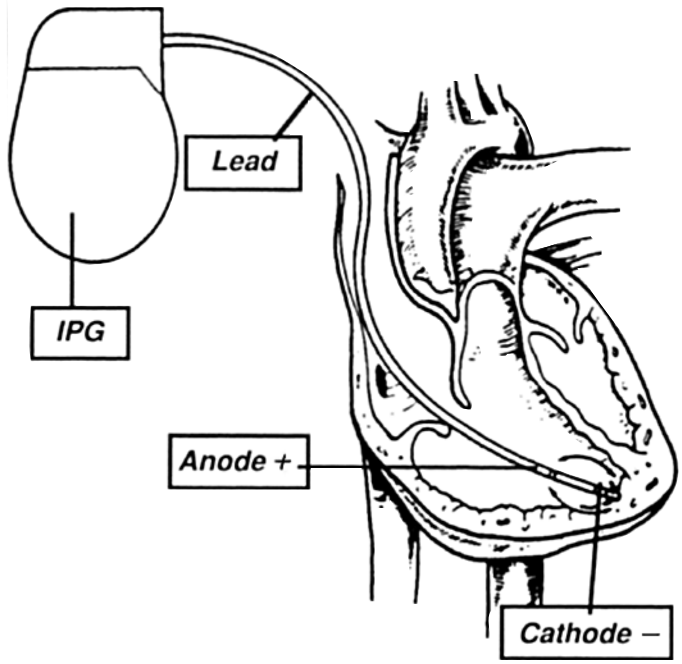
Electrical Concepts

Pacing Circuit



A pacing system forms an electrical circuit in the patient's body by combining with body tissues and fluid.

A pacing circuit consists of a power source, lead, cathode, anode, and body tissue. These form a conduction pathway along which electricity flows.

The pacemaker battery is the ***power source*** that, along with the circuitry, generates electrical impulses. The ***lead*** conductor wire carries the impulses to the heart. The ***cathode*** is an electrode with a negative charge that delivers the impulse to the myocardium. The ***anode*** is an electrode with a positive charge to which the impulse returns after stimulating the heart. ***Body tissue and fluids*** between the anode and cathode are part of the conduction pathway.

During pacing, an electrical impulse begins in the pacemaker battery, travels along the lead to the cathode, stimulates the heart, then returns through body tissue to the anode to complete the pacing circuit.

Notes

A pacing circuit is the path along which electricity flows. It consists of electrical components, body tissues and fluid.

Questions:

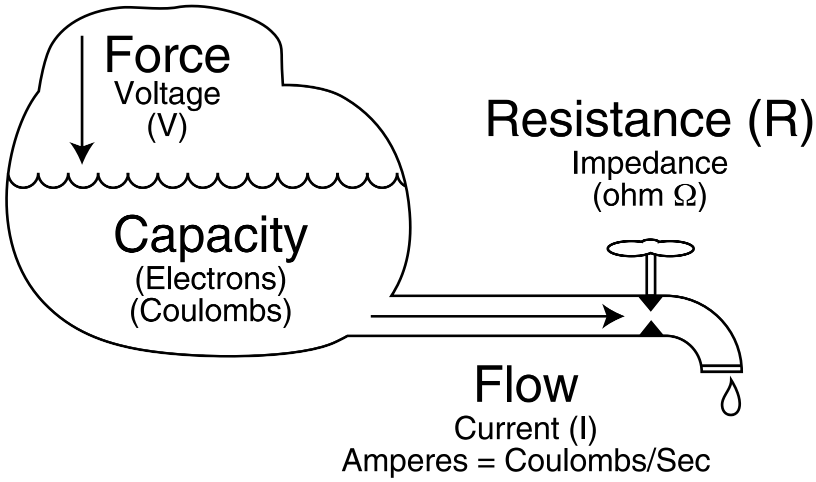
The ***energy*** for pacing is provided by the ______________.

The ***stimulating electrode*** is called a ______________.

An electrical impulse returns via ______________ to the anode.

Answers: battery / cathode / body tissue

Pacing Impulse



A pacing impulse has current, voltage, and impedance.

> ***Current (I)*** is the movement of electrons through an electrical circuit over time. It is measured in amperes (A). One ampere is equal to an electron flow rate of one ***coulomb*** per second. A ***coulomb*** is a unit of electrical charge.
>
> ***Voltage (V)*** is the force that causes current to flow. It is measured in volts (V). In a pacing system, voltage is referred to as ***amplitude*** and reflects the strength or intensity of a pacing pulse.
>
> ***Impedance (R)*** is the sum of all factors that resist the flow of current along the conduction pathway. It is measured in ohms (Ω). The main sources of resistance in a pacing circuit are the lead conductor, electrode, and the concentration of electrically-charged ions at the electrode-tissue interface (called polarization).

Notes

The interdependent characteristics of a pacing pulse are current, voltage, and impedance.

Questions:

The ***movement of electricity*** in a pacing circuit is the ____________.

The ***force that maintains current flow*** is the ____________.

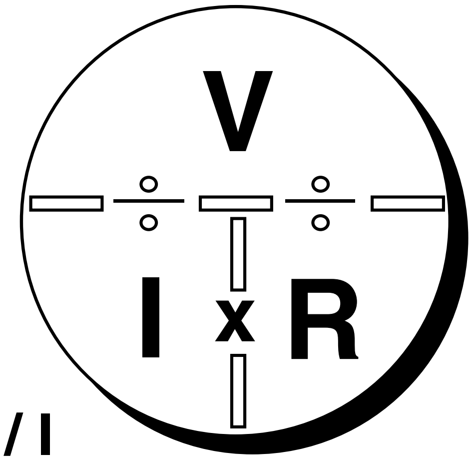
Resistance to current flow is ____________.

Answers: current / voltage / impedance

Ohm’s Law

$$\frac{V}{I \times R}$$

Voltage (V) = I x R
Current (I) = V / R
Impedance (R) = V / I



Ohm’s Law describes the relationship between voltage, current, and impedance.

> ***Ohm’s law*** is a fundamental principle of pacing technology. It is used to calculate the amount of current flowing through a pacing circuit:
>
> 5 V ÷ 500 Ω = 0.01 A (10 mA)
>
> - If the voltage is cut in half, the current flow is cut in half:
>
>   2.5 V ÷ 500 Ω = 0.005 A (5 mA)
>
> - If the impedance is doubled, the current flow is cut in half:
>
>   5 V ÷ 1000 Ω = 0.005 A (5 mA)
>
> Ohm’s law shows that if output voltage is decreased, current flow is decreased and if output voltage is held constant and impedance is increased, current flow is decreased. Voltage and impedance are important determinants of battery longevity.

Note: See Medtronic Pacing Glossary for definition of electrical terms (UC198900885I EN).

Notes

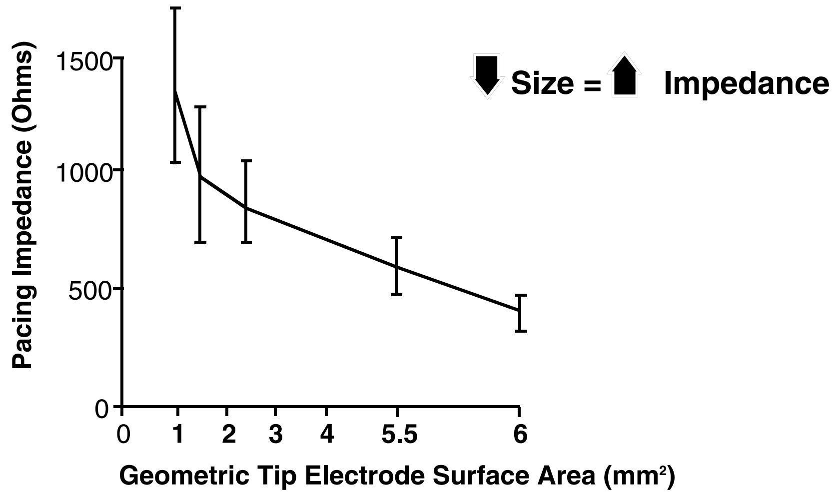
Ohm’s law shows that low voltage and high impedance are important for reducing battery current drain and extending pacemaker longevity.

