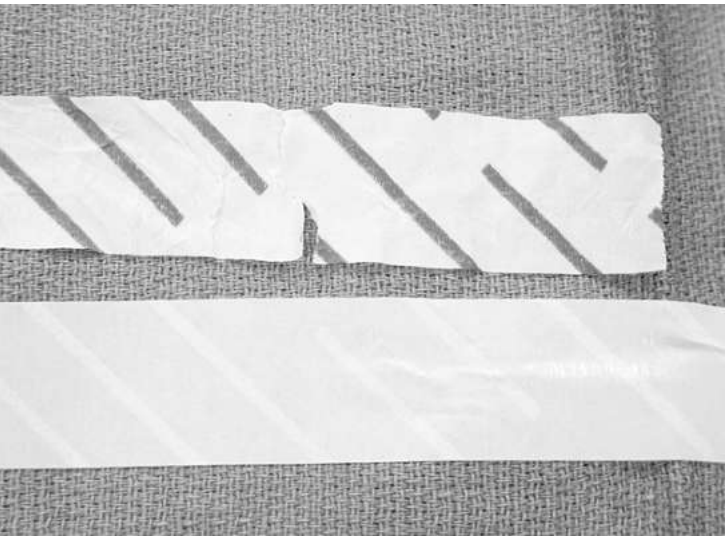
Sterilization Monitoring

on validation is achieved by using a combination of
al, chemical, and biological indicators (19,40). Using
oncert will give the greatest possible confidence that
sterile.

nical Indicators

al monitors indicate time, temperature, and pressure
t autoclaves provide a permanent record of these
rs. The temperature in a floor-loading sterilizer is
measured in the chamber drain piping. In small tabletop
where the steam is generated within the chamber, the
re is usually measured in the chamber. Some tabletop
do not have a recorder. With

s important to monitor physical conditions during the
.



e 34.5 Autoclave tape is an example of an external process
tor. The exposed tape is at top.

cal Indicators

indicators are divided into five classes (41,42,43,44).
r the class, the more sensitive the indicator.

dicators are internal and external process indicators.
orm the user that the item has been exposed to the

on process. The most common example of an external
ndicator is autoclave tape (Fig. 34.5). Most tapes do
nd to all the parameters of sterilization but do offer
of that the pack has been through the process. Internal
ndicators usually exhibit a color change from white to
e autoclave tape, they have limited sensitivity to the
rs of sterilization but do indicate exposure to steam.

dicators relate to the Bowie-Dick test for vacuum
rilizers. They do not determine if the sterilization
rs have been met but only assess vacuum pump
and detect the presence of air leaks and/or gases in
. The indicator is placed in a pack of towels (handmade
sed) on the front bottom shelf over the drain and a 3.5-
te cycle is run. Many new sterilizers are equipped with
cycles, so these indicators do not need to be used.

dicators are single parameter. An example is the
re tube that contains a chemical that melts and
s changes color when the appropriate temperature is
These indicators are helpful in determining if the
te temperature was achieved in the center of large
lse-positive results have been reported (43).

dicators respond to one or more sterilization
rs. They contain an ink that changes color when
o the correct combination of sterilization parameters.

dicators are also known as integrating indicators or
s. They respond to all parameters of sterilization over a
range of temperatures. False-positive and false-
results have been reported (41).

indicators can detect failures or errors in packaging,
sity, loading, insufficient humidification, inadequate
time at the selected temperature, or sterilizer
on. An important advantage is that they can be read as
he packs have been opened. Another advantage is that
so inexpensive that one can be used in every pack.

and all major U.S. organizations that issue
on-related standards or guidelines advocate that a
indicator be attached to every package that goes
sterilization cycle and within each package to be
in what is expected to be the most difficult-to-sterilize

both U.S. (45,46,47) and international
,51,52,53) standards for chemical indicators.

ical Indicators

indicators are standardized preparations of spores
strips or ampoules) that are placed in the most
-sterilize location(s) in the load (37,43). Alternatively,
al indicator that is enclosed in a commercial test pack
ed. The indicators are exposed to the sterilization
ieved, incubated, and examined for microbial growth. A
iological indicator is indicative of a possible
on process failure. Commercial mail-in biological
g services eliminate the need for on-site incubation.

of biological indicator contains a rapid detection

at is based on the interaction of an enzyme in the spore with a substrate in the growth medium. nce occurs when the viable biological indicator is o ultraviolet light. This type of indicator can be read in ith a wrapped item or in 1 hour with an unwrapped ay be particularly useful in the operating or ambulatory here products are often sterilized unwrapped in a splacement sterilizer (43,54).

problem with biological indicators is the time needed tion. Biological monitors should be used at least once ut preferably daily and after major repairs to the (37,43).

both U.S. (55,56,57,58,59) and international ,63) standards for biological indicators.

tages and Disadvantages of aving

toclaving can kill all bacteria, viruses, and spores. es include speed, good penetration, economy, ease of nce of toxic products or residues, and reliability. The an be prepackaged and kept sterile until used. It poses o

nment. A major advantage is that at least one is available in every modern operating theater.

ipal disadvantage of autoclaving is that many pieces of t are damaged if subjected to steam. Autoclaving can nted cutting edges, metal surface corrosion, and life of electronic components. Fiber-optic laryngoscope ow a decrease in light transmission with repeated ng (64).

eat Sterilization

s used for items that might be damaged by moist heat). While slow, this technique penetrates well and does le metal and sharp instruments (68). It is useful for us liquids or semisolids such as talc, glycerin, oils, jelly, waxes, and powders.

d temperatures frequently used for dry heat sterilization C for 60 minutes, 160ยC for 120 minutes, and or 150 minutes (32,68). Some of the newer dry heat can attain temperatures up to 210ยC (65). n hot air sterilizers improve heat transfer by using . These units have comparatively fast cycle times.

both U.S. and international standards for biological for dry heat sterilization processes (69).

cal Disinfection and Sterilization

(cold) disinfection/sterilization involves immersing an solution that contains a disinfectant (3). This method is useful for heat-sensitive equipment. It can be hed by automated equipment, which typically provides cleaning, rinsing, disinfection, rinsing, and sometimes

tion and Labeling

regulates formulations and labeling of chemical
s (70). The labeling must provide certain information,
precautionary statements, directions for use, the
contact time, recommended use temperature, use
se life, and shelf life. The EPA also requires that the
v the ability of the chemical agent to destroy certain
s such as *M. tuberculosis.* It is imperative that the user
lows the directions provided by the manufacturer.

clears liquid chemical sterilants. The current listing of
quid chemical sterilants and the time-temperature
sterilization and high-level disinfection can be
at http://www.fda.gov/cdrh/ode/germlab.html.

s Influencing Chemical Disinfection

ntration of the Chemical

, higher concentrations of the active ingredients
he disinfectant's bactericidal ability. An exception is
ols. However, extremely high concentrations increase
tial for damage both to inanimate objects and to the
mucous membranes of personnel. For best results,
should be used according to the manufacturer's
ndations.

on equipment will dilute the chemical and render it
tive. Dilution can become significant with frequent
can reduce the concentration to a level that is too low
ctive. For this reason, equipment should be dried
dergoing chemical disinfection or sterilization. In some
technique (manual or automatic) may determine how
oncentration falls (71).

rature

mperatures usually increase the effectiveness of
agents. Special devices are available for heating some
solutions. Too high a temperature may cause the active
s to evaporate or degrade. The label should tell which
re should be used.

ration and Light Deactivation

tion is in an uncovered container, evaporation can
ually, evaporation is not as serious as dilution.
if the chemical agent is more volatile than the diluent,
vaporation can be very important. Chlorine products are
susceptible to evaporation and deactivation from
to light.

den

, the higher the level of microbial contamination, the
exposure to the chemical germicide necessary before
microbial population is killed. Thus, items should be
sly cleaned. Liquid agents vary widely in their
ess against various types of microorganisms. Table
s the capabilities of some commonly used agents.

ve acidity or alkalinity of disinfectants can influence the
ctivity. An increase in pH tends to decrease the
f phenols, iodine, and hypochlorites. In contrast, it will
he antimicrobial activity of glutaraldehyde and
y ammonium compounds. Soluble calcium or
m in the water supply can react with detergents to form
precipitates, which tend to neutralize some disin-
4).

cteristics of the Item to Be Disinfected

tant solution will be effective only if it can contact all
(inner and outer) of the item to be disinfected (72).
r porous surfaces resist chemical disinfection. Air

nt can prevent contact between the liquid and parts of
e.

TABLE 34.1 Capabilities of Disinfecting Agentsa,b

sinfectant	*Gram-Positive Bacteria*	*Gram-Negative Bacteria*	*Tubercle Bacillus*	*Soores*	*Virusus*	*Fungi*
ternary monium pounds	+	ยท	0	0	ยท	ยท
hols	+	+	+	0	ยท	ยท
araldehydes	+	+	+	ยท	+	+
rogen xide-based pounds	+	+	+	ยท	+	+
naldehyde other nts	+	+	+	-	+	+
nolic pounds	+	+	ยท	0	ยท	ยท
rine	+	+	+	-	+	+

m Chatbum RL. Decontamination of respiratory care
pment what can be done, what should be done. Respir Care
9:34:98; and Berry AJ. Infection control in anesthesia. Anesth
North AM 1989;7:967Ì€“981.

good; ยท, fair, 0, little or none.

ttern, Use Life, and Storage Life

uct label should be examined for information on the use
se life, and storage life. Use pattern refers to how
es the solution can be used. Use life commonly applies
limited to disinfectant products that applies, but is not
require mixing of two ingredients for activation. Once
tant solution is mixed, there will be a limited period of
g which the activated solution may be used. The
should be marked with the date the solution was
and the date it expires. The storage life is the time
er which the unused and/or unactivated product is no
emed effective.

required for different chemical agents to function
varies from seconds to hours and will depend on the
st mentioned. Some microorganisms are killed faster
rs. Contact time may make the difference between
on and high-level disinfection. For high-level
on, a minimum contact time of 20 to 30 minutes is
nded (3). A lower level of disinfection can be achieved
ne. Leaving devices in the disinfectant too long can
arder to rinse off the chemical (22).

ractices

d areas for chemical disinfection should be strongly
ed (2,5,73,74,75,76,77,78,79,80,81). Ideally, the area
cleaning should be separate from the space where the
is used. Both of these spaces should be separate from
ocedure and personnel support areas. Traffic should be
trained personnel.

disinfectants should be used in an area that is large
ensure adequate vapor dilution with an air exchange
ess than 10/hour. The fresh air inlet should be placed
e room from the local exhaust ventilation.

aust ventilation (either a ductless system or a ducted
d) should be installed to capture chemical vapors. A
me hood should be connected to a non-recirculating
ystem that goes to the outside atmosphere at a
way from people and air intake ducts. Self-contained
fume hoods (Fig. 34.6) encapsulate the soaking
and have a blower that draws fumes away from the
and delivers them to a system that chemically
s the germicide and returns clean filtered air to the
s eliminates the need to install a duct.

oyer should provide training to each employee who
ermicides and verify that each employee has received
rstood the required training.

d processing equipment can reduce exposure to
s. Hoods designed for automatic washing machines are

should wear appropriate protective equipment
to protect the skin, eyes (goggles or full face shields),
ng from splashes when using chemical germicide
Impervious gloves and gowns should be worn. The
ld double glove and/or change single gloves frequently.

e clothing should be removed quickly if it becomes
and should be laundered before reuse. There should
access to means to decontaminate the eyes and skin in
of contact with the solution.

eparation and activation of germicide solutions, every
uld be made to minimize splashing, spilling, and
exposure. The chemical should be kept in a closed
with a tight-fitting lid. Agitation and splashing should
d when the solution is poured. Safety nozzles can be

e exposure to vapors created when pouring solutions.

e 34.6 Glutaraldehyde user station. Fumes are drawn away from the or and into a filter, where they are neutralized.

cessary to transport an activated solution, a method of
tion that will minimize the potential for spills and the
of personnel exposure to the solution or vapor should
ed. Transporting solutions in containers such as trays
s should be avoided.

fectant solution should be stored in a tightly closed
in a well-ventilated area. Containers that minimize the
rea should be used. The lid should be kept on the
at all times except when items are placed into or
from the solution.

uld be immersed in the chemical solution gently, taking
sturb and agitate the surface as little as possible.
solution must be manually irrigated or flushed through
hannels or lumens, care should be taken to avoid
. The syringe should be carefully filled with the solution
ely attached to the channel opening or all-channel
nd the solution pushed slowly.

uld be gently removed from the solution and rinsed

y in clean or sterile water. Rinse water should be
promptly, not reused. Semicritical items should be
h sterile water to prevent organisms that may be in tap
m contaminating them. Alternately, the items may be
st with tap water and then with alcohol.

g a chemical solution involves high risk of employee
The solution should be discarded, along with copious
of cold water into a drain connected to a sanitary
hemical germicide solutions should not be discarded
c systems.

ntainment response team should be created and be
le for developing and executing procedures for
spills. If there is a chemical that can be used to
the germicide and reduce ambient vapor levels in spill
, it should be readily available.

ls and droplets can be absorbed and neutralized by
cial mats that are highly absorbent and treated with the
ng chemical. Alternately, they can be wiped up quickly
onge, towel, or mop that has been neutralized with an
te chemical agent and then wiped up. The sponge,
mop should be thoroughly rinsed with large amounts of
the water discarded through the drain.

ills are best treated by using chemical spill kits that
n approved deactivator/neutralizer to pour over the
sonnel should wear suitable protective attire. The spill
contained and neutralized or contained and collected
al. After the solution is removed, the area where the
vas collected should be thoroughly rinsed. The cleanup
uld be rinsed with a large amount of water and the
carded down the drain.

e a safe work environment and establish compliance
mmended limits and guidelines on occupational
to germicides, several air sampling and monitoring
s can be used. Sampling should be conducted in all
ere workers might be exposed to vapor. Monitoring
conducted during normal use and whenever there is a
nge in protocol, workplace ventilation, case load, or
air to washers or other automated equipment. Special
should be given to periods of time when airborne
tions of vapor might be particularly high (e.g., when the
pouring the spent solution down the drain or pouring
tion into a container). Monitoring should be
ed and records maintained.

can be determined by using a sampling pump to pull a
antity of air through a tube containing an absorbent
This is analyzed later by

rial laboratory. A passive monitoring badge can be worn
nel. The germicide vapor is converted into a stable
and analyzed.

