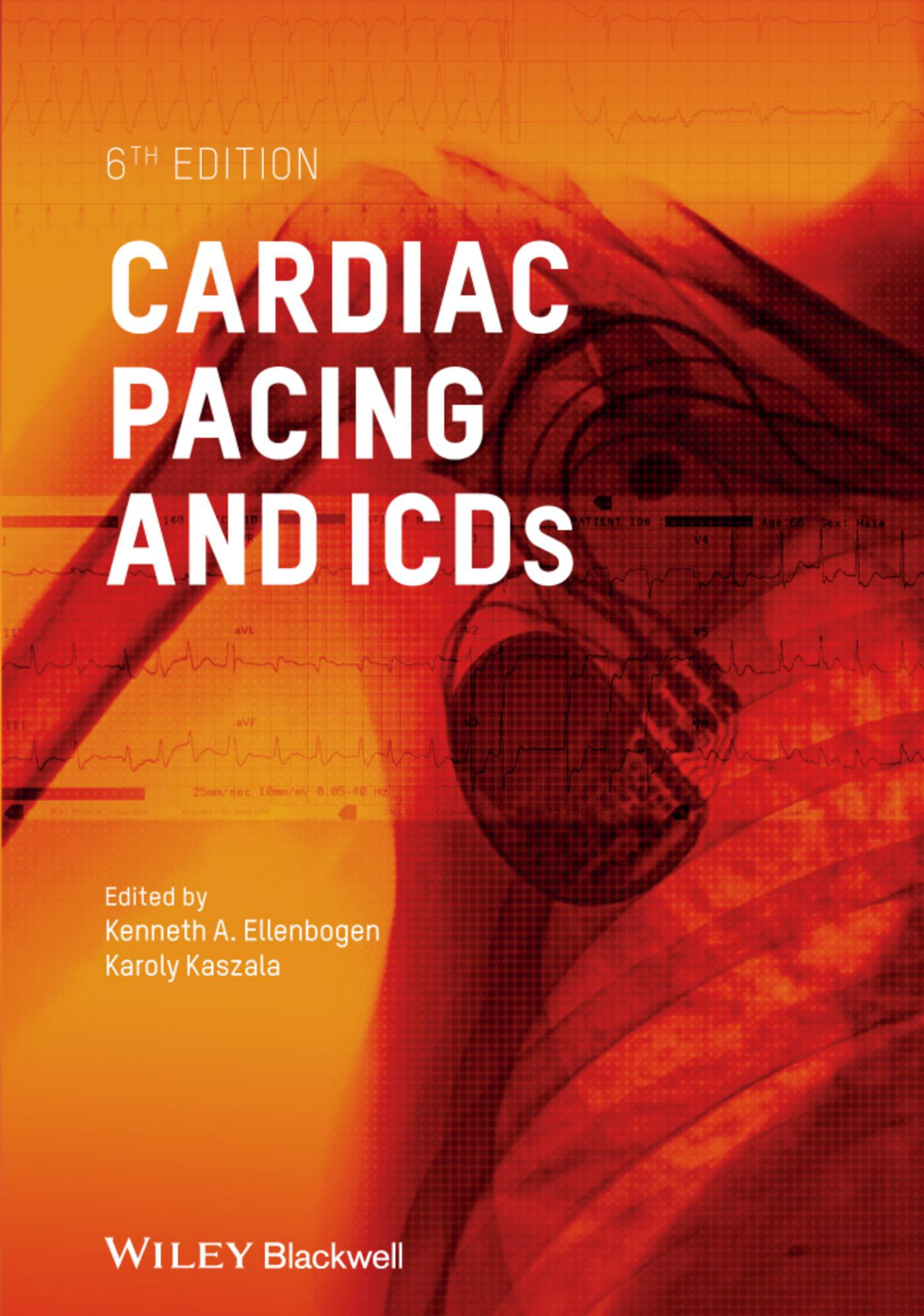
6TH EDITION

CARDIAC PACING AND ICDs



Edited by
Kenneth A. Ellenbogen
Karoly Kaszala

WILEY Blackwell

Cardiac Pacing and ICDs

To my parents, Roslyn and Leon Ellenbogen, who inspired a lifelong thirst for learning. To my wife, Phyllis, and children, Michael, Amy, and Bethany, whose patience and love made this project successful.

Kenneth A. Ellenbogen, MD, FHRS

To my parents, Karoly Kaszala and Dr Agnes Kaszala for their guidance, unconditional support and love, to my wife Gabriella, and children Julia, Dalma, and Balazs for their love, patience and understanding.

Karoly Kaszala, MD, PhD, FHRS

Cardiac Pacing and ICDs

6th Edition

EDITED BY

Kenneth A. Ellenbogen MD, FAHA, FACC, FHRS

Kontos Professor of Medicine
Chair, Division of Cardiology
VCU Pauley Heart Center
Electrophysiology Division
Medical College of Virginia/VCU School of Medicine
Richmond, VA, USA

Karoly Kaszala MD, PhD, FACC, FHRS

Director, Cardiac Electrophysiology Laboratory
Hunter Holmes McGuire VA Medical Center;
Associate Professor of Medicine
Medical College of Virginia/VCU School of Medicine
Richmond, VA, USA

WILEY Blackwell

This edition first published 2014 © 2014 by John Wiley & Sons, Ltd.