Circle the correct answers:

Low (voltage, impedance) and high (voltage, impedance) decrease battery current drain.

Answers: voltage / impedance

Impedance



Electrode resistance improves pacing efficiency; lead conductor resistance and polarization do not.

Electrode (tissue) resistance is resistance to current flow from the electrode to the myocardium. This type of resistance concentrates the current and allows the delivery of a more intense pacing pulse. Electrode resistance, therefore, uses current efficiently.

Lead conductor resistance is resistance along the conductor wire. It produces a small loss of energy (voltage drop) to waste heat as the pacing pulse is conducted along the lead wire. Because lead conductor resistance does not contribute to myocardial stimulation, it is inefficient.

Polarization is resistance caused by the concentration of oppositely-charged ions at the electrode. It is an effect of electrical stimulation. The ions form a barrier that resists current flow during the time an electrical pulse is applied. Polarization results in an increased voltage requirement and is therefore not efficient.

Notes

Pacing impedance affects the characteristics of a pacing pulse and influences pacing efficiency.

Circle the correct answer:

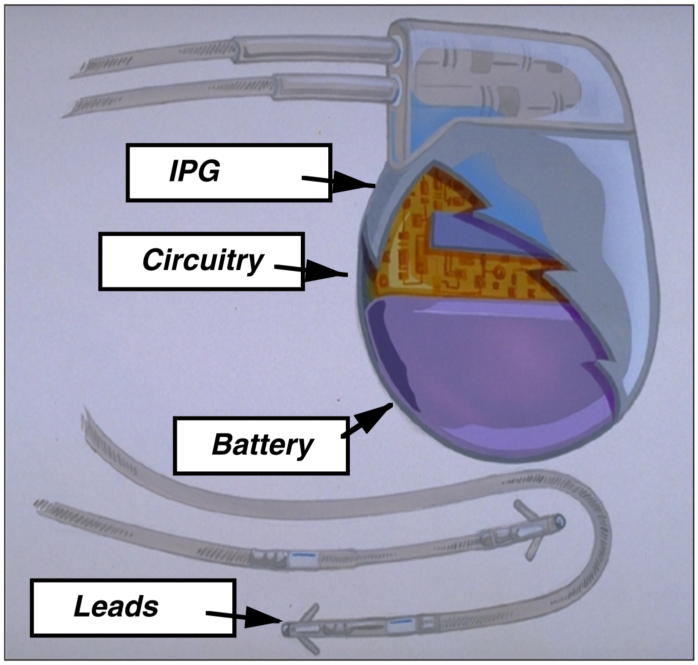
Electrode resistance (reduces, increases) pacing efficiency.

Polarization resistance (reduces, increases) pacing efficiency.

Answer: increases / reduces

Pacemaker Components

Basic System



The basic pacing system consists of an implantable pulse generator and one or two leads.

The ***implantable pulse generator (IPG)*** contains the battery and the output, sensing, and timing circuits that control pacemaker operations. Most IPGs have a telemetry coil for sending programming instructions and receiving diagnostic data. Many have sensors that measure indicators of exertion and use the results to change heart rate.

Leads are insulated conductor wires that deliver electrical impulses to the heart and return sensed electrical signals from the heart to the IPG. One end of the lead connects to the pulse generator and the other is in contact with cardiac tissue.

Notes

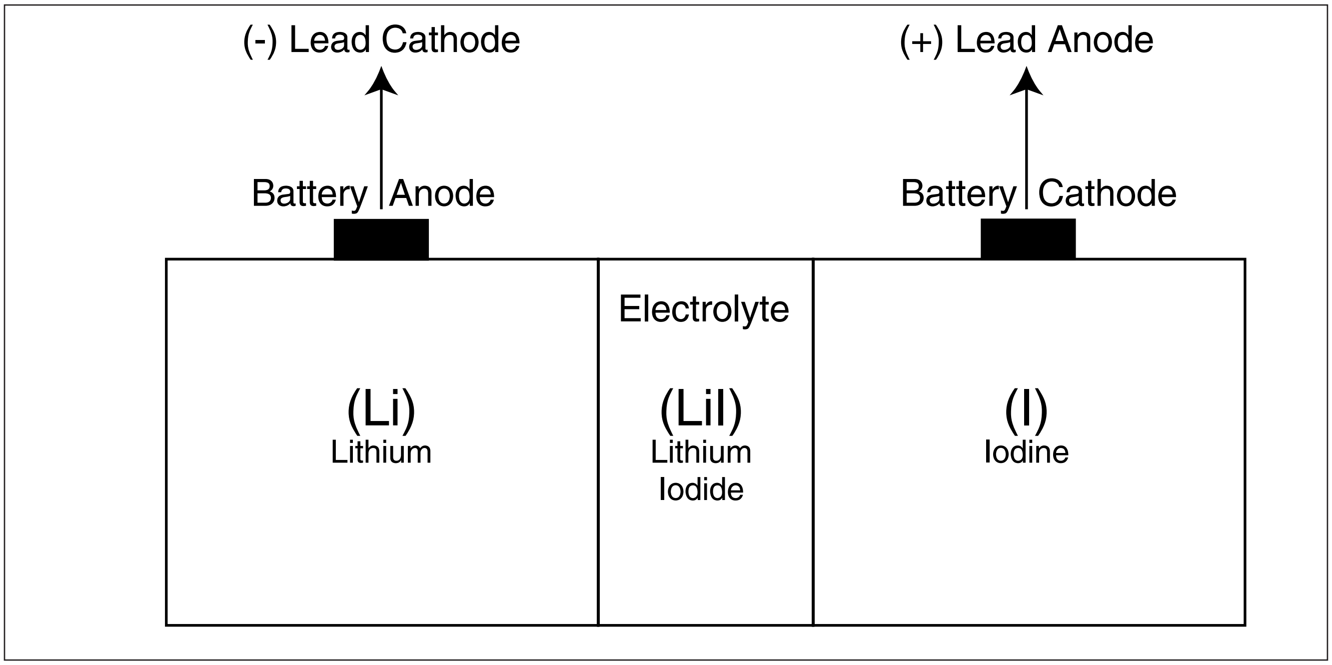
Questions:

Pacing operations are controlled by electronic ____________.

Electrical signals are transmitted between the IPG and heart tissue via ____________.

Answers: circuits / leads

Pacemaker Battery



Most pacemakers use lithium iodine batteries, which generate electricity through a chemical reaction between lithium and iodine.

Electricity in a ***lithium iodine battery*** is generated through a transfer of electrons from the anode to the cathode of the battery. Lithium is the anode and iodine is the cathode. The lithium ionizes (loses an electron) and reacts with iodine to form a layer of lithium iodide (LiI). Free electrons can't pass through the LiI and are left behind, creating a negative charge at the anode. If a conduction pathway (pacing circuit) exists, the free electrons are carried to the cathode, creating the electrical current used to pace the heart.

A lithium iodine battery has an initial open circuit voltage of 2.8 V and a predictably low self-discharge rate. This allows for anticipation of battery depletion (through battery impedance measurements) and provides time for scheduling pacemaker replacement.

Lithium iodine batteries can be hermetically sealed and are therefore resistant to corrosion. They also provide high volumetric energy density.