oring Chemical Disinfection

biological preparations are available only for
on processes and cannot be applied to disinfection. The
to assess the lethality of disinfection is to use the

say sterility test of the finished product (4). This test is nd time consuming, renders the tested object unusable subsequently recleaned and decontaminated, and is insensitive in its ability to detect low-level ation.

disinfection procedures cannot be effectively monitored ly, they must be monitored physically. Records exposure time, temperature, and pressure (if e) should be maintained.

s

cal germicide is suitable for all purposes. A number of ould be considered in selecting one, including the microbial death needed; the nature and composition of eing treated; whether the item is critical, semicritical, ical; and the cost, safety, and ease of use. Antiseptics ppropriate for disinfecting inanimate surfaces or

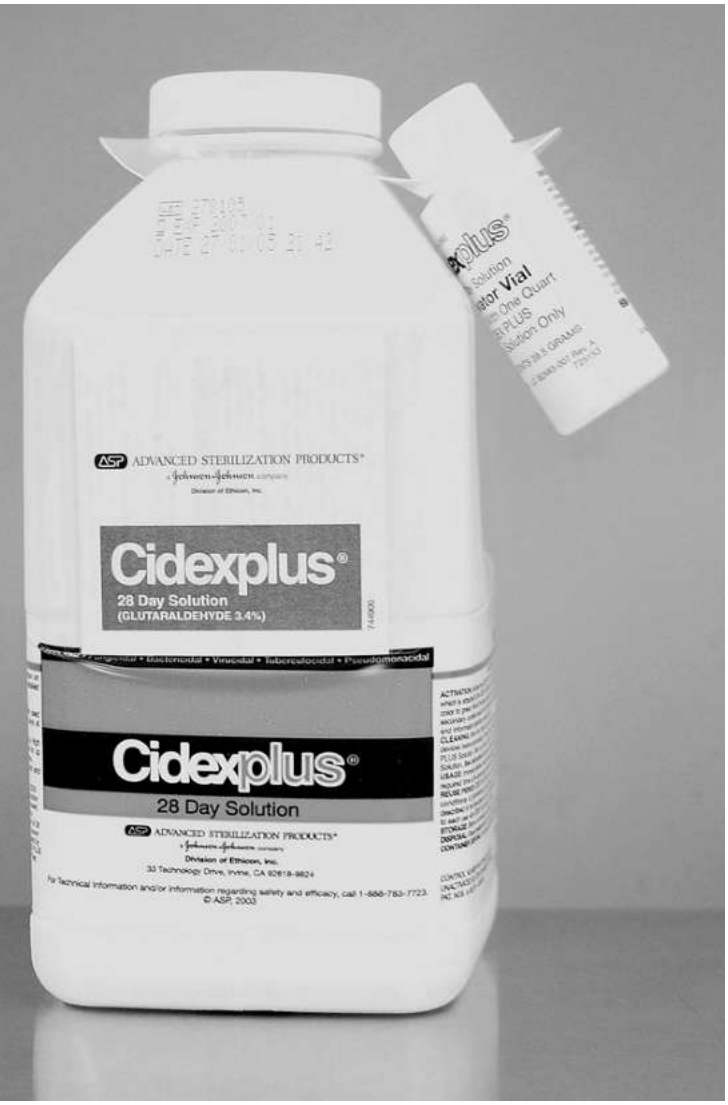
aldehyde

ehyde-based solutions have been widely used because xcellent germicidal properties, activity in the presence matter, noncorrosiveness with most equipment, and agulation with proteinaceous material 70,82,83,84). Glutaraldehyde has an extensive shelf y be used as long as 30 days after activation, provided ution and organic stress are properly controlled.

ehyde is effective against bacteria, fungi, and viruses at perature. High-level disinfection requires 20 to 30 85,86,87,88). It is also sporicidal, provided adequate otted. Three to 10 hours are required for sterilization. the temperature can shorten these times (89). The urer's instructions should always be consulted.

ften occurs during use, and it is important to ensure ment is disinfected with an acceptable concentration of utaraldehyde concentration test strips that are dipped olution to determine the active concentration are Problems with these strips have been reported (90). It lly recommended that 1% to 1.5% glutaraldehyde be the concentration for high-level disinfection (88). Solution tion should be monitored at least once every day and a f each test (81).

riety of brand-name products is available. They differ n the concentration of glutaraldehyde and additives. eous solutions are acidic and must be activated (made o become sporicidal (Fig. 34.7). Acid glutaraldehydes ble and do not require activation, but some studies wn them to have less microbiocidal activity than alkaline ons (88). The pH needs to be between 7.5 and 8.5 to be (5).



e 34.7 Glutaraldehyde. The small container contains the activator, must be added to the contents of the large container.

ehyde solutions evaporate at room temperature. to glutaraldehyde can result in a variety of reactions in re workers, including headaches; skin, eye, and mucous e irritation; and asthmalike symptoms (91,92,93,94). gland enlargement attributed to oropharyngeal airways ely rinsed after exposure to glutaraldehyde has been (95). These symptoms are usually temporary and when the individual leaves the area of exposure but may rbated with repeated contact. If it contacts the eyes, be corneal injury. Unfortunately, some institutions d glutaraldehyde inappropriately to disinfect floors, d linen (96).

fume hoods are available for glutaraldehyde (Fig. 34.6).

zer should be added to the solution when it is time for
This will eliminate

s that are created when disposing of the solution. In
alities, it is illegal to put un-neutralized glutaraldehyde
ewage system. Glutaraldehyde-neutralizing absorbent
be placed under and around baths and washers to
d neutralize spills.

ohthalaldehyde

alaldehyde (OPA or Cidex OPA) can achieve high-level
on at room temperature after a 12-minute exposure and
orter time at an elevated temperature (30,97,98,99). It
dal with prolonged exposure (100). It is often used in
atic endoscope processing system, which reduces the
g time to 5 minutes (30). It is noncorrosive. Test strips
re the minimum effective concentration are available
d be employed prior to each use. Some localities
at OPA be neutralized before disposal. Neutralizers
ge color with deactivation are available.

a number of advantages compared with glutaraldehyde.
lude faster disinfection, minimal odor, no need for
or mixing, and no OSHA vapor limit. It can be
through the drain. It is effective in the presence of
oil. While significantly more expensive per gallon than
hyde, it may be more economical at high-volume
01).

e effects and hazards are less with OPA than with
hyde, eye contact may cause stinging, excess tearing,
ss. It stains proteins (including unprotected skin), and
contact may cause dermatitis. Lesions of the skin, lips,
d esophagus have been reported following prolonged
ransesophageal echocardiograph probe that may have
roperly processed with this agent (102).

rnary Ammonium Compounds

y ammonium compounds (quats) are low-level
nts (5). They are bactericidal, fungicidal, and virucidal
emperature within 10 minutes but have not
ated sporicidal effects. If a spore is coated with a
y ammonium compound, it will not develop into a
e cell as long as the germicide remains, but if the
removed, the spore can germinate. These compounds
effective against gram-positive than gram-negative
Quats inactivate the human immunodeficiency virus
some do not inactivate the hepatitis virus. They are
e against *M. tuberculosis* or hydrophilic viruses (2,87).

eration quats were affected by factors such as hard
ap, anionic residues, and proteinaceous soils. They
tivated by organic materials (e.g., cork, cotton, and
ds). Some, either used in insufficient concentrations or
ns deteriorated by age or deactivated by the presence
soil, not only failed to kill some microbes but actually
their growth (8). Newer ones are mixed with various
es to produce synergistic antimicrobial and detergent
while maintaining the hard water, protein, and anionic

necessary in environmental disinfectants. They are
ng, relatively nontoxic, and noncaustic and do not
oxious fumes. They are useful for cleaning as well as
on.

lic Compounds

compounds (phenolics, phenols) are derived from
cid (phenol), one of the oldest germicides (2,5,8,87).
sometimes combined with detergents to form detergent
s. They are good bactericides and are active against
ey are active in the presence of organic matter and
enols are very stable and remain active after mild
nd prolonged drying. When moisture is applied to a
at has been previously treated with a phenolic
d, it can redissolve the chemical so that it again
bactericidal. Phenolics remain active in contact with
oil and for this reason are often the disinfectants of
hen dealing with gross organic contamination in general
ping.

nolics have a bad odor and are irritating to skin. They
bed by rubber and may damage the skin or mucous
es that they contact. They are difficult to rinse from
erials, and residual disinfectant may cause tissue
or hyperbilirubinemia in neonates.

are considered intermediate- to low-level disinfectants.
nolic detergents are tuberculocidal, fungicidal, and
al when used as directed. Certain viruses, including
ociated with widespread common respiratory illnesses,
ant to these compounds. The phenolics are not
except at or above 100ยฐC. They are used mainly on
ental surfaces and for noncritical devices.

ols

alth care facilities, alcohol usually refers to either ethyl
yl alcohol, both of which are water-soluble compounds
ntermediate- or low-level disinfectants (3). The alcohols
used at concentrations of 70% to 90% by volume. Both
ive against most viruses, including those for hepatitis B
d AIDS (or HIV). The CDC recommends exposure to
nol for 15 minutes to inactivate HBV, but 1 minute
adequate for HIV. Alcohols display high activity
ram-negative bacteria, fungi, and *M. tuberculosis* but
activate bacterial spores. Isopropyl alcohol cannot kill
ydrophilic viruses.

have a cleansing action, but wiping a surface with an
olution may not maintain a 1-minute contact time
he surface to be disinfected and the solution (11). They
vated by protein but not by soap. It is not necessary to
s soaked in alcohol, because it evaporates rapidly. For
n, an alcohol flush cycle is used in some automatic
g

. The flush cycle may be useful to disinfect the
of flexible fiber-optic endoscopes. After high-level
on with a chemical germicide and a tap water rinse,
an remove minor water contaminants. Its speed of

on promotes rapid drying in the channels. Alcohols are
d to clean the external surfaces of fiberoptic cables and

ant use of alcohol is in hand rubs (103). These reduce
ria count on hands more rapidly than antimicrobial
detergents. The Association for Professionals in
Control and Epidemiology (APIC) guidelines urge use of
l-based rub before and after patient contact and after
ble contact with body fluids and substances, mucous
es, broken skin, or contaminated objects.

nd agents containing alcohol must not be allowed to get
hesia gas sampling lines, as this can lead to incorrect
hen measuring anesthetic agents (104). Alcohols can
he lens mounts on instruments and tend to swell and
bber and certain plastics with repeated use (2).
are flammable, so care must be taken not to use them
sence of a heat source that could ignite the vapor.
olutions should be stored in special flammable-materials
(Fig. 34.12).

Compounds

hor is a combination of iodine and a solubilizing agent
with the resulting complex providing a sustained-
eservoir of iodine and releasing free iodine in aqueous
2,3,5,8). Iodophors are bactericidal, virucidal, and
cidal but may require prolonged contact time to kill
ngi and bacterial spores. Some iodophors do not kill *M.*
sis (87).

are used principally as antiseptics but are capable of
ate- and low-level disinfection. Iodophors formulated as
s are not suitable for disinfecting medical instruments
mental surfaces (8). Some iodophors are unstable in
nce of hard water, heat, and organic soil, but most are
eneral-purpose disinfectants if used in concentrations
nded by the manufacturer. Some metallic instruments
me corroded if they are routinely disinfected with
; nonmetallic items are seldom damaged but may be
discolored.

tic Acid

(peroxyacetic) acid is bactericidal, fungicidal, virucidal,
cidal at low temperatures
05,106,107,108,109,110). It remains effective in the
of organic material. It may be effective against prions
important advantage is that its decomposition products
id, water, oxygen, and hydrogen peroxide) are not
t can corrode copper, brass, bronze, plain steel, and
d iron, but these effects can be reduced by additives
odifications (88). A concentrated solution can cause
kin damage, but it has no OSHA exposure limit.

is a patented product that has been developed
ly for Steris processors. The active ingredient is a
te of 35% peracetic acid plus corrosion and
on inhibitors that are contained in a sealed, single-use
It should be used only in a Steris processing system.

ntended for open-pan techniques.

ystem is shown in Figure 34.8. Equipment to be must be clean but need not be dry. The equipment is a special tray, which is then

the processor. The sterilizer has a variety of trays, s, and adaptors to accommodate various medical Each tray has holes for fluid entry and drainage and is so that there is a continuous flow of sterilant on surfaces and through internal channels of instruments.

e 34.8 The Steris system **A:** Items to be sterilized are cleaned, then in a tray. The tray is then placed in the sterilizer. **B:** After the lid ed and the processing cycle is started, the processor automatically the sterilant concentrate and mixes it with filtered water. The use n of the sterilant enters the tray, covering the instruments, and is ted for 12 minutes. It is then drained from the chamber, and the er and tray are rinsed four times with sterile water. Next, sterile air ped into the chamber to displace the rinse water. A printout is ed, confirming that the sterilization parameters were met.

e 34.9 The sealed package of sterilant is placed processor, and the lid is punctured before the lid ed.

tray is positioned in the Steris processor, a sealed
of sterilant concentrate is placed in the sterilizer (Fig.
e lid is closed and the processing cycle started. During
the lid is sealed. The processor automatically opens
ant concentrate and mixes it with a controlled volume of
erile water heated to between 50ยฐC and 56ยฐC. The
erilant enters the tray, covering the instruments, and is
for 12 minutes. It is then drained from the chamber,
nstruments and chamber are rinsed four times with
ter. Then, sterile air is pumped into the chamber to
he rinse water. The cycle takes from 20 to 45 minutes,
g on the initial temperature of the water and how
ly the local water supply must be filtered. After the
omplete, the unit flushes the diluted sterilant and rinse
ectly into a drain. The tray can be transported directly
e field.

s processor monitors and maintains the parameters
to ensure sterile processing. It will stop the cycle if a
rror is detected. At the end of each cycle, a printout
g that the sterilization parameters were met is provided.
ps can be used as biological monitors. These go
he sterilizer and are then retrieved for culturing.

s system provides a quick method of disinfecting a wide
heat-sensitive immersible instruments, including
es (112,113) (Fig. 34.10). The Steris system has been
be effective in sterilizing the lumens of endoscopes
anic soil and salt were present (114).

e 34.10 Endoscope in Steris processor. Note the
s that are connected to the channels.

s system is less damaging to delicate instruments than
rilization and is compatible with a wide variety of
including plastics, rubber, and most heat-sensitive
s important that the absence of long-term effects on the
eing sterilized by the Steris system are confirmed with
ment manufacturer. Polymers, glasses, coatings,
, and sealants that are typically used in medical
re compatible with the process. Untreated metals such

, brass, silver, aluminum, and iron are subject to
Aluminum anodized coating can become dull.

s system is especially useful for items requiring a quick
d time. It is faster than sterilization with EO or
hyde and can be used on wet or dry items. No sterilant
necessary, and personnel are not exposed to any toxic
. Consequently, it can be located in the operating room
site requirements are a tap water supply, a drain, and
. It leaves no residue. Wrapping is not necessary.

em does have some disadvantages. Unlike some
d processors, the Steris machine has no cleaning cycle.
cycle are greater than if glutaraldehyde is used (115).
s that can be totally immersed can be sterilized, and
all number of instruments can be processed in a cycle.
cannot be used for extended storage, so processing
onsistent with ‾€just-in-time‾€ delivery.

ne Compounds

hlorine compounds are available for use as
nts, including sodium and calcium hypochlorite
d bleach), chlorine dioxide, and chloramine T
. The hypochlorites are

widely used. They are inexpensive and fast acting.
available in both liquid (sodium hypochlorite) and solid
ypochlorite) form. Relatively low concentrations of
ypochlorite (50 ppm) exhibit rapid activity against
e bacteria. One hundred ppm is effective against most
ny viruses are inactivated at concentrations of 200
HIV being susceptible at concentrations as low as 50
exhibits marked inactivation at 500 ppm.
ations of 1,000 ppm are considered adequate to
igh-level disinfection. A 1:5 to 1:10 dilution will destroy
of Creutzfeldt-Jakob disease (CJD) after an exposure
hour (117).