Notes

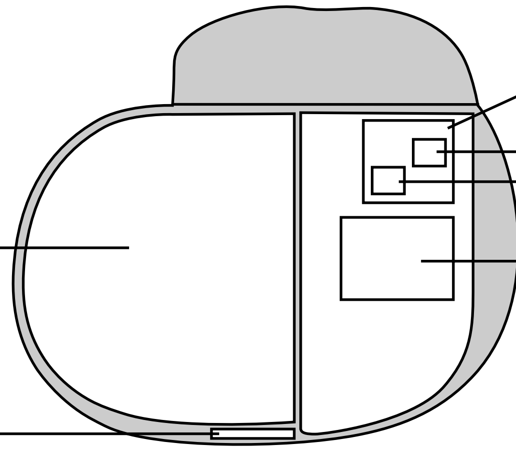
Most pacing systems use lithium iodine battery chemistry to power pacing functions.

True or False

The depletion status of a lithium iodine battery can be reliably predicted.

Answer: true

Pacemaker Circuits



Pacemakers are microprocessor-based with integrated circuits, which allow complex operations without excessive drain on battery energy.

An ***integrated circuit*** combines circuit elements into a single component. The integrated circuits contain both ROM (read only memory) and RAM (random access memory). Basic instructions - programs that direct the microprocessor - reside in ROM and are used to guide pacing, timing, sensing, and telemetry operations. Programming instructions are sent, via a programmer, to RAM for input into the microprocessor. Diagnostic data are also stored in RAM.

Combined with a microprocessor, integrated circuits permit potential:

- programming of more pacing therapies and diagnostic functions,
- upgrading of features via software changes rather than design changes,
- downloading of new features into implanted pacemakers via telemetry.

The microprocessor used in a pacemaker is custom designed to operate efficiently with a lithium iodine battery, which has a limited power supply.

Notes

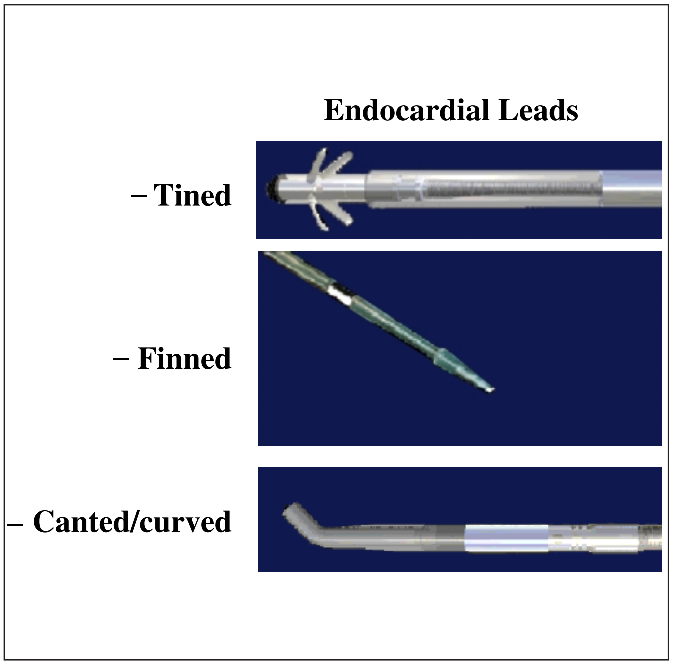
Integrated circuits and the use of a custom designed microprocessor extend battery longevity and allow more therapy options, event storage, and diagnostics.

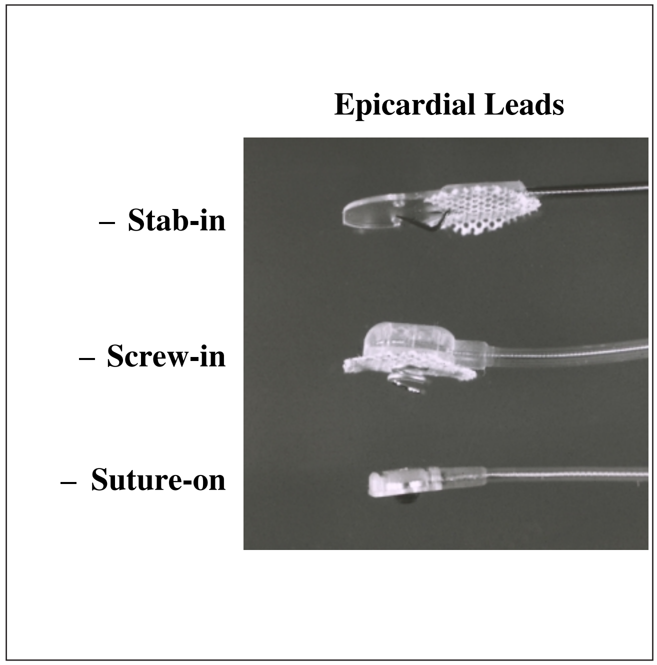
True or False

The microprocessor used in a pacemaker operates on a limited power supply.

Answer: true

Leads





A pacing lead may be endocardial or epicardial. Endocardial leads are used in about 95% of implants; epicardial leads in only 5%.

Endocardial (transvenous) leads are threaded through veins - usually subclavian or cephalic - and contact the endocardium in the right atrium and/or ventricle. Placement requires the use of an introducer (hollow tube) and stylet (stiff wire). Imaging (usually fluoroscopy) is used to guide lead insertion and final placement.

Epicardial leads are attached to the external surface of the heart (epicardium) with sutures or another mechanism (screw-in/stab-in). Placement requires a thoracotomy (chest incision) and is therefore used only when endocardial placement is not an option.

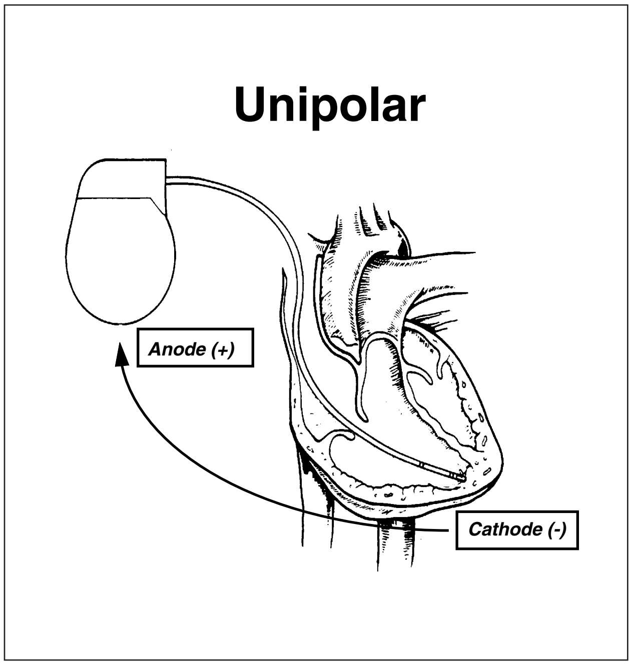
Notes

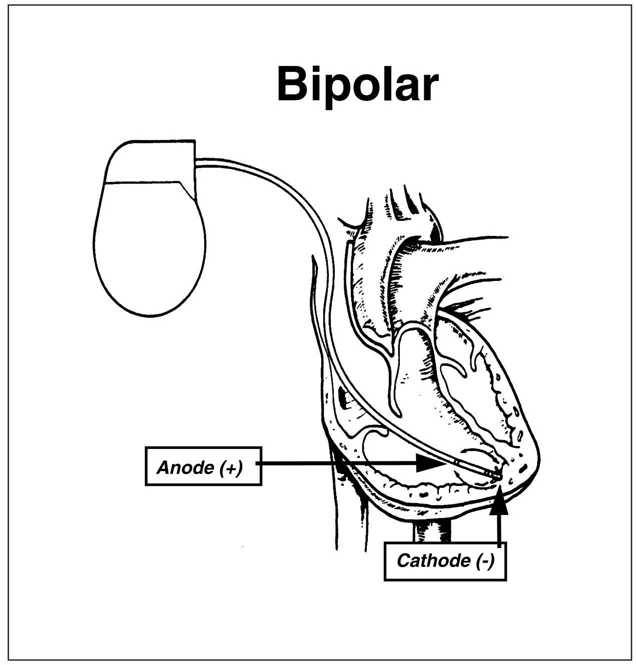
Circle the correct answer:

Most implanted leads are (endocardial, epicardial).

Answer: endocardial

Lead Polarity





A pacing lead may be unipolar or bipolar.

A ***unipolar lead*** has one conductor wire and one electrode at the tip of the lead body. The cathode is in contact with the heart and the anode is the IPG can. In a unipolar system, a pacing pulse travels from the IPG to the tip electrode (cathode) to stimulate the heart; then returns to the IPG can through chest tissues to complete the pacing circuit. Current flows through a substantial part of the chest and forms a large current loop (the pacing spike is easily seen on a surface ECG).

A ***bipolar lead*** has two conductor wires and both the anode and cathode are in contact with the heart. The anode is the ring electrode located two to three cm* above the cathode. It has a separate conductor wire connection to the IPG. In a bipolar system, a pacing pulse travels from the IPG to the tip electrode and then to the ring electrode. It returns to the IPG by way of the second conductor wire. The current path is within the heart and the current loop is small.

* Varies with lead design.

Notes

Bipolar systems have two electrodes in contact with the heart. Unipolar systems have one.

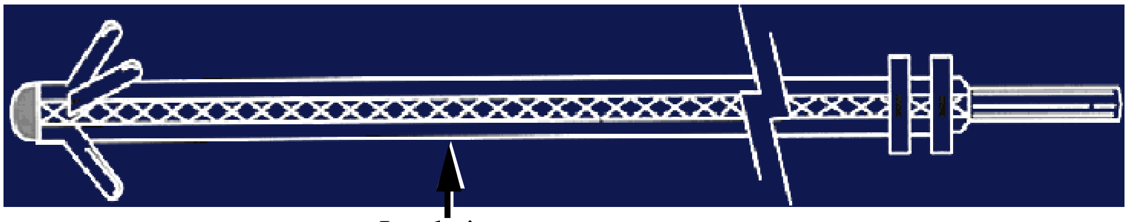
Circle the correct answer:

The current loop in a (unipolar, bipolar) lead system is small.

The anode in a unipolar system is the (ring electrode, IPG can).

Answers: bipolar / IPG can

Lead Insulation



Lead insulation prevents contact between the conductor wire and body tissue and ensures that stimulation occurs only at the tip electrode.

Polyurethane is biocompatible, strong, and has a low coefficient of friction. Its strength allows the construction of leads with a small diameter, which are easier to place in veins. Its lubricity (low friction) allows easier manipulation of the lead, an important advantage when placing two leads in a single vein.

Silicone can withstand in-vivo stresses (cracking and oxidation) over time. Compared to polyurethane, silicone is fragile and has a high coefficient of friction. These disadvantages have been addressed by using platinum-cured silicone rubber to produce a more durable lead and a coating process to produce a lead as friction-free as polyurethane.

Fluoropolymers (ETFE PTFE) are the most biocompatible insulating materials available. Their strength allows the construction of leads with a very small diameter. Its disadvantages: The lead is stiff when manufactured in thicknesses over 0.003 mm and is difficult to manufacture in thin tubes.

Notes

Lead insulation is expected to be biocompatible, durable, and easy to slide into veins.

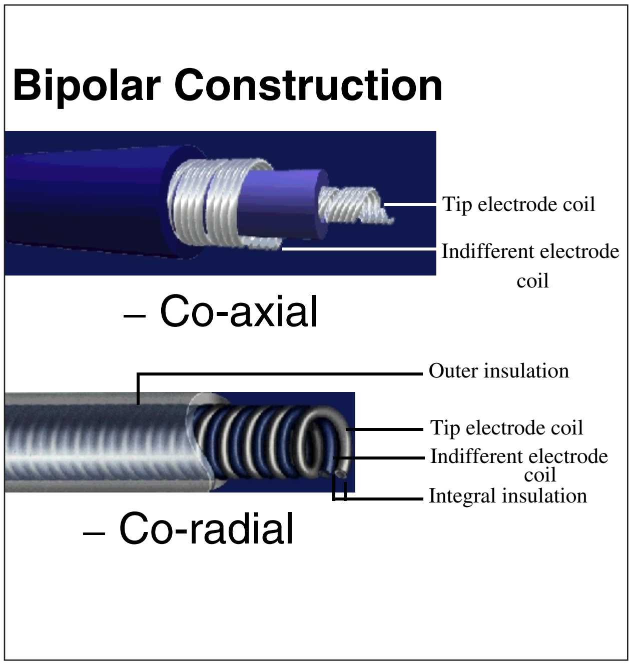
Lead insulation failure results in low impedance measurements (<200 Ohms), increased current drain, and loss of sensing/stimulation function.

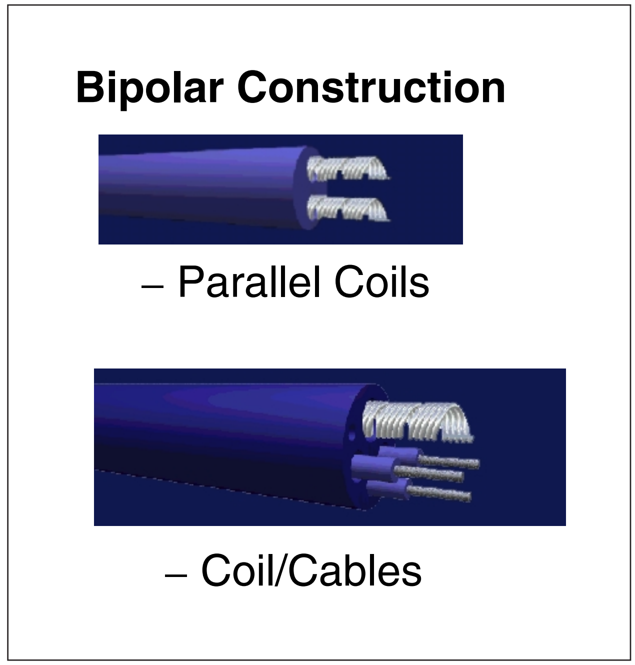
Question:

Existing insulation materials include ________, ________, ________.

Answer: polyurethane, silicone, fluoropolymers

Lead Conductors





The conductor wire conducts electricity from the IPG to the stimulating electrode.

A ***conductor wire*** flexes with every heartbeat and has a high potential for fatigue and fracture. Conductors are made of alloys (metal mixtures) resistant to corrosion. Examples are MP35N nickel alloy and platinum alloy. Multifilar conductors, made of multiple strands of wire, have better tensile strength and fatigue resistance than monofilar (single wire) conductors.

Unipolar leads are constructed with a single conductor wire, coiled around a central axis and encased in a sleeve of insulation. ***Bipolar leads*** have two conduction wires with various designs. In a ***co-axial design***, one wire is coiled and placed inside the second coiled wire. Insulation is placed around both wires. In a ***co-radial design***, the wires are wound together and insulated from each other with a thin coating. This allows the construction of a lead with a smaller diameter. Older bipolar leads used a **parallel design** in which the conductors are placed side by side within a sleeve of insulation.

New manufacturing processes and the availability of biocompatible materials will continue to influence the design and construction of pacing leads (see coil/cable figure above).

Notes

A conductor wire is expected to be suitable for conduction and resistant to corrosion and mechanical stress.