LE 34.2 Preparation of Household Bleach for Disinfectionaa

ed Chlorine centration	***5,000 ppm***	***1,000 ppm***	***500 ppm***	***100 ppm***
ion for within 24 s	1:10	1:50	1:100	1:500
ion for for 1 to ays	1:5	1:25	1:50	1:250

rting with 5.25% NaOCl, which contains
00 ppm of free chlorine.

2 shows the dilution of 5.25% NaOCl (household
eeded to achieve the desired chlorine concentration.
that will be used for extended periods (1 to 30 days)

ve an initial concentration twice as high as actually
nd should be stored in an opaque container.

solutions are not often used for instrument disinfection
been used widely in environmental disinfection. Current
ulations consider dilutions of 1:10 to 1:100 chlorine to
able for use with blood spills. Other uses include spot
on of countertops and floors and decontamination of
ion manikins.

lorine compound concentrations are corrosive as well
g to personnel, and their use should be limited to
in which there are unusually high concentrations of
nisms (8). Their use is limited by their corrosiveness,
on by organic matter, and relative instability. They may
sidue and are irritating to the skin, eyes, and
y tract.

dioxide is used in a gaseous phase (118). It is not
t is generated at the point of use. Advantages are that
ittle residue and is nonozone depleting. Disadvantages
aterial incompatibility.

gen Peroxide

peroxide is an effective bactericide, fungicide,
and sporicide (2,3,5,119,120). It is commercially
in several different concentrations. It is not inactivated
c matter. There are no restrictions on disposal. It
ses effectiveness when exposed to heat and light and
careful storage. It can damage rubber and plastic and
de copper, zinc, and brass. It is an irritant to the skin
A 7.5% solution achieves high-level disinfection in 30
An effective low-level disinfectant, 3% hydrogen
s useful for work surfaces. Hydrogen peroxide is used
a sterilization (see below).

erilizers use oxygen, water, and electricity to produce
21,122,123). The gas is humidified and dispersed into a
on chamber. A sterilization cycle includes three stages:
ation, followed by air and ozone mixture admission; an
stage; and a stage of vacuum-drying and ozone
After the cycle, the ozone passes through a catalytic
that changes it back to oxygen.

erilization is good for most goods that need low-
re sterilization. It is not approved for flexible scopes
ive metals such as copper and brass. It is compatible
anodized aluminum sterilization containers and all
ntainers. It is unsuitable for devices that contain
m rubber products, some plastics, and some metals
rass and copper.

to the manufacturer, ozone can sterilize single
steel lumens with an inside diameter of 2 mm and no
n 250 mm, lumens with an inside diameter of 3 mm or
no longer than 470 mm, and those with an inside
of 4 mm and no longer than 600 mm (121,122).

ss is environmentally friendly and produces no toxic

It requires no vent or drain and uses only oxygen, , and a little water. The sterilizer can be transported o exhaust gas ventilation duct is required in a room that tely ventilated. The treated objects are dry. No rinsing ing is required. While significantly slower than gas his process is less expensive.

ldehyde

hyde is a highly toxic and flammable gas that has been disinfectant and a sterilant in both a water-based formalin) and the gaseous state (5). It is noncorrosive t inactivated by organic matter.

formalin is a high-level disinfectant, its uses are limited gent odor and fumes, which irritate the skin, eyes, and y tract. Its toxicity requires that disinfected materials be y rinsed before use. NIOSH has indicated that yde should be handled as a potent sensitizer and carcinogen. Kits are available to absorb and neutralize yde spills. Sterilization with low-temperature steam and yde is used in some countries (5,124).

tages and Disadvantages of Chemical ection and Sterilization

es of liquid chemical disinfection include economy, d simplicity. This is especially important in busy y suites because it enables equipment to be used mes a day. It is useful for equipment that does not erilization but does require high-level disinfection.

disinfection cannot be used for all types of equipment. ices cannot be soaked. Prepackaging is not possible, quipment will be wet. There is a risk of recontamination bsequent rinsing, drying, or wrapping. With most terility cannot be guaranteed. It is more expensive, less and more prone to human error than steam on. Hinged instruments must be opened and those with multiple parts disassembled.

utions are irritating to tissues and have unpleasant rsonnel who handle them must take precautions to onged skin contact or vapor inhalation (92). The may be absorbed onto the treated items, causing harm ient.

ant disadvantage of cold sterilization is the lack of a hod for validation. The efficacy can be monitored only through surveying patient outcomes, to identify nt infections that can be attributed to exposure to the device (125). Most health care institutions have an veillance program in which infection control ers seek to identify nosocomial infections.

terilization

cteristics of Ethylene Oxide

oxide (EtO, EO) is a colorless, poisonous gas with a or (126,127,128,129,130,131,132,133,134). It is

in high-pressure tanks and unit-dose ampules and
. It is flammable in concentrations of 3% or greater.
urers have dealt with this hazard in two ways. EO may
with carbon dioxide or hydrochlorofluorocarbons
lixtures containing up to 12% EO in these inert diluents
ammable but retain their sterilizing ability. A mixture of
hlorofluorocarbon (CFC) was used in the past, but the
Cs was banned because of damage to the ozone layer.
similar to CFCs but are less damaging to the ozone
7,135). Their use will be eliminated in the United States

plied mostly as 100% in small cylinders, cartridges
1), or ampules. Equipment is designed for gas
ent and to minimize the risk of fire or explosion
136). A cartridge is punctured only after it is secured in
and locked sterilization chamber. An ampule is broken
it is placed in a bag with the medical device to be
Explosion-proof cabinets should be used for storing
of 100% EO (Fig. 34.12).

acteria, spores, fungi, and viruses. It penetrates into
and through permeable bags. It is not degraded by
il but will not penetrate dried protein material.

ation for Ethylene Oxide Sterilization

rtant to verify that a device is suitable for sterilization
The manufacturer's instructions should be consulted.
ices need to be sterilized at a lower temperature.

ckaging, items must be disassembled, cleaned, dried,
ed. Disassembly is important to remove barriers to
ment of gas. Caps, plugs, valves, and/or stylets must
ed. Hollow-bore

such as needles and tubes must be open at both ends.
ping must be permeable to EO gas and water vapor
proper aeration (137).

e 34.11 Cartridge of EO. The cartridge is punctured only after the
er door is closed and locked and proper conditions are met. There
external tanks, hoses, or gas source hookups, which are major
es of potential operator exposure to EO.

e 34.12 Explosion-proof cabinet for flammable
als.

l other proteinaceous materials can act as a barrier to
t and protein are present in a narrow lumen,
on will not be achieved consistently (114). Therefore,
t must be thoroughly cleansed and rinsed before
on.

gas sterilization must be free of water droplets. They
allowed to dry in ambient air or towel dried. The use
air should be avoided because EO sterilization
on the presence of adequate (but not excessive)
A relative humidity between 35% and 70% and a
re between 18ยC and 22ยC throughout the
g and storage facility are recommended (23,128).

hould be sorted according to the sterilization time and
nded temperature. Items to be sterilized are placed in
ets, metal sterilizer carts, or other carriers that do not
O. The sterilizer manufacturer's instructions for loading
carefully followed. Items should be loaded loosely to
to penetrate throughout the load. Items should be
such a fashion that packages will not contact the
walls or the operator's hands when the load is
d to the aerator. Some instruments are sterilized in
ainers that have filters on the lid and bottom to allow
of sterilant gas. There may also be an additional lid
o the upper lid.

erilization Process

ssing Parameters affecting Ethylene Sterilization

ncentration

O concentration increases at a given temperature and umidity, the microbial inactivation rate increases up to range when it begins to plateau (126). EO tions between 450 and 750 mg/L are commonly used in g medical products. The solubility of EO in the product iffusion rate through the product will influence the concentration. The operating pressure of the EO cycle y influence the gas diffusion rate. Packaging may also . Devices that perform continuous EO monitoring in the on chamber are available.

rature

g the temperature can decrease the necessary exposure y sterilizers provide a selection of temperatures. In re, processing cycles are commonly performed between d 60ยฐC. Some conduct sterilization at room ure. This is equally efficacious if other factors (exposure concentration) are adjusted.

e Humidity

hydrates microbes, making them more susceptible to n by EO. Therefore, humidity must be controlled in the nd cleaning/processing area and in the sterilizer itself. chambers are held between 40% and 80% relative Desired humidity levels are usually accomplished by erature steam injection. For tabletop monitors, it is to add water to the sterilizer.

re Time

ssary sterilization time will depend on the factors d previously. The time generally ranges between 1.5 rs in automatic sterilizers. Up to 12 hours may be

zers

zers range in size from small tabletop to large floor- odels (126). The basic design includes a pressure- sel with a port for admitting air, a vacuum pump to the chamber gas contents, a jacket to heat the vessel, ource to humidify the chamber and its contents, and a inject the sterilant. A recent change has been to computers, microprocessors, and software into the onitoring, and documentation of sterilization g. Ancillary equipment such as recirculation blowers to e the chamber environment, exhaust systems to release of sterilant into the work environment on door and a sterilant removal/reclamation system to handle emissions are commonly used.

sterilizers are sophisticated units with a choice of
cycles. A source of EO gas (cylinder or cartridge) is
and a sterilization cycle is selected. After the sterilizer
s tightly sealed and the controls set, a typical cycle
he following: (a) warming the chamber, (b) evacuating
troducing moisture and maintaining it for a ‘dwell’
) introducing the EO, (e) raising the chamber pressure
sterilizers), (f) raising the temperature (if required), (g)
to EO for the time required, (h) releasing the pressure
mber, and (i) removing the EO mixture (purge cycle or
ome sterilizers provide several successive purge
A sterilizer without a purge cycle can release a cloud of
hen the door is opened. This necessitates an extraction
ve the door with a dedicated exhaust system and may
e operator to EO gas (138). The last phase is (j) re-
ng atmospheric pressure by introducing filtered air into
ber.

carry out sterilization at room temperature and
umidity are available. Special ventilation cabinets are
for exhausting the EO from these units to atmosphere.

tors

es of indicators are available. For maximum value, they
used in combination.

al Indicators

monitors include sterilizer components that measure
time, temperature, and humidity and/or pressure during
e. They should be examined at the beginning, middle,
f each cycle.

cal Indicators

indicators change color when certain conditions
for sterilization (temperature, gas concentration, and
have been met (41). Color change varies with the
They are available as tapes, strips, cards, and sheets.
be attached to the packaging material or enclosed in
ges.

mmended that a chemical indicator be used with each
hat undergoes EO sterilization. In most packages, the
indicator is placed in the geometric center. In rigid
zed packaging systems, the chemical indicator is
the corner (128).

ical Indicators

al indicator should be placed in the most inaccessible
n the sterilized load (54,139,140,141). The CDC
nds their use at least once a week. They should always
fter a sterilizer is installed, after any repairs or
ons are made to the sterilizer, and any time there are
n packaging procedures or materials or the composition
d. The Association for the Advancement of Medical
tation (AAMI) recommends that one be used with every
O sterilizers (30). Problems with these indicators have
rted (142).

on

nly comes in contact with the surfaces of articles being but also penetrates some items, which then retain mounts. These items need aeration (degassing, n, offgasing) to reduce EO to a level safe for both and patient use. Aeration may be done passively in air aeration) or actively in a mechanical aerator.

nt Aeration

eration is slower than mechanical aeration. The time is highly variable because of the lack of re and air flow control. The temperature in the aeration ld be at least 18ยC. Items that require between 8 and of mechanical aeration may require 7 days of ambient Some items take between 5 and 6 weeks.

eration may increase worker exposure to EO. If eration is unavoidable (for heat-sensitive items that thstand the elevated temperatures of conventional abinets or when an aerator is not available), measures taken to minimize traffic in the aeration area and to at personnel who must enter the area are not exposed hazardous concentrations.

nical Aeration

nical aerators, a stream of filtered air is directed over zed items. An EO sterilizer may be combined with an o that one chamber is used for both processes.

s Affecting Aeration

Characteristics

unt of residual EO and the length of time needed for it te depend on the device being sterilized (143). Thicker nd wraps require longer aeration times than thin ones. ed nonporous metal and glass items do not absorb EO re little or no aeration but must be aerated if wrapped sorbent material.

rubber, cloth, paper, and muslin may absorb significant . Items that consist of a combination of absorbent and bent materials (e.g., a metal item with rubber parts) reated as though they were made entirely of absorbent The most common material that retains large amounts olyvinyl chloride (PVC). Teflon and nylon absorb little ver, it is bound tightly and therefore requires a long period of time to elute. When the composition of a in doubt, it should be treated as if it were PVC.

e Size and Arrangement in the Aerator

items loosely in the aerator will allow faster aeration.

ures with fluorocarbon require a longer aeration time e diluted with carbon dioxide.

ngs

aging material should allow for easy gas transfer.

rature

g the temperature accelerates desorption. The usual emperature is between 50ยฐC and 60ยฐC. If these ures would be damaging to a device, aeration should be ut at room temperature.

w

s affected by the rate of air exchange and the air flow ncreasing air exchange beyond a certain point will not hance aeration unless the temperature is increased.

teristics of an Ethylene Oxide Sterilizer

s that subject materials to hot gases under elevated can result in higher levels of EO in the items sterilized.