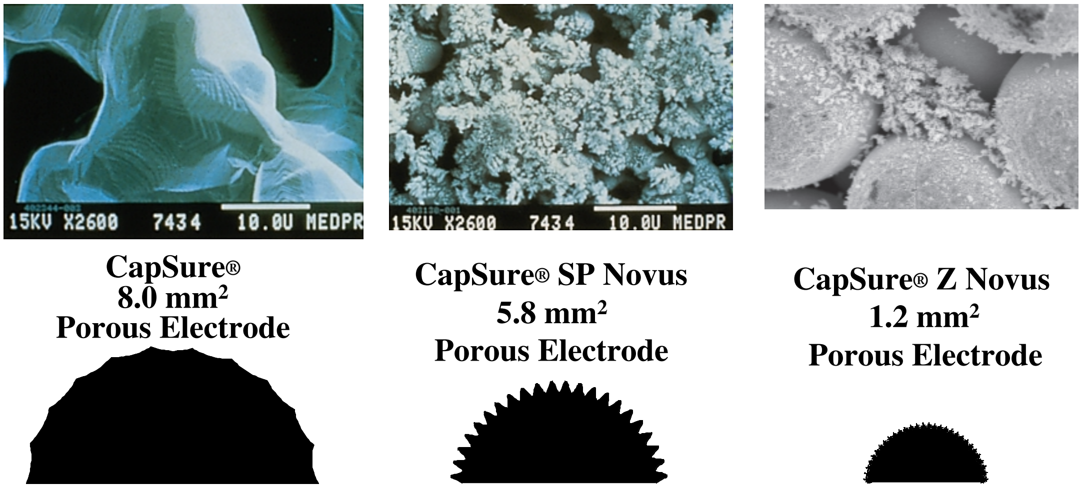
Conduction fracture results in increased impedance measurement (>30% change) and loss of pacing function.

True or False:

When constructing leads, size and flexibility are balanced with strength and durability.

Answer: True

Porous Electrode Surface



Small electrodes with a porous surface increase electrode resistance and reduce the effects of polarization.

Electrodes with a ***small radius*** provide high current density and increased electrode resistance, which allows the delivery of a more concentrated and efficient pacing pulse to cardiac tissue. The smaller the radius, however, the greater the effect of polarization.

Electrodes with a ***rough, porous surface*** have a large functional (total) surface area, compared to electrodes with a smooth, polished surface. The pores are bored with a laser beam, then coated and roughened. This process significantly increases the electrode surface area without increasing the radius and thus reduces the wasteful effects of polarization.

The porous surface also promotes tissue ingrowth and improves sensing by providing a larger electrode-tissue contact area.

Notes

A porous electrode surface decreases the effects of polarization and improves stimulation and sensing efficiency.

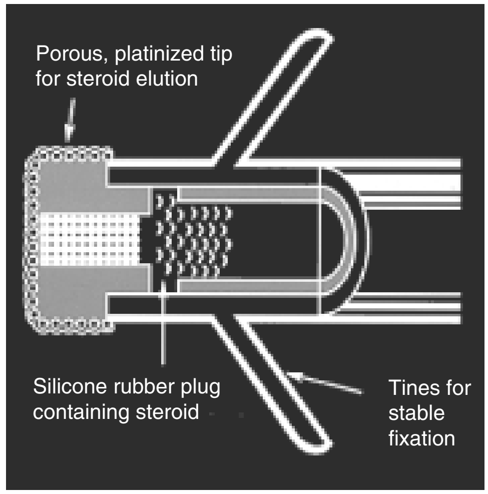
Electrodes with a small radius and porous surface result in increased pacemaker longevity and decreased current drain.

Circle the correct answer:

Porous electrodes have a larger (functional surface area, radius) than smooth electrodes.

Answer: functional surface area

Steroid-Elution



Steroid-elution reduces inflammation and fibrosis and helps maintain a better electrode-tissue interface.

Inflammation and fibrosis are two stages of the lead maturation process. ***Inflammation*** starts when the pacing electrode comes into contact with cardiac tissue. The immune system reacts by secreting biochemical toxins that alter or destroy the excitability of the myocardial cells near the electrode-tissue interface. Inflammation rises after implant and peaks several weeks later.

Fibrosis, the growth of fibrous tissue around the electrode, occurs when inflammation subsides. Fibrous tissue conducts electrical impulses, but is not excitable. Inflammation and fibrosis increase the distance between the electrode and excitable cardiac tissue and increase the voltage needed to trigger depolarization.

Steroids reduce the production of biochemical toxins and thus reduce inflammation and limit fibrotic development. ***Steroid-eluting*** electrodes have a rubber silicone plug that contains a small dose (less than 1 mg) of steroid. Body fluids seep into the electrode and dissolve the steroid, which then flows along with the body fluids to the electrode-tissue interface. Initially, the rate of steroid elution is high, but the rate decreases over time. Typically, the steroid lasts for several years.

Notes

Steroid-elution reduces inflammation and the energy needed to stimulate the heart, thereby decreasing thresholds and current drain, and increasing longevity.

Question:

Steroid-elution reduces ______.

Answer: inflammation and fibrosis

Fixation Mechanisms

Passive Fixation

– **Tined**

– **Finned**

Active Fixation

– **Fixed screw**

– **Retractable/extendible**

Stable positioning of an electrode may be achieved with passive or active fixation.

Passive-fixation mechanisms include tines (most common), and fins. These lodge in the trabeculae (muscle) and are eventually anchored by the growth of fibrous tissue. Passive-fixation leads are fairly easy to implant and cause minimal tissue trauma. Fixation can be confirmed by gentle rotation or traction. Potential disadvantages: They require a larger venous introducer and may be more difficult to explant.

Active-fixation leads have screws (most common), hooks, or barbs that extend into the endocardial tissue. They can be attached to any area of the endocardium, which is of benefit in the presence of a smooth heart wall or abnormality, such as a missing atrial appendage. Potential disadvantages: They may be more difficult to implant and may cause more tissue trauma than passive fixation leads.

Notes

The performance of a lead is dependent on stable positioning of the electrode.

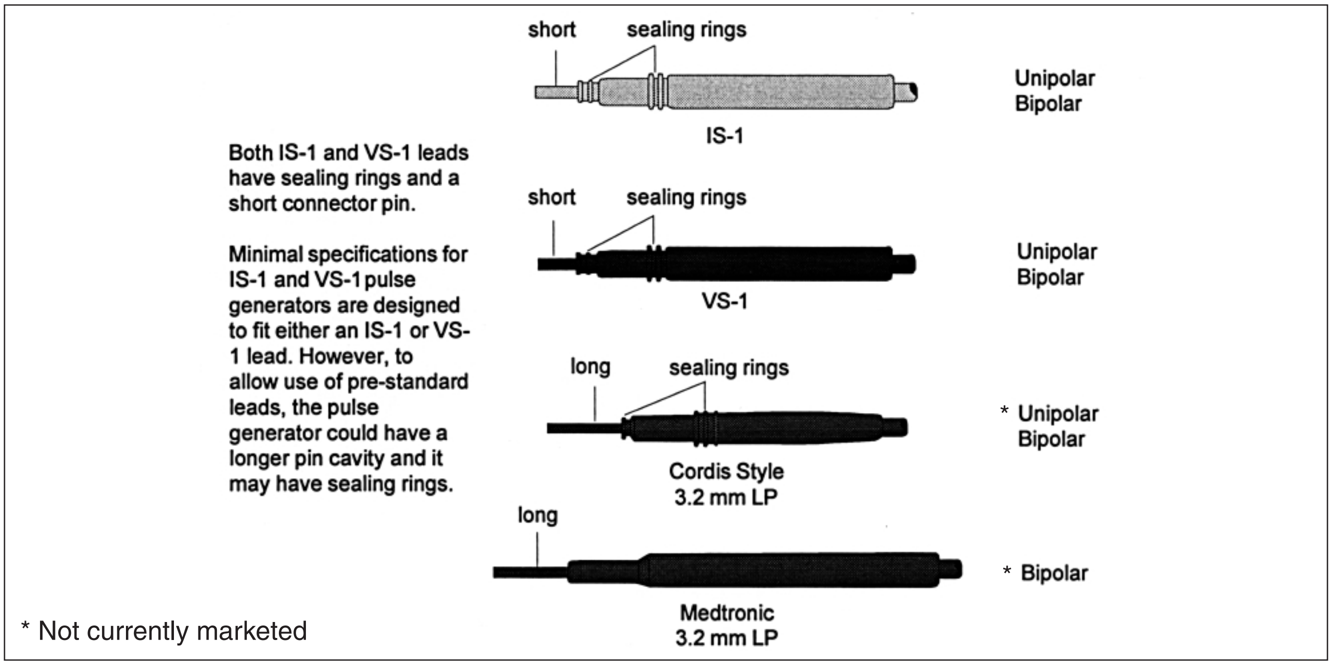
Circle the correct answer:

A screw-in helix is an (active, passive) fixation mechanism.

Tines are commonly used in (active, passive) fixation leads.

Answers: active / passive

Connector Pin



The connector pin connects the proximal end of the pacing lead to the connector block of the pacemaker. A tight fit seals out body fluids and completes the conduction pathway.

A major problem for manufacturers of leads and pacemakers has been compatibility between connector pins and connector blocks. The earliest pacing leads had connector pins with a 5 to 6 mm diameter. Current connector pins have a 3.2 mm diameter. VS-1 and IS-1 configurations include sealing rings on the proximal portion of the lead. Others place the sealing rings in the connector block.

The currently established international connector standard is IS-1. The variety of available connectors and IPG headers remains confusing, however, and it is the implanter's responsibility to ensure that compatibility exists.

Notes

Proper connection of the lead to pacemaker is critical to pacemaker function.

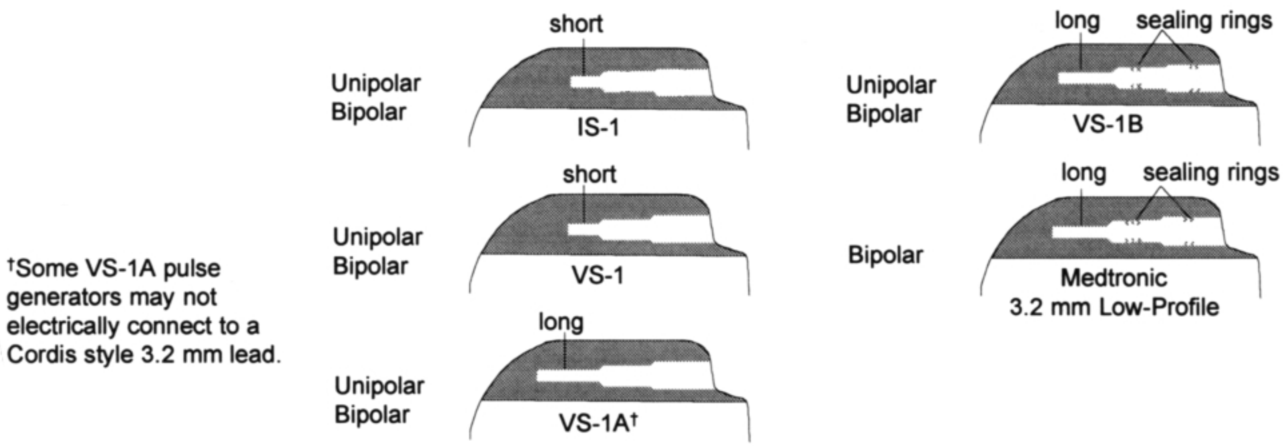
Leads are labeled IS-1 Uni or IS-1 Bi. Unipolar connectors have a blue connector ring as a visual indication that the lead is unipolar.

True or False:

True or False. The connector pin on existing leads varies in diameter and length.

Answer: True

Connector Block



This illustration shows the variety of pulse generator connector blocks.

Compatibility is achieved by using a lead connector that matches the configuration of the IPG connector block. Another option is to use an adaptor to up-size or down-size the connector pin and the sealing mechanism to fit the connector block.

Notes

Compatibility may not ensure reliability and adaptors must be used with caution (last resort). Care must be taken in selecting components that are closely matched. Ideally components from the same manufacturer provide both compatibility and reliability.

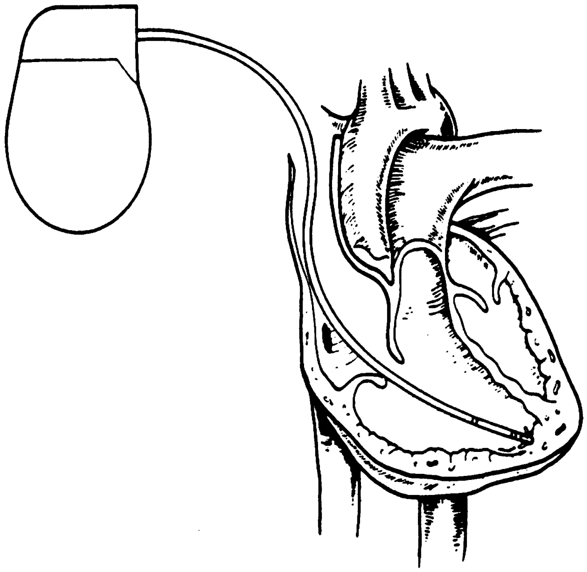
Sealing rings must be present on either the lead connector pin or within the connector block to exclude body fluids.

Question:

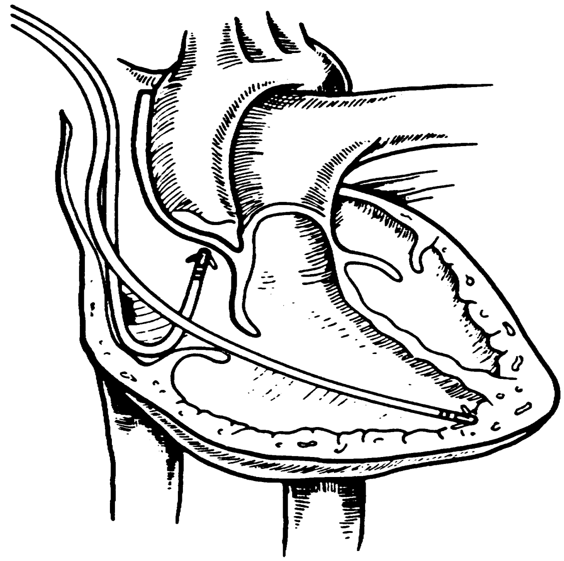
Which header type has both sealing rings and a long pin

Answer: VS-1B

Single vs. Dual Chamber Systems



Single Chamber



Dual Chamber

A pacing system may be single or dual chamber.

A ***single chamber system*** uses one lead, which may be placed in the right atrium or right ventricle. A ***dual chamber system*** uses two leads. One is placed in the right atrium and the other in the right ventricle.

A single ventricular lead cannot provide AV synchrony and a single atrial lead does not provide ventricular backup pacing if AV conduction is lost. Dual chamber systems attempt to provide AV synchrony.