d Use of the Device

he item is to be external to the body, within a body ravascular, or implanted will affect the acceptable level l EO.

years, aerator manufacturers passed out information aeration times for different items. This has changed, because the growing multitude of EO-sterilized devices mpossible to keep up with all the changes required. A ndation that aeration should be performed for 12 hours has evolved (143). Another is 8 hours at 60ยฐC.

ications of Ethylene Oxide zation

t Complications

ions of EO sterilization that stem from failure to residual gas from sterilized items include skin reactions gotracheal inflammation. When blood is exposed to EO-aterials, hemolysis can occur. Sensitization and xis from exposure to products that are sterilized with EO n reported. However, the risk of patients developing suffering other adverse health effects from exposure to EO is negligible (144).

chlorhydrin is formed when EO comes into contact with ons that may be present in previously ฮณ-irradiated s. The American National Standards Institute at one mmended that PVC items that have been ฮณ-irradiated resterilized with EO but very low levels of by-products ed products treated with EO have cast doubt on this ndation and EO sterilization of ฮณ-irradiated PVC items cceptable if strict attention is paid to aeration.

sterilized using EO may increase the risk of latex ion (145).

ment Alteration

exposure of some plastics to EO and heat may leach rs and weaken their structural integrity. Rubber and stic tracheal tubes may soften, kink more easily, or ticky. In one case, the balloon on a disposable al stethoscope that was sterilized with EO became (146). Damage to the flexible sheath of a flexible e has been reported (147).

nnel Complications

e Ethylene Oxide Exposure Hazards

ence of gaseous EO in very high concentrations is ected because it is irritating to the eyes and mucous es, but odor is not a reliable way to detect its presence not provide adequate warning of hazardous tions.

posure to significant levels of EO usually provokes an sponse. Upper respiratory complaints, eye irritation, , blunting of taste or smell, a metallic taste, and frequently occur. With higher concentrations, nausea, diarrhea, increased fatigability, memory loss, s, weakness, dizziness, lack of coordination, chest t, shortness of breath, difficulty swallowing, cramps, ulsions may occur (148). Respiratory paralysis and l nerve damage have been reported after massive The onset of neurologic signs and symptoms may be or 6 hours or more after exposure. EO gas is heavier nd can cause asphyxiation in enclosed, poorly , or low-lying areas.

xposure can affect the eyes (corneal burns, cataracts, keratitis), the central and peripheral nervous system, irritant and allergic reactions). Respiratory infections, nd impaired cognitive function may occur. EO is a d mutagen and carcinogen and may adversely affect ductive system.

tional Safety and Health Administration tions

ulations limit worker exposure to an 8-hour time- average (TWA) of 1 ppm with a short-term excursion L) of 5 ppm (149,150,151). In facilities where worker exceeds these levels, employers must institute certain to meet OSHA regulations. However, a facility is rom these requirements if it can document that the EO on system employed does not expose workers to TWA ve 0.5 ppm during 8 hours or 5 ppm during 15 minutes on levels). The purpose of action levels is to encourage to achieve an even lower maximum exposure level. By ating compliance with the action level, a facility is not o conduct routine monitoring (other than after an t or facility modification or maintenance), scheduled training, or periodic employee medical examinations.

ulations do not identify a specific monitoring sampling but do set forth accuracy requirements for sampling

(149). There are

approaches to monitoring workplace levels of EO:
and environmental area monitoring. Personnel
g includes devices that can be affixed to employee
determine operator ‘breathing-zone’ exposures. Area
g includes devices that rapidly measure EO levels
t the sampling location (Fig. 34.13). They are used to
O concentrations around equipment or in the workplace
ent. They are useful to evaluate the effectiveness of
ng changes and can help to estimate personnel
Most also serve as alarm systems for problems such
or failures in the ventilation system.

e 34.13 Area monitoring device for EO (on
).

uires employers to provide respiratory protection and
protective equipment for work such as maintenance,
other activities where engineering and work practice
re not feasible.

e Oxide Exposure Sources

eight areas where EO is likely to contact personnel:
n front of the sterilizer when the door is opened after
is completed, the freshly sterilized goods themselves,

on cabinet, the sterilizer, the floor drain, where the
or cartridge is changed, the safety valve, and where the
nks or cartridges are stored.

mendations to Reduce Exposure

ecessary use of EO should be avoided (149). It should
eserved for products that must be sterilized and cannot
stand other methods of sterilization.

re must be strict adherence to the manufacturer's
allation and operating instructions for sterilizers and
tors. Each sterilizer and aerator must have regular
entive maintenance to ensure that malfunctions,
ecially leaks, are minimized. Records must be kept on
malfunctions and repairs.

cylinders must be stored in a designated area that
ts building codes and OSHA regulations and is out of
way of traffic. Cylinders must be chained upright to a
d structure and the protection cap kept in place when
in use. The storage area must be ventilated to prevent
dup of a significant EO concentration in the event a
ainer leaks.

tion must be exercised when changing tanks and filters
void personnel exposure. Protective attire (e.g.,
gles or a face shield, heavy-duty gloves, full-body
s) must be worn. There must be check or shutoff valves
e lines close to the connection point to limit the release
as during cylinder changes. A local exhaust hood must
nstalled near the EO cylinder connection area to
ure EO released during changeover and leaks around
connections. It must exhaust the EO to the outside or
emission control system.

ilizers and aerators must be located in well-ventilated
s with limited access. The room(s) in which the
ilizer and aerator are located must be large enough to
ure adequate EO dilution. The ventilation system must
non-recirculating, allow at least ten air changes per
, and be designed so that air flows over the sterilizer
opening to an exhaust fan, blower system, or
ssion control system. Signs warning that high levels of
are possible must be posted at the entrances. No
olies or unnecessary equipment should be stored in the
ity of sterilization/aeration equipment.

ducts that are to be sterilized with EO must be
nized into full loads, and those requiring the same
ilization times should be grouped together.

sterilizers, sterilizer relief valves, and aerators must be
ed to the outside, an emission control system, or a
tary floor drain. Running vent lines in ways that would
ase EO within the building, allowing re-entry of EO-
aminated air into the building or releasing EO near
estrian traffic, is prohibited.

EO sterilizer must be constructed so that the cycle
not be initiated or allowed to continue unless the door

osed and secured. It must not be

sible to open the door when the chamber is under
ssure or before the postevacuation cycle is completed.
al exhaust ventilation systems must be installed to
ure EO as close to the source as possible and exhaust
the outside atmosphere.

ombination sterilizer/aerator will reduce EO exposure
ociated with opening the sterilizer door and transferring
ds to an aerator (128).

osure to EO can be avoided by using a loading cart
or wire baskets that can be moved directly into the
ator. Items must be loaded in such a manner that they
not touch the operator's hands when the cart or basket
ansferred.

sterilizers without a purge cycle, the single greatest
ce of EO exposure occurs when the sterilizer door is
ned after the sterilization cycle is complete. Items must
be left in a closed sterilizer after the cycle is complete,
his will allow high concentrations of EO to build up in
sterilizer and be released into the room when the door
rst opened. The chamber door should be opened 6
es immediately following a cycle on some sterilizers. A
-opening device allows the operator to push a button
then walk away while the sterilizer door slowly opens.
operator should leave the immediate sterilizer area for
nimum of 15 minutes after opening the door.

purge characteristics of some newer sterilizers prevent
from accumulating inside the chamber. These sterilizers
uld be unloaded immediately upon opening the door,
ause this is when the EO concentration in the chamber
west.

ilized items must be transferred rapidly to the aerator.
ds should never be handled directly. Transfer carts
uld be used to remove items from large sterilizers and
es and forceps for items in small sterilizers. Carts must
ulled, rather than pushed, to the aerator so that
onnel are not upwind of the goods. Baskets must be
ied at the side and not at the front of the person. Items
uld be placed in the aerator without delay. Unaerated
s must never be left outside the aerator, where they
nt contaminate the environment or be used prematurely.

able EO sterilizers must be used only in a well-
ilated room. If a sterilizer does not have a venting
hanism other than the door or lid, the health care
ity must determine that the ventilation system
ctively minimizes employee exposure to EO. Possible
sures include using local exhaust ventilation and
ng a chemical neutralization system or EO absorbent
e sterilizer.

EO-sterilized items must be aerated before handling. A
hanical aerator is best. If ambient aeration is
voidable, the aeration area must be segregated from
eral work areas and have limited access. It must have
d ventilation and be at a negative pressure with respect

djoining areas. Storing supplies in the area where
ient aeration is practiced should be prohibited.

sonnel and environmental monitoring must be practiced
nsure that recommended levels are not exceeded
2,153,154). Checking for leaks must be performed
ılarly. The monitoring frequency required by OSHA
ends on the levels found in the work environment.
ges that can be worn by employees are available.
ruments to aid in instantaneous leak detection and to
t personnel should be installed (Fig. 34.13).

seals on sterilizer and aerator doors must be inspected
cracks, tears, and foreign substances before each load.
ilizer and aerator valves and fittings must be inspected
ılarly and replaced as necessary. Intake air filters for
restricted access area must be inspected and cleaned
ılarly.

mited number of EO cartridges can be stored in the
ediate vicinity of the sterilizer, preferably in a special
net (Fig. 34.12).

n facility in which EO is used must have a written
rgency plan for dealing with EO leaks and spills (149).
includes procedures for alerting personnel, avoiding
contact, evacuating unprotected personnel, contacting
opriate safety personnel, and specifying the criteria for
re-entry by unauthorized personnel.

loyees who operate sterilizers or aerators must be
erly instructed in the hazards of EO and appropriate
ty procedures.

nmental Problems

is emitted, it remains in the air without breaking down
eriods of time. People who live near facilities with
or aerators may, therefore, be exposed to significant
airborne EO. Some state and local areas limit the
f EO that can be emitted into the air (135,155).
converters that break EO down into carbon dioxide and
available.

tages and Disadvantages of Gas zation

zation is very reliable because the gas penetrates into
narrow lumens, and regions blocked by liquids. It can
n a wide variety of items, including those that would be
by heat or moisture. It is the only reliable and practical
r sterilizing many devices that are used today. Damage
quipment is minimal. Items can be packaged before
n and stored sterile for extended periods.
ging eliminates the danger of recontamination that can
ing rinsing and packaging following

ization and allows items to remain sterile during long-
age. A large amount of equipment can be sterilized at

number of disadvantages. Fires and explosions

sterilizers have occurred. A major disadvantage is the
processing time required. This may make it necessary
ultiple sets of equipment. EO is more costly than most
s of sterilization. Personnel need to be highly trained
rvised. Measures to reduce employee exposure and
vels of EO must be taken. Equipment that is to be
needs to be dry. Some materials deteriorate after
EO sterilization, especially at elevated temperatures. It
used to sterilize devices that have petroleum-based
in or on them, because EO cannot permeate these.

ion Sterilization

adiation uses an electromagnetic wave produced during
egration of certain radioactive elements. If the dosage
a product is large enough, all microorganisms,
bacterial spores and viruses, will be killed.

many advantages to ฮณ-radiation. The product can be
in a wide variety of impermeable containers before
. The package will not interfere with the sterilization
The treated items remain sterile indefinitely until the
seal is broken. As there is virtually no temperature
g treatment, thermolabile materials can be sterilized
olabile packaging can be used. Items may be used
ly after treatment with no risk from retained
ity.

adiation is not practical for everyday use in health care
It requires expensive equipment and is used only by
ufacturers to sterilize disposable equipment. Some
e facilities send their own packs to outside facilities for
.

lasma Sterilization

ma is sometimes described as the fourth state of matter,
of a cloud of reactive ions, electrons, and neutral
d molecular particles (109,156,157,158,159). It is
by applying energy to certain gases. Hydrogen
vapor is most often used. The reactive species in the
teract with the molecules that are essential for the
m and reproduction of living cells.

be sterilized need to be thoroughly cleaned and
y can be unwrapped or enclosed in a nonwoven wrap
llulosic materials should not be used for wrapping,
hey absorb the sterilant vapors, reducing its
tion.

e 34.14 Gas plasma sterilizer. (Picture courtesy
rrad, a division of Johnson & Johnson Company.)

izer (Fig. 34.14) runs on an automatic cycle that is
by a microprocessor. The machine produces a printout
oad processed. If for any reason the process is outside
l limits, the cycle is interrupted and the printout gives
n.

ogen peroxide is contained in a sealed disposable
(Fig. 34.15) that is placed inside the sterilizer along
tems to be sterilized.

rtant to read the instructions with the sterilizer,
when devices with small lumens are processed. Early
uld not sterilize devices with long narrow lumens
ter models can sterilize most of these devices, although
cycle time may be required.

items to be sterilized are placed in the sterilization
the door is closed and the gas in the chamber is
d (Fig. 34.16). Moisture remaining on or in the objects
mber will make it difficult to achieve the recommended
and the cycle will abort (23,159). Filtered air is then
d to restore atmospheric pressure. This is the

a (vacuum, preconditioning) phase.

e 34.15 Once the hydrogen peroxide cassette has

laced in the sterilizer, it is automatically
ced by the machine.

ber is again evacuated, and a small volume of aqueous
peroxide is injected from a cassette. The hydrogen
vaporizes and diffuses around the items to be sterilized
d period of time. This is the diffusion phase (Fig.
hen, a low-temperature plasma is generated by
radio frequency energy. This is the plasma phase.
e plasma phase, the temperature increases about

radio frequency is turned OFF, the free radicals lose
energy and recombine to form oxygen, water vapor,
nontoxic products. With some sterilizer models, this
s repeated with the exception of the preplasma stage.
cycle(s) has been completed, filtered air is introduced
hamber, displacing the vapor from the chamber and
through a device specially designed to decompose the
peroxide. This is the vent phase.

erature during the whole cycle does not exceed 50ยฐC.
time varies with the sterilizer model. Different models
rent sizes, shapes, numbers of shelves, and number of
stages. A chemical indicator should be included in each
a biological indicator used at least once a week