Notes

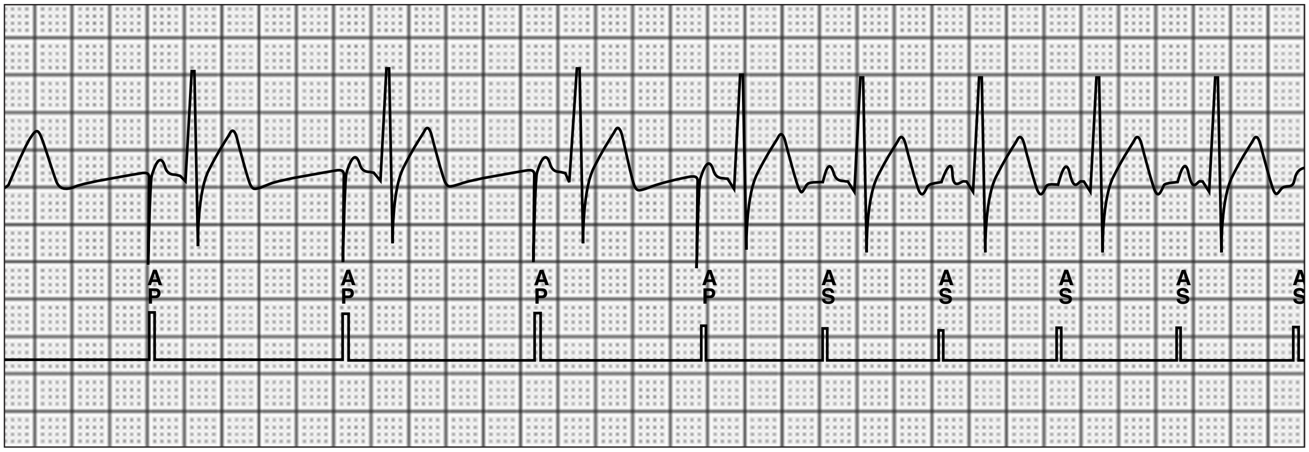
Questions:

A ____________ pacemaker is used to pace either the atrium or ventricle.

A ____________ pacemaker is used to pace the atrium and ventricle.

Answers: single chamber / dual chamber

Basic Pacemaker Functions



Single Chamber Atrial Pacemaker

Pacemakers stimulate cardiac depolarization, sense intrinsic cardiac activity, respond to metabolic need, and store diagnostic information.

All single and dual chamber pacemakers can provide fixed rate pacing, in which the heart is paced at a predetermined rate. Most also provide rate adaptive/responsive pacing, in which the pacing rate increases and decreases in response to the input from rate-adaptive sensors.

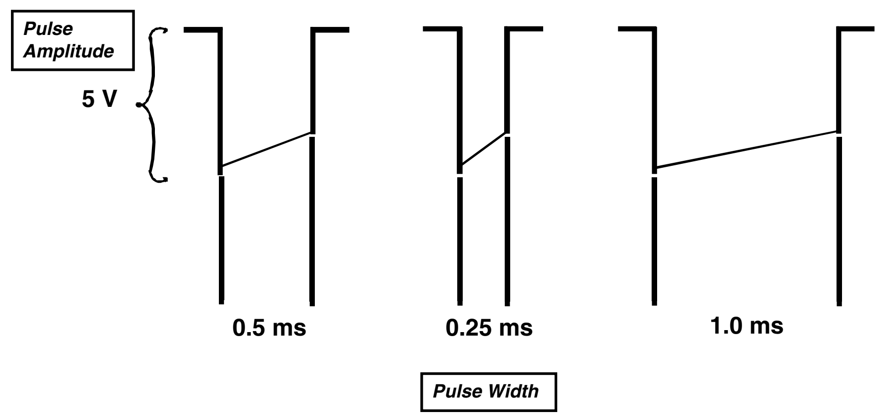
Pacemakers have the ability to sense the intrinsic heartbeat and inhibit pacing when the heart is beating on its own. This prevents the pacemaker from competing with normal cardiac function.

Finally, most pacemakers collect and store information about the patient's heart and the implanted pacemaker. This allows the clinician to monitor pacing therapy, optimize programmed settings, and check the battery and lead status.

Notes

Stimulation

Pulse Width Is the Time (Duration) of the Pacing Pulse



Stimulation in pacing is the delivery of electrical impulses to the myocardium to maintain an effective heart rate and ensure the pumping capacity of the heart.

The output voltage of the pulse generator produces an electrical field at the electrode-tissue interface. The field changes the electrical charge of myocardial cells and triggers cardiac depolarization. (See Action Potential in Module 1.)

To capture the heart (trigger depolarization), the output pulse must be strong enough and last long enough to spread throughout the myocardium, causing the heat to contract. The strength of an output pulse is determined by the programmed value of the ***pulse amplitude***, measured in volts. The duration of the pulse is determined by the programmed value of the ***pulse width***, measured in milliseconds.

The minimum pulse amplitude at a given pulse width that consistently captures the heart outside its refractory period is the ***stimulation threshold***.

Notes

The programmable parameters of a pacing impulse are pulse amplitude and pulse width.

A unipolar pacing configuration generates a larger stimulus (pacemaker spike) on an ECG monitor than a bipolar configuration.

Questions:

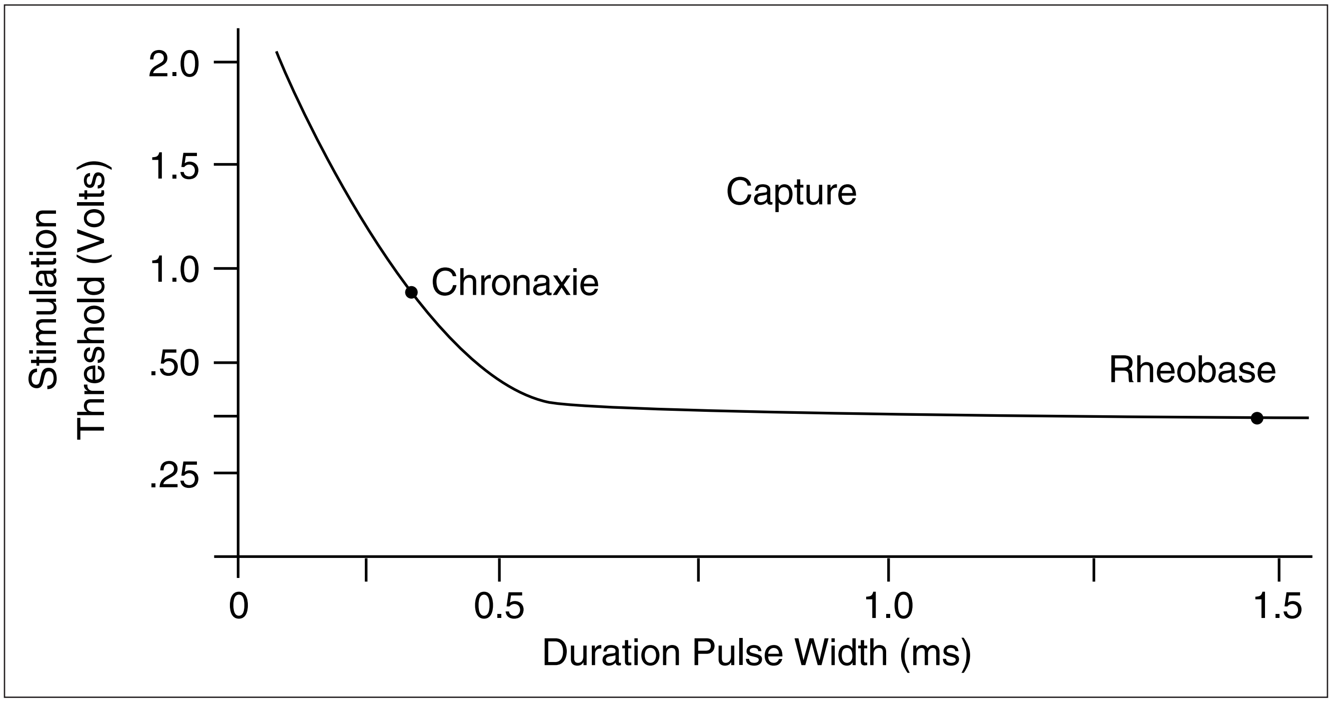
The ***duration of a pacing impulse*** is the ______________.

The ***intensity of a pacing impulse*** is the ______________.

The ***minimum level*** of stimulation that maintains capture is the ______________.

Answers: pulse width / pulse amplitude / threshold

Strength-Duration Curve



The strength-duration curve is used to determine the patient's stimulation threshold.

The ***strength-duration curve*** shows the lowest combinations of pulse amplitude and pulse width that capture the patient's heart. The values on or above the curve capture the heart. The values below the curve do not. The battery energy needed for stimulation increases as amplitude and pulse width increase.

The ***rheobase*** is the lowest point on the curve. It represents the minimum amplitude at an infinitely long pulse width required to maintain consistent capture. The ***chronaxie*** is the point at which the amplitude is twice that of the rheobase amplitude. It represents the minimum pulse width (at twice the rheobase amplitude) needed to maintain consistent capture.

Low stimulation thresholds are achieved by proper electrode positioning and the use of small, porous, steroid-eluting electrodes.

Notes

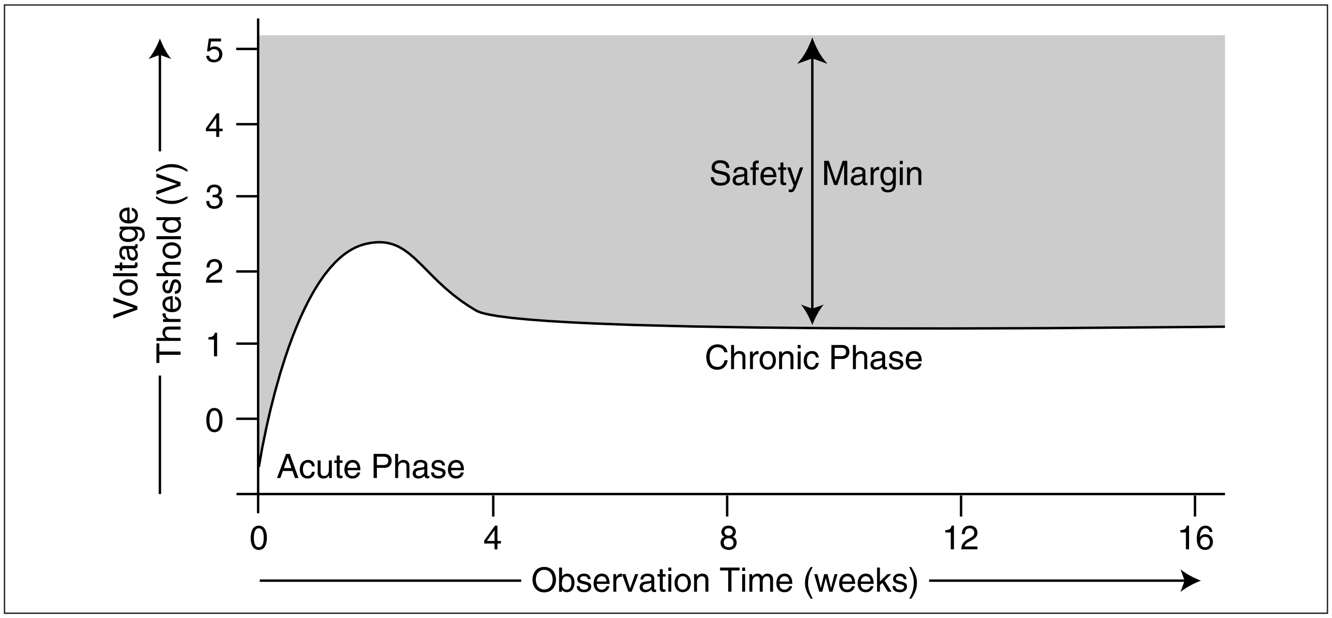
The strength-duration curve plots the minimum voltage needed to capture the myocardium at varying pulse widths.

Question:

The __________ depicts the stimulation threshold.

Answer: strength-duration curve

Safety Margin



A safety margin is added to the stimulation threshold to prevent loss of capture due to threshold variations.

After pacemaker implantation, the stimulation threshold rises, peaks (acute phase), and then settles into a stable pattern (chronic phase). The stable or ***chronic threshold*** is achieved three to six weeks after implant. Once stabilized, the stimulation threshold may vary slightly because of changes in daily activity (sleeping increases the threshold, exercise decreases it), the use of cardiovascular drugs, or changes in the condition of the myocardium.

To cope with acute and chronic threshold variations, the output pulse is programmed with a ***safety margin***. A 3:1 safety margin is usually needed immediately after implantation (acute phase), especially if non-steroid-eluting leads are used. A 2:1 safety margin is used when the threshold stabilizes (chronic phase). Some pacing systems have automated tests to determine appropriate and safe output settings. The general rule for programming a 2:1 safety margin is:

- If the threshold pulse width is 0.3 ms or less (at 2.5 V or lower), hold the amplitude constant and set the pulse width to three times its threshold value.
- If the threshold pulse width is greater than 0.3 ms (at 2.5 V or lower), hold the pulse width constant and double the amplitude.

Notes

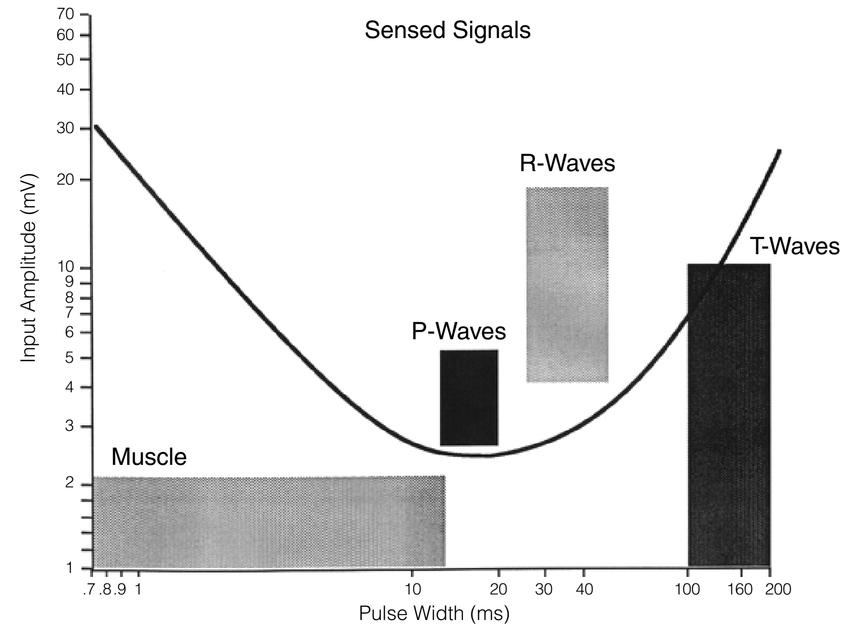
The output pulse is programmed with a 3:1 safety margin after implantation and a 2:1 safety margin when the threshold stabilizes.

Question:

A ____________ prevents loss of capture due to acute and chronic stimulation threshold variations.

Answer: safety margin

Signal Processing



The sensing circuit filters sensed signals on the basis of frequency content and eliminates those outside a certain range.

> ***Frequency content*** is the number of repetitions of a wave in a given period of time. It is measured in hertz (Hz), cycles per second. The dominant frequencies of P- and R-waves range from 10 to 30 Hz.
>
> The bandpass filter of most sensing circuits is designed so that frequencies above and below the center (parabolic curve in illustration) are attenuated (the amplitude is reduced). High slew rates have a high frequency content, and broad signals with low slew rates are not sensed, even if the amplitude is large. Filtering removes low frequency signals, typical of T-waves, and high frequency signals, typical of skeletal myopotentials.
>
> **Note**: In addition to filtering, a pacemaker manages unwanted electrical signals by including blanking and refractory periods in their timing cycles. This topic is discussed in the last section of this module.

Notes

Question:

The bandpass filter differentiates between electrical signals on the basis of ____________.

Answer: frequency content