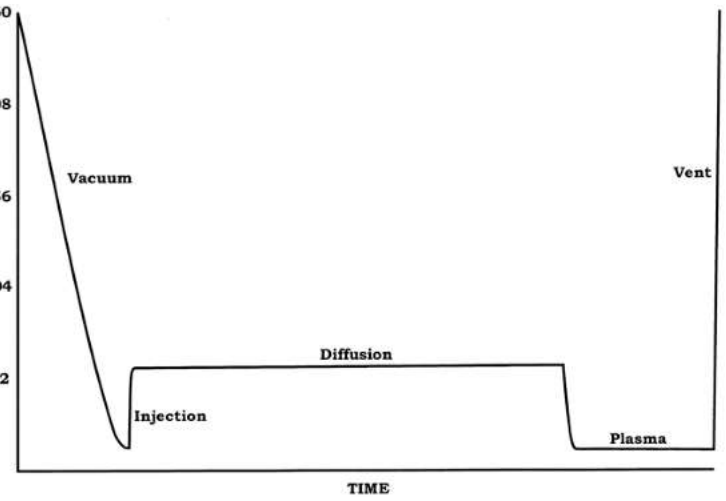
ma is an effective sterilization process. It can be used
eat-labile and moisture-sensitive items with the
of cellulosic materials (e.g., cotton, linens, paper),
liquids, implants, and devices containing long, narrow,
lumens. It produces less effect on metal items than
rilization. It is compatible with ceramics, silica, glass,
e range of plastics including polyethylene,
lene, PVC, silicones, and fluorinated silicones. It can
with a variety of hinged and non-hinged instruments,
ith lumens (not dead ended), electric and fiberoptic
atteries, and rigid endoscopes. It can sterilize stainless
ens that are 1 mm or larger and no longer than 125
ns that are 2 mm or larger and no longer than 250 mm,
ns that are 3 mm or larger and no longer than 400 mm

sma sterilizer is simple to operate. It uses relatively
ntrations of the sterilizing agent, does not leave toxic
and has short processing times. There is no need for
r cool-down time. The sterilized products are dry and
ly available for use or can be stored for later use.
o need for cooling or aeration. There are no emissions
-products. The primary end products of the process
n and water.

orker exposure and environmental contamination are
vantages. No personnel or exhaust monitoring is
Results from monitoring around the sterilizer have
8-hour TWA concentration of 0.005 ppm hydrogen
105). The OSHA limit is 1 ppm. No water source,
r outside venting is required. Thus, it can be located in

ximity to the area where the instruments will be used. It oved around easily.

these are low-capacity sterilizers, the volume of processed per unit of time may be equivalent to that of acity EO sterilizers. In cost comparisons with other on technologies, plasma sterilization was less than EO but more expensive than steam 163).



e 34.16 Gas plasma sterilization cycle. (Redrawn from a figure in ture of low-temperature sterilization technology in healthcare. A able discussion, April 28, 1995.)

m has a number of disadvantages. These include the e of the sterilizing chamber. Cellulose materials, paper, wders, liquids, and implants cannot be processed. ith a dead-end or a lumen 400 mL or longer cannot be without a special adaptor. Penetration is not as good O (164). The sterilization process is impaired when salt is present (156,165,166). Devices that are to be must be able to withstand a vacuum. Items whose rmits the surfaces to collapse onto each other (e.g., uld not be processed unless some means is used to surfaces separated. This process requires special e.g., indicators, trays, wraps) that are compatible with m. It may also require modification of some wrapping ing techniques.

gram for Anesthesia Equipment

al Considerations

o are concerned with anesthesia equipment find es faced with a dilemma as to how much time, effort, y should be expended to prevent infection ion. With increased pressure to hold down costs, the

n to do less may be strong. Proponents for more measures argue as follows:

es of cross contamination caused by anesthesia and piratory equipment have been reported ,168,169,170,171,172,173,174).

risk of cross contamination may be greater than is erally believed. The lack of documentation of many ocomial infections secondary to anesthetic practice may ect a long incubation period, difficulty in pinpointing the ce of infection, or inadequate follow-up (175,176,177). sthesia interferes with ciliary and mucous activity, and ery can impair the patient's ability to cough and the deeply, so patients are more likely to develop piratory infections than the normal population. sthesia care providers often care for unocompromised patients, and these patients may be ble to protect themselves against what were once ght to be harmless organisms or insignificant ulums.

ough there is general agreement that sterilization or -level disinfection of equipment is essential after use a patient having a respiratory or bloodborne infection, impossible to identify all of these patients.

n if the incidence of infections resulting from anesthesia aratus is low, the cost of a single such

ction in terms of mortality, morbidity, and resource enditure is high.

od contamination of anesthesia equipment surfaces is mon (178). Visual inspection is not a reliable means detecting blood.

s for Disease Control and Prevention ines

has published guidelines on how to prevent or control al infections based on a classification of instruments items by the risk of infection involved (68).

l Items

lude vascular and regional block needles and . These items must be sterile, because they bear a high ection if they are contaminated.

ritical Items

al items do not pierce mucous membranes. Equipment nto this category includes endoscopes; laryngoscope eusable rectal, nasopharyngeal, and esophageal ure probes; face masks; oral and nasal airways; ion bags; breathing tubes and connectors; oxygen sophageal stethoscopes; and tracheal and double- es. Ideally, semicritical items should be sterile. high-level disinfection is an acceptable standard of n sterilization is not practical.

tical Items

l items come into contact with intact skin. Items in this include stethoscopes (not esophageal); blood pressure tubing; arm boards; pulse oximeter sensors and ectrocardiogram (ECG) cables and electrodes; reusable erature probes; temperature monitor cables; head ood warmers; carbon dioxide absorber assemblies; for oxygen sensors; and the exteriors of the anesthesia ventilator, humidifiers, scavenging system, ion bags, intravenous fluid pumps, monitors, and t carts. Since intact skin normally acts as an effective most microorganisms, these items need only cleaning y intermediate- or low-level disinfection.

berts add another categoryÎ€"-environmental surfaces e include surfaces that do not ordinarily come into ntact with the patient, but if they do, it is only with intact se surfaces may potentially contribute to secondary tamination by health care workers or medical ts that subsequently come into contact with patients. faces can be further divided into *medical equipment* such as adjustment knobs or handles and *housekeeping* such as floors, walls, and windowsills.

s Influencing Cleaning Procedures

agent or procedure is adequate for all purposes. hat should be considered in the selection include the microbiologic inaction required for the particular e nature and physical composition of the device, and nd ease of using a particular procedure. Costs can be to direct and indirect costs (179). Direct costs include g (cleaning, sterilization packaging), purchasing (initial tallation, shipping), repair, replacement, labor, and Indirect costs include infection control (employee tion and education), liability (compensation, insurance, atory compliance), administration (procedure writing), evenue (processing difficulties, product failures, and delays).

bility for anesthesia equipment decontamination should in one individual who devises and administers a nsive program. This person should be a member of the 's infection control committee. An infection control t documents procedures to prevent transmission of agents to patients and personnel and that is approved ection control committee should be in place for a (180,181). It is imperative that equipment cleaning fection or sterilization be performed by conscientious, ed individuals who understand standard precautions. actor necessary for a successful decontamination s surveillance to check that techniques are adequate. elines do not recommend routine cultures. Cultures e taken only if a problem becomes evident.

g system should be in place to enable reusable ts to be traced to an individual patient in the event of a incidentÎ€ (e.g., failure of the decontamination process e being used on a patient with unsuspected CJD)

rthermore, some anesthetic equipment (e.g., laryngeal
um elastic bougies) should only be reprocessed a finite
f times, so this must be documented.

now that an effective filter at the patient port will
e breathing system and environment from
ation (182,183,184,185). An additional benefit is that it
umidify the inspired gases and lowers the humidity that
idestream monitors. However, the efficacy of filters in
patient cross infection is unproven. The Association of
tists of Great Britain and Ireland and the Australian and
and College of Anaesthetists have recommended that a
aced at the patient port for all adult patients
188), while the ASA concluded that there was
nt clinical outcome data to recommend routine use (2).
when a patient with a respiratory infection must be
alational

a, a filter should be used. Filters are discussed in
. Choosing the proper filter is tricky, because the
ions are difficult to interpret. Filters are more effective
ting bacterial than viral transmission.

en suggested that a filter is used with each patient and,
-saving measure, the anesthesia circuit is reused (189).
not address outer surface contamination that may
n breathing circuits that are not changed between
190). The debate about using filters and reusing the
system is not resolved at this time (191).

ment Choice

e equipment may be for ‘€single use‘€ or ‘€single
se‘€ (181,192,193,194,195). Single use indicates that
facturer intends for the item to be used only once on an
patient and then discarded. Single patient use
that the manufacturer advises that the item may be
e than once on the same patient.

artments have struck a balance between disposable and
tems. This balance should be periodically reassessed
changing technologies, costs, and waste management
Most departments keep at least some disposable items
for use with known infected cases. Disposables ensure
atient will always receive a sterile or clean item, and
o need for decontamination after use. Among the
ages is the need to keep a large inventory and an
n the waste generated by a facility.

lations require manufacturers of new or redesigned
evices labeled as reusable to provide written
ns for cleaning, decontamination, and, if appropriate,
on or sterilization. A reusable device often requires
ply, cleaning, drying, reassembly, repackaging, and
on or sterilization before reuse. While equipment is
aned, it cannot be used. This may necessitate a larger
There is a limited life span for reusable equipment.

cessing of disposable equipment is a controversial

96,197,198,199,200,201,202,203). In an effort to
sts, some health care facilities have been or have
d reusing single-use devices (204,205). Third-party
ors are available. In some cases, their reprocessing
lower than reprocessing at the health care facility. The
ires institutions that reprocess single-use devices to
same regulatory requirements as the original
urer of the product (206). This shifts the liability for
afety and effectiveness from the manufacturer to the
g the reprocessing (180). The ASA Task Force on
Control does not recommend reuse of disposable
t (207).

he controversy related to reuse of single-use devices
erned expensive items such as cardiac catheters. Pulse
sensors have been recycled (208). Successful
ing of Combitubes has been reported (209).

h care facility must formulate a policy to ensure the
s, physical integrity, and functionality of the device
ocessing. It is recommended that an interdisciplinary
e within each institution be developed to assess
o reprocess and reuse any device labeled single use
able. Both the efficacy of the reprocessing procedure
kelihood that the device will function as intended after
ing must be considered (197,204,210,211,212).

perative Considerations

a providers should always work from a clean surface.
rt of a case, only those articles that are likely to be
uld be placed there. Clean and dirty areas need to be
ed and equipment placed in the proper location. Since
e used during parts of the procedure where the risk of
ith blood or body fluid is greatest, they can become
ated, and this contamination can be transferred to
t. Any reusable item that is touched with a dirty glove
placed in the container for dirty equipment. This may
ater with detergent to prevent secretions or blood from
.

pment such as laryngoscope blades can be isolated by
them in a glove or the packaging from another item
the end of the case, the receptacle for dirty equipment
taken to the decontamination area. Used disposable
uld be discarded in suitable containers.

other body fluids on equipment or environmental
should be removed with water and detergent followed
amination using an intermediate-level disinfectant. A
100 dilution of 5.25% sodium hypochlorite has been
nded by the CDC for cleaning blood spills.

IA, and CDC guidelines state that syringes are single-
ems (214). Once a syringe has been connected to or
used to enter a patient's intravenous infusion, the
nd needle are considered contaminated, because blood
backed up into the tubing. Syringes should not be
dminister medication to multiple patients even if the
changed. Unfortunately, some anesthesia providers
inges on more than one patient (177,215,216,217).

solutions represent a potential source of transmissible
e infections (174,216,218,219,220).

nesthesia Work Area

thesia work area is usually the site where cleaning and
cedures are performed unless the equipment goes
a central reprocessing area.

es include disassembly, cleaning, disinfection, and
on. How much is done in the anesthesia workroom will
n how much can be carried out by the operating room
service department for the entire facility. Even if most
cedures are performed in another area, it may be
to disassemble dirty items in the anesthesia workroom,
gross soil and rendering them safe for handling prior to

uipment should be transported on dedicated carts or
al conveyances that are clearly marked to indicate that
are contaminated. These should be placed in a
d area for timely transport to the central processing
nt or the reprocessing area in the operating room. A
soiled cart lift from the operating room to the central
partment is recommended if they are on different

cessing area should have adequate space for the
procedures. It may be desirable to have a machine to
taminated items. Sinks should be large enough that
ns will fit into them and have attached counters on
ed and clean items can be placed separately. There
enough sinks to accommodate concurrent soaking,
and rinsing. Racks for drying will be needed.

deration of Individual Items

e of decontamination method will depend on a number
, including the nature of the contamination; the time
or processing; the heat, pressure, moisture, and
tolerance of the item; the availability of processing
t; and the risks associated with the decontamination
81). The manufacturer's instructions should be studied
ved carefully.

nesia Carts

a carts are used as a repository for equipment and
ntainers that hold drugs, syringes, needles, and such
cleanable. Attention should be paid to how equipment
in the drawers. For instance, a blood pressure cuff that
n several patients with no attempt to decontaminate it
cases should not be placed in the same drawer as
r masks that are not kept in sterile containers, but the
be placed in a drawer containing items such as suction
and syringes that are kept in disposable wrappers.
t that is not kept sterile should be placed in drawers
ess frequently opened, that is, not in the same drawer
ntly used drugs. The top surface should be cleaned of
terial between cases and at the conclusion of the
and disinfected with a germicide (8). A clean covering

placed on the top of the cart at the start of each case. urfaces should be cleaned at the end of the workday or obvious contamination. At least once a month, all t should be removed and the drawers and containers then wiped or sprayed with a germicide.

ylinders

ders are transported to the facility in open trucks and ently stored outside. Before taking a tank into the room suite, the wrapper, if present, should be The cylinder should be washed with water and and wiped or sprayed with a germicide. After placing er on the anesthesia machine, it should be considered e machine and treated accordingly.

hesia Machines

principles apply to cleaning anesthesia machines as to e top surface should be supplied with a clean cover for e. The machine should be cleaned between cases and d of the workday, then sprayed or wiped with a . Care should be taken not to get liquid in the vaporizer nels. Particular attention should be paid to frequently os. Equipment should be removed from drawers and the leaned and disinfected regularly.

hesia Ventilators

de of the ventilator should be treated the same as the f an anesthesia machine. Many bellows and tubings can ed by using EO. An important feature of the newer n of anesthesia ventilators is that most parts that come ct with respiratory gases can be easily removed and toclaved (Fig. 34.17). The manufacturer's ndations should be followed.

ectional Valves, the Adjustable re-limiting Valve, and Water Traps

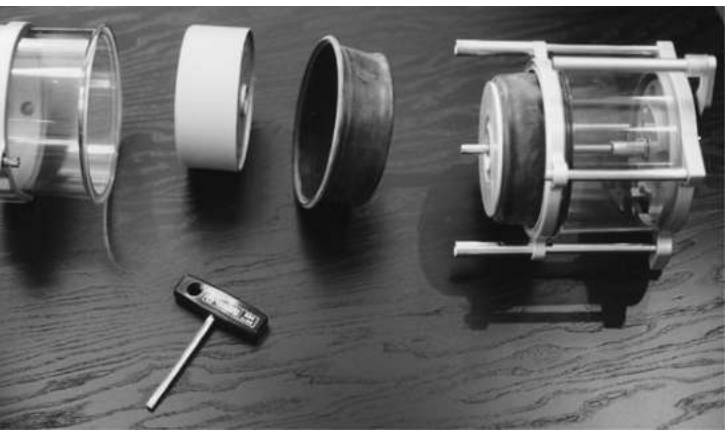
de of APL and unidirectional valves should be cleaned fected periodically. Unidirectional valves are usually assembled and cleaned by wiping the disc, the inside of c dome, and the valve seat with alcohol or a detergent. L valves may be autoclaved, and some can be ed (221). Using glutaraldehyde on APL valves may ckiness and increase the opening pressure (222). Water uld be cleaned and disinfected periodically and water is visible (223).

bers

oxide absorbent is a somewhat effective filter, and uggest that patients rarely contaminate it with high bacteria (184,224,225). The

urer's instructions should be consulted with respect to ply, cleaning, and disinfection. Many of the newer a workstations have absorber assemblies that can be assembled and steam autoclaved (Fig. 34.18). should be cleaned when the absorbent is changed,

cular attention to screens, as they are susceptible to
n. Some canisters can be steam autoclaved, and some
erilized using EO. Others can be disinfected by
in a liquid such as glutaraldehyde.



e 34.17 Drager Divan ventilator that is disassembled for steam aving.

sorbers use one or more disposable plastic receptacles.
smaller than those used in older absorbers and are
more frequently. Since they are disposable, they do not
e cleaned. The user manual should be checked to
if the connections to the breathing system need
eaning.

voir Bag

nstitutions, reservoir bags are supplied with the
e breathing tubes as part of a set, so they do not need
Reusable reservoir bags should be cleaned and then
or subjected to high-level disinfection. Bags can be
anually or in an automatic washing machine. EO can
o sterilize the bag. Aeration times should be carefully
and the bag filled and emptied a few times before use.
gs may be pasteurized, although this will result in
eterioration. Chemical disinfection can be used. The
be filled with liquid to remove air pockets.

ing Tubings

ave shown that corrugated tubing is contaminated after
cially at the end closest to the patient. Water commonly
s in the expiratory tubing. If the tubing is lifted up, this
y run down into the airway or the absorber, reservoir
entilator. These tubes should periodically be drained
n the patient and the condensate discarded (2).

e tubings are widely used today. These tubings are
upplied clean but not sterile. When it is necessary to
e breathing tubes in the sterile field, it is important to
ain that they are sterile.

cost of disposable tubings makes their use attractive,
ng the cost and difficulty of cleaning and disinfecting
tubings. Reusable breathing tubings should be cleaned
sterilized or subjected to high-level disinfection (226).
uld be rinsed soon after use to prevent drying. They
be soaked in a container that contains water and
. The long length and corrugations preclude a brush
g effective in cleaning. Ultrasonic cleaning can be used
e debris. A washing machine may be used. After
the tubings should be thoroughly dried unless they are
o pasteurization. Special tube dryers are available (Fig.

ation can be used for corrugated tubings. The Y-piece
removed beforehand; otherwise, a loose fit may result.

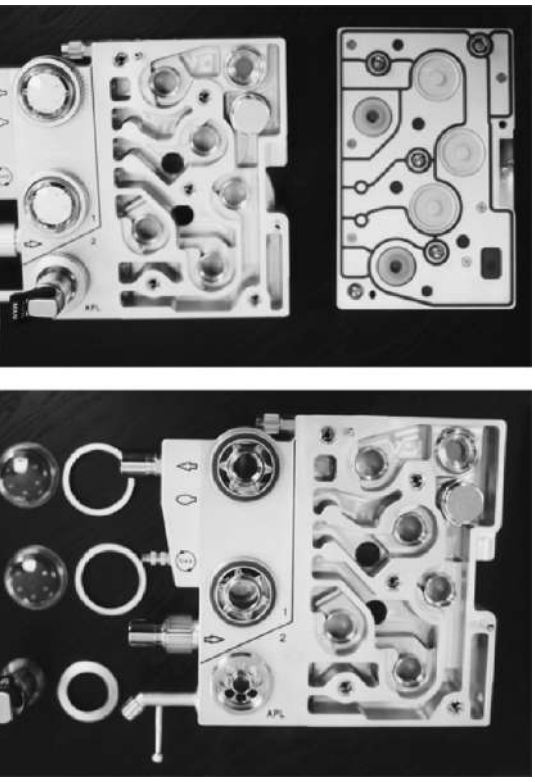
disinfection can be carried out by using an automatic
machine or by immersion in a liquid agent. It is
that the tube be inserted vertically, making certain that
on the inside and that there are no air pockets. One
nd that machine-assisted chemical disinfection with
hyde was superior to machine-assisted pasteurization
s (227).

e

ece is contaminated in a high percentage of cases. It
postulated that a contaminated Y-piece may have
atient-to-patient transmission of hepatitis C virus (HCV)
se (169). Disposable Y-pieces that are permanently
o disposable tubings are commonly used.

e Y-piece should be cleaned and sterilized or subjected
vel disinfection (226). After use,

be removed from the corrugated tubings and rinsed. It
en be soaked in a solution of water and detergent, then
manually or placed in a washing machine. If chemical
on or EO sterilization is to be used, it should be
y dried. Y-pieces may be pasteurized, immersed in
nts, or sterilized by using EO or plasma sterilization.



e 34.18 A: Absorber assembly that is partly embled. **B:** The APL and unidirectional valves so disassembled. The assembly can now be sterilized.

son Systems

Mapleson systems should be disassembled and the nts cleaned. Metal components can undergo ng. Rubber and plastic parts can undergo gas or plasma on or a liquid chemical agent may be used. In many sposable tubings are more cost-effective.

and Lack coaxial circuits present problems with because of the central tubing. It is best to use e circuits.

ors

that are used near the patient are contaminated in a entage of cases. After use, they should be rinsed and ed in a solution of detergent and water. They may be anually or in a washing machine. Rubber and plastic may be sterilized with EO, plasma sterilization, or in a h as glutaraldehyde. Metal adaptors may be autoclaved rized.

nging Equipment

tory method of treating scavenging equipment is to

device in a detergent solution monthly and to change
that connect the device to the breathing system and
at the same time (221). Lint may accumulate in the air
ves on closed scavenging interfaces. These valves
removed and cleaned frequently.

lasks

ks are among the most heavily contaminated pieces of
t. Because of their proximity to the patient, infection
ion is a definite possibility. For obviously contaminated
sposable masks should be used.

hould be practiced when using face masks. A face
uld not be allowed to drop onto the floor or be exposed
s contamination. After use, the mask should be kept
patient's head or with the dirty equipment. It should not
d to contaminate clean equipment.

face masks should be cleaned then sterilized or
to high-level disinfection. Immediately after use, the
should be removed and the mask rinsed, then soaked
bed. It may be cleaned automatically in a washing
Masks should always be thoroughly rinsed and dried.

sterilization, the mask can be kept sterile for long
f time. Aeration must be adequate; otherwise, facial
y result. Most automatic EO sterilizers employ a
t least once during the sterilization cycle. This vacuum
e the pneumatic cushion on the mask to be damaged.
be prevented by removing the plug that seals the
r by using a sterilizer that does not have a vacuum

toclaving is sometimes used for face masks. As with
zation, it involves a vacuum phase that will damage the
ushion, so the plug should be removed beforehand.
ation has been used for face masks.

emical agents are often used to disinfect or sterilize
ks. Thorough rinsing is important to remove residual
acks in the mask cushion can allow liquid agent to enter
ce. When placed on a patient's face, the liquid can be
out, possibly into the eyes.

Straps

head straps should be subjected to cleaning with a
, then soaked in a disinfectant solution or sterilized
or plasma sterilization.

rs

hould be treated as clean objects and not allowed to
the floor. Most airways are now disposable. They
placed in a suitable container.

as possible after use, reusable airways should be rinsed
water, then placed in a solution of water and detergent.
be washed manually or in a machine. They should be
y rinsed to remove residual detergent.

ation, liquid chemical disinfection, and EO and plasma
on have been used for airways. Rubber airways may be
d, but this will shorten their useful life.

Laryngoscopes

e laryngoscopes are discussed in Chapter 18. Either
or the blade and handle may be disposable (228).

ation of rigid laryngoscope blades and handles is
and there are reported cases of cross infection arising
aminated laryngoscopes
231,232,233,234,235,236,237,238).

copes should be stored under clean conditions.
e covers that fit over the handle and/or blade are
(239,240,241) (Fig. 34.19).

the handle and blade are contaminated and should not
on a clean surface. The glove that the operator is
may be inverted over the blade and handle to prevent
contamination (242,243).

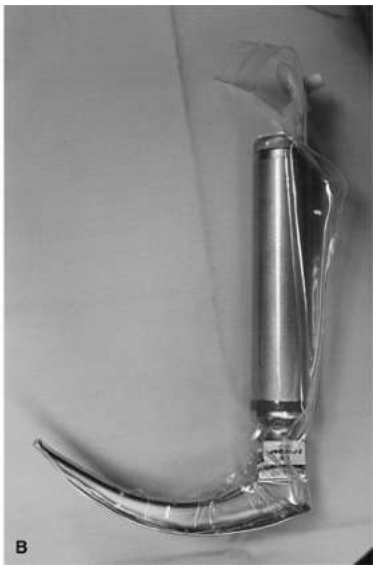
no consensus on what constitutes adequate blade or
ocessing, and the methods employed range from
l cleaning to sterilization (24,244,245,246). If prions
ly contaminant, disposable blades should be used, if
238).

the outside of the handle should first be wiped clean
r and detergent, then with alcohol. The batteries (and
nber, if present) must be removed prior to disinfection
ation unless the handle is designed to be waterproof.
ries must be removed if the method of sterilization
a vacuum cycle, pressure, or heat. After the batteries
ved, the handle can be sterilized by using steam,
r gas sterilization.

as possible after use, the blade should be rinsed, then
in water and an enzymatic detergent. It should be
ently but thoroughly by using a soft brush, with
attention to the area around the bulb or light bundle.
is often inadequate (24,232,233). Ultrasonic cleaning
not recommended. After cleaning, the blade should be
d dried.

ay be sterilized with EO, steam, plasma, or treated with
micals. There is one reported case in which tongue
was thought to be caused by a reaction to
hyde that was used on the laryngoscope blade (247).
s system can be used (248). EO is appropriate for most
rovided a temperature of 180ยฐF and pressure of 8
er square inch are not exceeded. No aeration is
Some blades can be sterilized by using steam. Flash
on is not recommended.

ng fiber-optic blades may cause detrimental effects to
that transfer light (64,249,250). Fiber-optic blades
t be immersed in cold water after autoclaving, as the
c bundles may crack.



e 34.19 Disposable laryngoscope covers. **A:** Covering for blade Picture courtesy of Blue Ridge Medical, Inc.) **B:** Covering for both and handle.

e Endoscopes

es are semicritical devices that carry a real risk that may be transmitted to patients
08,251,252,253,254,255,256,257,258,259,260,261,262,263,264,265,266,267,268,269,270,271,272,273,274,275,276,277,278,279,280,281,282,283,284,285,286,287,28
fections have also been reported
292,293,294,295,296,297,298,299,300,301,302,303,304).

oscopes that are submersible should be used.
e suction valves may help to reduce the risk of cross (251,266,268). A fiber-optic endoscope should be a clean area with the distal tip protected.

ope is complex, fragile, and heat-sensitive, which difficult to clean and disinfect or sterilize. It may be ave it decontaminated in an endoscopy unit. Pressure) testing should be performed before immersion to tly damage that can occur during the cleaning process ecial leakage testers are available for this purpose. If a tected, the endoscope should be removed from service anufacturer consulted.

ely after being removed from the patient, the exterior of cope should be wiped with a disinfectant. The e should not be squeezed tightly (257). All channels flushed with water and/or an enzymatic detergent. It is that the enzymatic solution is properly diluted; , the endoscope may be damaged (257).

testing, the fiberscope should be immersed in an detergent solution. It is important to place a water-cap over the video connector before submersion (257). els should be filled with the solution and allowed to he time stated on the label (usually 2 to 5 minutes).

scope should then be cleaned. Special cleaning devices
e inserted into the channels are available. Short
hould be used to gradually introduce the brush. If
t resistance is felt, one should proceed from the other
rather than force the brush through a blocked channel.
ing device cannot be passed easily through a channel,
should be sent for repair. The solution should be
through all channels until they are free of debris.
g fluid and air alternately removes more debris from
an suctioning only fluid (101). Special kits to check for
idue in the channel are available.

cleaning, the fiberscope and all of its channels should
ghly rinsed with sterile water or rinsed with tap water
hol. Tap water rinsing that is not followed by alcohol
s been linked to contamination (281). Endoscopes
hung vertically to allow any remaining fluid to drain
insertion tube (101).

cleaning, fiberscopes should be sterilized or receive
disinfection. Current data suggest that high-level
on provides the same degree of safety as sterilization
e scope is totally immersible, chemical disinfection can
All lumens and/or channels must be filled.
ehyde, hydrogen peroxide, and OPA are effective
nts (101,120,305). After disinfection, the device should
ghly rinsed with sterile water, followed by 70% alcohol
e Steris system, using special adaptors for the lumens
0), consistently sterilizes fiberscopes, even with protein
n the narrow lumen (110,113,114,309,310).

d endoscope reprocessors that perform disinfection and
e available, but some have been implicated in
and pseudoinfections
276,277,278,292,293,294,295,296,306,307,308). All
reprocessing systems have filtration systems (261). It
nt that the filters are changed regularly. The scope
allowed to cool about 5 to 7 minutes after it has been
(257).

ization may also be used. It is effective but will keep
cope out of service for a long period of time. Some
lves can be autoclaved (266). Most fiberscopes have
at are too narrow and too long for plasma sterilization.

eve that stylets should be kept sterile because they are
side a sterile tracheal tube. Reusable gum elastic
re frequently contaminated (311,312,313,314). Sterile
e stylets are available (315), but they may not work as
ultiple-use ones (316).

s possible after use, the stylet should be rinsed and
ersed in water and disinfectant. Stylets, depending on
struction, may be autoclaved, gas or plasma sterilized,
with liquid chemicals. Of the liquid chemical agents,
nd glutaraldehyde are used most frequently. Peracetic
ydrogen peroxide can also be used. If EO is used for
on, no aeration time is required unless the stylet is in a

eal and Double-lumen Tubes and ctors

l or double-lumen tube is placed into an area of the is normally sterile. It should be kept free of ation until used. Disposable sterile tubes are available low cost that it usually is not cost-effective to use ones. The tube should be kept in its package until just e, and the patient end should not be touched. Studies hat tracheal tubes can be used for up to 28 days after ned but not removed from the package (317,318,319). s, stylets, and suction catheters for use with these uld be free from contamination. If possible, the tube t touch any part of the mouth or pharynx during

rcentage of tracheal tubes show contamination with er use (320). If the tube is reusable, secretions should ated from drying by rinsing and then soaking in a solution. Before immersion, the inflating tube should ed. The connector and any tape should be removed. should then be washed inside and out, taking care not he cuff on any sharp object. Tracheal tubes may also d in a washing machine.

should be rinsed thoroughly, making certain to flush . Thorough drying is important before chemical on or gas sterilization. Unless the tube is to be steam d or pasteurized, the connector should be reinserted ning.

opular method for sterilizing tracheal tubes. The end of ng tube should be open. With repeated gas on, rubber and some plastic tracheal tubes soften and easily. Spiral latex tracheal tubes should not be gas with a vacuum applied during the sterilizing cycle, as ause the latex layers to separate.

erilization has been used in the past for certain tracheal peated autoclaving makes them more likely to kink and decrease in the elasticity of the cuffs. Spiral embedded especially susceptible to damage from autoclaving. he newer tracheal tubes that are made of plastic will not the high temperatures involved in autoclaving.

emical disinfection has been used for tracheal tubes. ing tube should be closed during immersion to prevent on from entering the cuff. The tube will frequently float s to be held down with an object that does not distort it t the solution from reaching all surfaces. Thorough necessary after use of all chemical agents except Pseudomembranous laryngitis has been linked to on of tracheal tubes with glutaraldehyde.

n Catheters

atheters are disposable devices that are discarded after s used in a closed suction system (Chapter 3). A ated suction catheter that may still be needed for a hould be rinsed with sterile water and then returned to

ging after use, not placed under the mattress of the
room table or draped over the carbon dioxide
At the end of the case, it should be discarded.

glottic Airway Devices

% of laryngeal mask airways (LMAs) have been found to
ılt blood on them after use (320,321,322,323).

ve been no cases of disease transferred between
y reuse of a sterilized LMA reported (324).

e supraglottic airway devices are available (325). They
ore economical to use than reusable devices when the
leaning and sterilization are factored along with the
f reuses that a device will tolerate.

ufacturer's directions with regard to cleaning and
supraglottic airway devices should be consulted.
ne reusable supraglottic airway in a dilute (8% to 10%)
f bicarbonate before cleaning will help to dissolve
s (326). The inflation valve should not be exposed to
(327). The supraglottic airway should be cleaned in
arbonate or mild detergent solution until all visible
aterial is removed. A pipe-cleaner type brush should be
hrough the distal aperture(s). Studies show that
removal of proteins from an LMA is often not achieved
328,329,330,331). Ultrasonic cleaning may be more
than other methods of cleaning to remove
eous material from the most inaccessible areas of the
1). Supplementary cleaning with potassium
nate will significantly reduce the amount of protein
(331). The LMA should be rinsed with water and then

ng is the only recommended method of sterilization for
e LMA. Temperatures up to 134ยฐC (273ยฐF) may be
6,327). Higher temperatures can cause the tube to
rittle and fragment. It may be preferable to use a
without a vacuum phase (332). As much air as possible
removed from the cuff shortly before autoclaving
. Residual air will expand in the heat and may damage
valve, or pilot balloon (335). After sterilization, the
ould be left in its package until just prior to use (336).

emical agents should not be used on an LMA, as they
bed onto the silicone and can cause pharyngitis and
as well as shorten the life of the LMA (326,337). Gas
on must not be used.

ufacturer's instructions should be consulted for
ns on cleaning and sterilizing other reusable
ic devices.

Applicators

spray applicators are frequently contaminated
. Consideration should be given to using disposable
f a multidose applicator is used, the nozzle should be
nd disinfected after use.

citation Bags

tion bags have been implicated as the source of cross (339). Their relatively low cost probably makes the e ones cost-effective. The primary source of ation is the valve. This should be disassembled and nd, if possible, disinfected or sterilized after each use gular basis if dedicated to a single patient. The urer's instructions should be followed.

Pressure Cuffs, Tubing, and scopes

ssure cuffs are frequently contaminated with blood and reservoir of bacteria (178,340). Spraying cuffs with a sinfectant will reduce their bacterial load (340). covers for cuffs are available (341). The arm can be with soft cotton before the cuff is applied to prevent act. Reusable cuffs should be cleaned with a detergent d of the day and when visibly contaminated (2). disinfection or sterilization is advisable. Most cuffs can d after the bladder is removed. After drying, the cuff ubjected to gas sterilization or chemical disinfection. cuffs can be sterilized by using plasma sterilization.

oscope is a potential source for transmitting bacteria 344,345,346,347,348). Single-use covers are available ethoscopes can be washed with water and wiped with Earplugs can be cleaned with an alcohol-saturated .

Oximeter Probes and Cables

meter probes and cables are frequently contaminated d and organisms (178,349,350). Disposable probes may essed for reuse by pulse oximeter manufacturers and re institutions. Reprocessing may be cost-effective . Reusable probes and cables should be cleaned at the e day or when visibly contaminated by wiping with the cleaning solution recommended by the urer (2). Cables can be sterilized by using plasma on.

rature Monitors

ure sensors should be cleaned with a disinfectant after Special soak stations for rectal probes are available. rity of temperature sensors are disposable.

sophageal Echocardiography Probes

phageal echocardiography probes are easily damaged ey should be cleaned carefully and then soaked in nt. A soak station shown in Figure 34.20. One is for the disinfectant, and the second one is used for rinse. Fumes are drawn away from the operator and cial filter, where they are neutralized.

ated reprocessor for ultrasound probes that completes ection and rinse cycles in less than 8 minutes is It uses a fresh bottle of a

hyde-based disinfectant for each cycle. This is pierced
reprocessor, avoiding splashes and spills. A vapor
ent system adsorbs chemical vapors.

e 34.20 Soak station for transesophageal
ardiography probes.

al burn secondary to a probe that may not have been
rocessed has been reported (102).

hat do not contact the patient but are contacted by the
a provider's fingers (the pen used to record data, the
keyboard, telephone, nerve stimulators, infusion
etc.) should be considered sources of contamination. A
vice for a pen has been described (353). Computer
s can be covered with a plastic cover that can be
or cleaned.

levels of safety for medical equipment surfaces may be
by thorough cleaning followed by application of an
ate- or low-level germicide (8). Adequate safety levels
es can be achieved by maintaining them in a state of
s by using water and a detergent or a hospital-grade

nt/detergent that is designed for general housekeeping
. Only when there has been a significant spill of blood
otentially infectious body fluid should the added use of
ediate-level chemical disinfectant be necessary.

nting Occupational Infection

OSHA mandated universal precautions. These are now
andard precautions. These precautions require that
d other barrier protection are used when health care
perform tasks that may result in exposure to blood and
y fluids, secretions, excretions, non-intact skin, or
embranes (2,12,354). For patients with specific
, additional transmission-based precautions are
hese are designed to reduce the risk of airborne,
r contact transmission of pathogens. Annual
al programs on the use of precautions are required for
s. Unfortunately, noncompliance with these procedures
n.

rs

te barrier precautions including gloves, fluid-resistant
ce shields, eye protection, and gowns or lab coats
sed when contact with body fluids, mucous
es, or broken skin is possible (2,355,356). It is
to remove or change these barriers immediately after
efore touching uncontaminated items or going to
atient (178,216,357). The use of gloves can reduce
cks, percutaneous injuries, and surface contamination in
nesia workplace (358). It should be noted that glove
is compromised with each activity performed and
when adhesive tape is torn, unless adhesive-sparing
ng cream is used (359). Therefore, it is important that
nfection be performed immediately after removing
full-face disposable plastic shield is best for eye
. Goggles or prescription glasses are less adequate. It
noted that the edge of the face shield could be a
injury to the patient (360).

Hygiene

a personnel can harbor high bacterial counts on their
1,362,363). Hand hygiene should be performed after
lood or other body fluids, secretions, excretions,
embranes, broken skin, wound dressings, or
ated items; prior to and between patient contacts; and
er time when microorganisms might be transferred to
ents, staff, or environments. The use of gloves does
de the need for proper hand treatment. If the hands

y soiled, hand washing should be performed. If there is
soiling, rubbing with an alcohol-based gel or solution
stent activity is more convenient and effective
365,366). Some hand solution manufacturers
nd a soap-and-water hand wash after eight to ten
ve applications to remove residual and organic
ants. A disadvantage of alcohol-based products is that
lammable (367). However, a study published in 2003
fires attributable to hand sanitizers, and the National

ection Association now allows alcohol-based hand dispensers in corridors and other public areas, provided strictions are observed (368). If a dispenser is mounted ay, the corridor must be at least 6 feet wide. The can project up to 6 inches from the wall and must be above handrail height.

shing should be performed by first wetting the skin, then e soap or cleansing agent. Tepid water should be used. s should be vigorously rubbed together for at least 15 covering and generating friction on all surfaces, then y dried. When using an alcohol-based rub, rubbing continued until the hands are dry. If the hands dry in a minute, more of the waterless rub should be used. It nt to make certain that the rub is applied to all parts of Studies show that this is frequently not done (369).

nting Needlesticks

eous injury, especially a needlestick with a hollow associated with the risk of transmitting bloodborne (370,371,372,373). Used needles should not be bent, or broken by hand or otherwise manipulated by technique that involves directing the point toward any e body. If it is necessary to recap needles, a single- echnique in which the needle is not directed toward an ed hand or a mechanical protective device should be 74). Puncture-resistant sharps containers must be in all work locations and should be located as close as o where sharps are used (375).

wearing gloves results in a significant reduction in ck and percutaneous injuries (358). Double gloving reased protection (376,377). Double-glove systems that ored inner glove make it easier to detect glove ns (378).

reduce needlesticks have resulted in a variety of new (371,379). Protective devices such as shielded needles, lancets, and needleless intravenous line connectors an important role in preventing needlesticks. Straight hat are used to suture central venous access (CVA) onary artery (PA) catheters are associated with frequent The CDC recommends using curved, instrument-held edles (380).

ency Ventilation Devices

uscitation is performed, mouthpieces, resuscitation other ventilation devices should be used as an e to mouth-to-mouth ventilation.

nnel with Cutaneous Lesions

re workers with breaks in the skin or exudative lesions frain from direct patient contact and from handling are equipment unless the open area can be protected er that is impermeable to blood and body fluids (381). stigation suggested that two patients became infected from a health care worker with severe exudative on the hands (382).

ic Disease States

culosis

s of multidrug-resistant TB have heightened concern
socomial transmission (175,380,383,384,385,386,387).
ulosis is spread primarily via droplet nuclei. Because of
ll size, droplet nuclei remain suspended in air currents
spread over great distances. TB is less infective after
as begun.

ation should be given to designing one operating room
patients with TB. To prevent suspended infectious
rom leaving the operating room, the ideal operating
ld have an anteroom that has a negative pressure
he corridor and operating room (383).

on room is desirable. It should have negative pressure
rounding rooms, outside air exhaust, an anteroom to
airlock, and ultraviolet lights to kill *M. tuberculosis* in
droplets (383). The caregiver in this area will need to
quate supplies readily available so that it will not be
to make many trips into the main recovery area.

has published guidelines for preventing *M. tuberculosis*
ion in health care facilities, including the operating
e (383,385,388). Respiratory isolation is required for all
uspected or known to have active pulmonary TB until
osis has been ruled out or therapy has been initiated
be demonstrated that the individual is no longer
. The patient with TB should be placed in a room that
ive air pressure, 12 or more air changes per hour, and
s air directly to the outside or high-efficiency
e (HEPA) filtration of air prior to recirculation.
t light can be used as an adjunct

ion (385,387). A health care facility with an obstetrical
d have a TB isolation room that is properly equipped
rical care.

procedures should be delayed until the patient is no
ectious. A patient with TB who is undergoing surgery
transported to the operating room wearing a surgical
3). Individuals caring for the infected patient, including
nsporting the patient, should wear respiratory protection
at meet CDC criteria for filtration and fit (385,387).
hoscopes can be used for auscultation (389). Standard
asks are generally not suitable.

ating room should have an anteroom that provides some
from outside hallways and negative air pressure relative
ridor and other operating rooms (390). Traffic in the
opening and closing doors during surgery should be
he patient should be the last case of the day or should
procedure performed at a time when minimal personnel
nt (214). Signs should be placed on the operating room
minimize traffic. Unnecessary or overstocked equipment
removed from the room. A HEPA filter should be
tween the breathing system and the patient (383).
stanesthesia recovery, the patient should be placed in
room that meets the recommended standards for TB

rooms. Since most institutions do not have such an room in the surgical suite, an alternative is to utilize hesia care unit (PACU) personnel to provide tive care in the operating room or in the patient's room.

t that has been used for a patient with TB should be or undergo high-level disinfection. In general, culturing a equipment for the presence of tubercle bacilli is not

heir participation in procedures that might induce anesthesia providers are at risk of acquiring TB. The mmends periodic tuberculin screening of all health care with retesting on a regular basis (385). If a positive test ed, a chest radiograph should be obtained and phylaxis instituted, if needed.

borne Pathogens

B virus (HBV), hepatitis C virus (HCV), an human eficiency virus (HIV) can be transmitted through blood body fluids. Anesthesiologists have an increased risk rom HIV and viral hepatitis (391). The greatest risk of is a needlestick injury. Large-gauge, hollow-bore ith visible blood and deep penetration increase the risk e risk of infection after a percutaneous exposure to rying HBV, HCV, and HIV is 10% to 30%, 2% to 4%, respectively (175). Contaminated multidose vials have icated in nosocomial infections with HBV, HCV, and 392). A breach in procedure by any one person can tiple patients at risk.

ontaminated with blood from patients infected with a virus or HIV should be sterilized or undergo high-level on (68).

survive for a long time on inanimate objects (7). Fifty f surfaces from which hepatitis B antigen can be do not have visible blood contamination. Multiple ave shown that anesthesia providers are at risk for HBV. The primary strategy for preventing HBV infection zation with hepatitis B vaccine, which is recommended esthesia personnel who do not have immunity. OSHA s require employers to provide the hepatitis B vaccine if occupational exposure is expected.

ansmitted by respiratory secretions as well as blood nsfer of HCV from anesthesia personnel to patients nts to anesthesia providers has occurred 393). Transmittal has been attributed to reusing nd syringes (215,381).

ction is a major cause of chronic liver disease and lular cancer and poses a considerable risk for a personnel. It is more common in health care workers general population. At present, there is no vaccine to prevent infection, neither is there effective sure prophylaxis. Current recommendations from the ot suggest that HCV-infected health care personnel be from patient care duties as long as they follow strict chniques and standard precautions (394,395).

atively unstable in the environment and is rapidly
d by a wide range of chemical germicides, even those
lassified as low level. There is a case where HIV was
d from a patient to an anesthesiologist (396).

tfeldt-Jakob Disease

he of a group of neurodegenerative disorders caused by
1,397,398,399,400,401,402). It is one of a class of
known as transmissible spongiform encephalopathies
of the pathologic changes in the central nervous
hese diseases are characterized by incubation periods
om months to years and followed by a rapidly
ve dementia. The disease is invariably fatal once
ymptoms have appeared. Currently, there are no known
s to inhibit its progression or outcome. There is no
that health care workers are at increased occupational
JD.

very that prions can lurk in body organs long before
hibit signs of disease has the alarming implication that
se devices used on

ndividuals can transmit the disease. The extensive
icular involvement that is present in CJD raises the
that devices that come in contact with lymphoreticular
uch as the tonsils could become contaminated (398). It
recommended that laryngoscopes and supraglottic
sed on patients with suspected CJD should be
(235,244,399).

LE 34.3 Methods of Inactivation of Prions[a]

Effective Methods	*Ineffective Methods*
neration onged steam sterilization ยฐC, 1 to 4 hours) ers: 270ยฐF for 18 minutes prevacuum sterilizer or at ยฐF for 60 minutes in a ity sterilizer (402) um hydroxide (1N, 1 hour) um hypochlorite (1:10 tion) rietary phenolics cetic acid in Steris system sibly)	Glutaraldehyde Formaldehyde Hydrogen peroxide Chlorine dioxide Phenolics Iodophores Alcohols Dry heat Boiling Desiccation Freezing Ultraviolet, ionizing, and microwave radiation Normally recommended autoclave cycles Ethylene oxide Gas plasma

[a] method has currently been shown to be 100%
ctive against prions. From Antloga K,

zaros J, Malchesky PS, et al. Prion disease
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2.

e notoriously hardy and demonstrate resistance to
ethods of sterilization. Standard washing techniques
e concentration of prions in an exponential fashion, but
cycles are required to produce negligible levels (181).
and ineffective methods of inactivation are summarized
4.3. Devices that are difficult or impossible to clean
discarded (403).

tzfeldt-Jakob prion requires a unique decontamination
. The preferred treatment of contaminated instruments
ning is steam sterilization for at least 30 minutes at a
re of 132ยฐC (121ยฐC is ineffective). When a
m sterilizer is used, 18 minutes at between 134ยฐC and
as been found to be effective. Alternatively, items can
sed in a 1N sodium hydroxide solution for 1 hour at
perature and then steam sterilized at 121ยฐC for 30
5). Noncritical patient care items or surfaces may be
d with either bleach (up to 1:10 dilution) or 1N sodium
at room temperature for 15 minutes. It may be
to sacrifice some equipment after use on a patient at
nsmitting this disease (404,405).

e Acute Respiratory Syndrome

cute respiratory syndrome (SARS) is a viral disease
nsmitted by respiratory droplets or contact
408,409,410,411). Anesthesia providers are at high
use of frequent exposure to patients' respiratory
s. Traditional precautions may not afford adequate
when handling SARS patients.

possible, patients should have a private, negative-
room with at least 6 to 12 exchanges per hour. If this is
le, they should have a room with a HEPA filter.

approved, fit-tested N-95 or greater respirator should
when contact with patients is necessary. Goggles or a
d, a disposable gown and cap, and double gloves
worn by the anesthesia provider and discarded when
e patient's room.

gery is required, efforts should be made to limit
to personnel and other patients. In addition to
standard precautions, the anesthesia provider should
pirator. Double gloves are recommended. The outer
ld be removed after direct patient contact and before
equipment or furniture in other areas of the room.
ould be washed immediately after gloves are removed.

nces

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tions

llowing questions, answer

B, and C are correct

and C are correct

and D are correct

is correct

B, C, and D are correct.

rning the three levels of disinfection recognized by

High-level disinfection means that bacterial spores are d

Semicritical items can be treated with intermediate-level nfection

The Creutzfeldt-Jakob virus is killed with high-level nfection

ntermediate-level disinfection means that *M. erculosis* is killed

wer

tages of steam autoclaving include

t is highly effective

tems can be packaged beforehand

t is inexpensive

Absence of toxic residues

wer

s that affect the effectiveness of chemical ion include

Temperature

Use pattern

pH

Characteristics of the item to be disinfected

wer

s flammable in concentrations exceeding 5%

s not useful for items containing petroleum-based icant

s odorless

Should not be used on items that are wet

wer

ng is important as the first step because

Retained salts and organic soil can inactivate chemical micides

Even after sterilization residues can cause a patient ction

Soil can protect microorganisms during disinfection and ilization

Residues may interfere with the device function even r sterilization

wer

rning the classification of items according to the

Semicritical items include tracheal tubes

Blood pressure cuffs are noncritical items

High-level disinfection is acceptable for semicritical ns

Phenols are useful for semicritical items

wer

of the following statements are correct?

An antiseptic can be safely applied to living tissue

A disinfectant is a germicide to be used solely on nimate objects

A sanitizer is a low-level disinfectant with no claim for erculocidal activity

A sterilant/disinfectant is a germicide that is capable of ilization or high-level disinfection

wer

le of the FDA is to

Require new germicides to demonstrate 10^6 sterility

Regulate medical devices

Require testing of formulations for microbicidal potency, bility, and toxicity

Regulate liquid chemical germicides that are used to rocess medical instruments

wer

nctions of the CDC include

Approving germicides

Regulating germicides

Testing germicides

Recommending broad strategies to prevent transmission nfections in the health care environment

wer

ices and procedures to reprocess reusable devices n published by which organizations?

American Society of Anesthesiologists

Association of Operating Room Nurses

American Association of Nurse Anesthetists

Centers for Disease Control and Prevention

wer

ntages of pasteurization include

No toxic residues or films

Can be used for prepackaged items

Can be used for tracheal tubes and breathing tubes

High temperatures can be used

wer

vantage(s) of steam sterilization include

Adequate penetration into a pack may not occur with e packs

All spores may not be killed

Danger to processing personnel

nstrument damage

wer

raldehyde is effective against which classes of s?

Spores

Viruses

Fungi

Bacteria

wer

rds of glutaraldehyde exposure include

Skin irritation

Headaches

Asthmalike symptoms

Gastrointestinal upset

wer

h agent(s) is(are) sporicidal?

Quats

Alcohols

Phenolics

OPA

wer

vantages of liquid chemical disinfection include

Prepackaging is not possible

Lack of good method for validation

No guarantee of sterility

Not effective against HIV

wer

h of the following are killed by EO?

Viruses

Fungi

Bacteria

Spores

wer

h factors are important for proper EO sterilization?

Exposure time

Relative humidity

Gas concentration

Temperature

wer

**nt complications associated with contact with EO-
items include**

Laryngotracheal inflammation

Anaphylaxis

Hemolysis when EO is exposed to blood

Cancer

wer

ntages of EO sterilization include

tems can be prepackaged

A large amount of equipment can be sterilized at one e

t can be used for items that heat or moisture could nage

Short processing time

wer

vantages of EO sterilization include

Not useful for equipment with small lumens

Danger of fires and explosions in sterilizers

Damage to some very small equipment

More costly than other types of sterilization

wer

ntage to ꝏ-radiation include

Product may be prepackaged

Thermolabile equipment can be sterilized

No temperature rise during sterilization

t is useful for the average hospital

wer

ntages of plasma sterilization include

No worker exposure or environmental contamination

Lack of toxic residues

Compatible with ceramics, silica, glass, and many stics

Sterilized products are immediately available for use

wer

opriate barrier precautions include

Eye protection

Face shields

Fluid-resistant masks

Gloves

wer

niques that are designed to prevent needlesticks

Wearing gloves when starting an intravenous infusion

Disposing of used needles in a central location

Using protective devices over the needle

Recapping needles as soon as they are used by using

n hands

wer

n of the following are part of the CDC guidelines for patient with TB?

The patient should be in a room with positive-pressure tilation

Respiratory isolation is required until TB is ruled out

Ultraviolet light is not helpful

Personnel should wear special protection devices that approved by the CDC for filtration and fit

wer

n statements are true of HIV?

The risk of HIV infection after a hollow-bore needle k is 0.3%

The virus is relatively stable in the environment

HIV is relatively unstable in the environment and is dly inactivated by a wide range of chemical germicides

HIV-contaminated devices need only intermediate-level ontamination

wer

n statements are true of HBV?

The risk of contracting HBV after a needlestick is 10% 0%

Multidose vials have not been found to facilitate ocomial infections

Devices contaminated with blood with patients from HBV uire high-level decontamination

HBV survives only a short time on environmental aces

wer

n statements concerning CJD are true?

Sterilization requires steam at 134ยฐC to 138ยฐC

Laryngoscopes and LMAs that are exposed to an cted patient should be discarded

The incubation period can be months to years

Glutaraldehyde, formaldehyde, and phenolics are not ctive against prions

wer

Abbreviations

AAGBI
Association of Anaesthetists of Great Britain and Ireland

AAMI
Association for the Advancement of Medical Instrumentation

AANA
American Association of Nurse Anesthetists

AARK
Automated Anesthesia Record Keeper

ABC
Argon beam coagulator

ACG or AMG
Acceleromyography

AEC
Airway exchange catheter

AIDS
Acquired immunodeficiency syndrome

AIMS
Anesthesia Information Management System

AIS
Anesthesia Information System

AMA
American Medical Association

AMD
Airway Management Device

ANSI
American National Standards Institute

APIC
Association for Professionals in Infection Control and Epidemiology

APL

Adjustable pressure limiting

APSF
Anesthesia Patient Safety Foundation

ARDS
Adult respiratory distress syndrome

ASA
American Society of Anesthesiologists

ASATT
American Society of Anesthesia Technicians and Technologists

ASSE
American Society of Sanitary Engineering

ASTM
American Society for Testing and Materials

BAAM
Beck Airway Airflow Monitor

BP
Blood pressure

BPM
Breaths per minute

BTC
Board of Transport Commissioners

cmH_2O
Centimeters of water

CDC
Centers for Disease Control and Prevention

CDRH
Center for Device and Radiological Health

CFC
Chlorofluorocarbon

CGA
Compressed Gas Association

CO

Carbon monoxide

COHb
Carboxyhemoglobin

CPAP
Continuous positive airway pressure

CSA
Canadian Standards Association

CTC
Canadian Transport Commission

DBS
Double-burst stimulation

DISS
Diameter Index Safety System

DLT or DLET
Double-lumen tube

DOT
Department of Transportation

ECG or EKG
Electrocardiogram

ECRI
Emergency Care Research Institute

EDD
Esophageal detector device

EMG
Electromyography

EO or EtO
Ethylene oxide

EPA
Environmental Protection Agency

ETC
Esophageal Tracheal Combitube

ETLDA

Esophageal-tracheal double lumen airway

FDA
Food and Drug Administration

FV
Flow-Volume

HbCO
Carboxyhemoglobin

Hb F
Fetal Hemoglobin

HBV
Hepatitis B virus

HCF
Hydrochlorofluorocarbon

HCV
Hepatitis C virus

HEPA
High-efficiency particulate air

HIV
Human immunodeficiency virus

HME
Heat and moisture exchanger

HVLP
High-volume, low-pressure

Hz
Hertz

ICU
Intensive care unit

ICC
Interstate Commerce Commission

ID
Internal diameter

I:E

ratio of inspiratory time to expiratory time

ILA
Intubating laryngeal airway

ILM or ILMA
Intubating laryngeal mask

IMV
Intermittent mandatory ventilation

ISO
International Standards Organization

JCAHO
Joint Commission on the Accreditation of Healthcare Organizations

kPa
Kilopascal

KMG
Kinemyography

KTP
Potassium titanyl phosphate

LAN
Local area network

LASER
Light amplification by stimulated emission of radiation

LCD
Liquid crystal display

LED
Light-emitting diode

LITA
Laryngotracheal Instillation of Topical Anesthesia

LMA
Laryngeal mask airway

LT
Laryngeal Tube

LTA
Laryngeal Tracheal Anesthesia

MAC 1
minimum alveolar concentration of an agent needed to produce an anesthetizing effect in 50% of the population; 2, monitored anesthesia care.

mbar
Millibar

metHb
Methemoglobin

mm Hg
Millimeter of mercury

MMG
Mechanomyogram

MMV
Mandatory minute ventilation

MRI
Magnetic resonance imaging

NFPA
National Fire Protection Association

NIBP
*n*oninvasive blood pressure

NIOSH
National Institute for Occupational Safety and Health

NMB
Neuromuscular block

NPPV
Non-invasive positive pressure ventilation

OD
Outer diameter

OMV
Oxford miniature vaporizer

OPA

Orthophthalaldehyde

OSHA
Occupational Safety and Health Administration

PACS
Picture archiving and communication systems

PACU
Post anesthesia care unit

PCV
Pressure control ventilation

PEEP
Positive end-expiratory pressure

PEL
Permissible exposure limit

PLM
LMA-ProSeal

ppm
Parts per million.

psi
Pounds per square inch

psia
Pounds per square inch absolute.

psig
Pounds per square inch gauge

PSV
Pressure support ventilation

PTF
Post-tetanic facilitation

PTC
Post-tetanic count

PV
Pressure-Volume

PVC

Polyvinyl chloride

RAE
Ring-Adair-Elwin

RBS
Rendell-Baker-Soucek

RF
Radiofrequency

SARS
Severe acute respiratory syndrome

SIMV
Synchronized intermittent mandatory ventilation

SLIPA
Streamlined pharyngeal airway liner

SNOWMED
Systematized nomenclature of medicine

SPT
Skin-prick test

STEL
Short-term excursion limit.

TOF
Train of four

TOFR
Train-of-four ratio

TB
Tuberculosis

TC
Transport Canada

TOF
Train-of-four

TWA
Time-weighted average

UL

Underwriters Laboratories

UPS
Uninterruptible power supply

USP
U.S. Pharmacopoeia

VCV
Volume control ventilation