Registered office: John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial offices: 9600 Garsington Road, Oxford, OX4 2DQ, UK
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK
111 River Street, Hoboken, NJ 07030-5774, USA

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com/wiley-blackwell

The right of the author to be identified as the author of this work has been asserted in accordance with the UK Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

The contents of this work are intended to further general scientific research, understanding, and discussion only and are not intended and should not be relied upon as recommending or promoting a specific method, diagnosis, or treatment by health science practitioners for any particular patient. The publisher and the author make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of fitness for a particular purpose. In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of medicines, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each medicine, equipment, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. Readers should consult with a specialist where appropriate. The fact that an organization or Website is referred to in this work as a citation and/or a potential source of further information does not mean that the author or the publisher endorses the information the organization or Website may provide or recommendations it may make. Further, readers should be aware that Internet Websites listed in this work may have changed or disappeared between when this work was written and when it is read. No warranty may be created or extended by any promotional statements for this work. Neither the publisher nor the author shall be liable for any damages arising herefrom.

Library of Congress Cataloging-in-Publication Data

Cardiac pacing and ICDs / edited by Kenneth A. Ellenbogen, Karoly Kaszala.—Sixth edition.
p. ; cm.
Includes bibliographical references and index.
ISBN 978-1-118-45951-5 (pbk.)
I. Ellenbogen, Kenneth A., editor of compilation. II. Kaszala, Karoly, editor of compilation.
[DNLM: 1. Cardiac Pacing, Artificial. 2. Defibrillators, Implantable. 3. Pacemaker, Artificial. WG 168]
RC684.P3
617.4'120645–dc23

2013049554

A catalogue record for this book is available from the British Library.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Cover image: iStock File #6484732 © ljiljana2004
Cover design by Andrew Magee Design Ltd

Set in 9.5/12 pt MinionPro-Regular by Toppan Best-set Premedia Limited

1 2014

Contents

List of Contributors, vii

In Memoriam—Dr Mark Allen Wood, ix

Preface, x

1 Indications for permanent and temporary cardiac pacing, 1
Roy M. John

2 Components of a pacing and ICD system: basic concepts of pacing, 34
Gautham Kalahasty, Suraj Kapa, and Joshua M. Cooper

3 Hemodynamics of cardiac pacing and pacing mode selection, 82
Bruce S. Stambler and Niraj Varma

4 Temporary cardiac pacing, 134
T. Jared Bunch, Jeffrey S. Osborn, and John D. Day

5 Techniques of pacemaker implantation and removal, 150
Joseph E. Marine and Jeffrey A. Brinker

6 Pacemaker timing cycles and special features, 211
Jose F. Huizar

7 Evaluation, troubleshooting, and management of pacing system malfunctions, 272
Karoly Kaszala

8 The implantable cardioverter–defibrillator, 323
Michael R. Gold and Charles Swerdlow

9 Cardiac resynchronization therapy, 374
Yong-Mei Cha

10 ICD follow-up and troubleshooting, 413
Fadi Mansour and Paul Khairy

11 Follow-up of the patient with a CIED, 453
Harish Doppalapudi, Mark L. Blitzer, and Mark H. Schoenfeld

Index, 504

List of Contributors

Mark L. Blitzer, MD
Clinical Instructor in Medicine
Yale University School of Medicine
Yale-New Haven Hospital
New Haven, CT, USA

Jeffrey A. Brinker, MD
Professor of Medicine and Radiology
Johns Hopkins University School of Medicine
Baltimore, MD, USA

T. Jared Bunch, MD
Electrophysiology Program Medical Director
Intermountain Heart Institute
Intermountain Medical Center
Murray, UT, USA

Yong-Mei Cha, MD
Consultant
Division of Cardiovascular Diseases
Mayo Clinic;
Professor of Medicine
College of Medicine
Mayo Clinic
Rochester, MN, USA

Joshua M. Cooper, MD
Assistant Professor of Medicine
Division of Cardiac Electrophysiology
Hospital of the University of Pennsylvania
Philadelphia, PA, USA

John D. Day, MD
Attending Physician
Intermountain Heart Institute
Intermountain Medical Center
Murray, UT, USA

Harish Doppalapudi, MD
Fellowship Director, Clinical Electrophysiology
Assistant Professor of Medicine
Division of Cardiovascular Disease
University of Alabama at Birmingham
Birmingham, AL, USA

Michael R. Gold, MD, PhD
Michael E. Assey Professor of Medicine
Chief, Cardiology
Medical University of South Carolina
Charleston, SC, USA

Jose F. Huizar, MD, FACC, FHRS
Director, Arrhythmia and Device Clinic
Hunter Holmes McGuire VA Medical Center;
Associate Professor of Medicine
Medical College of Virginia/VCU School of Medicine
Richmond, VA, USA

Roy M. John, MBBS, PhD, FRCP
Director, Cardiac Arrhythmia Research
Associate Director, Electrophysiology Laboratory
Department of Medicine
Cardiovascular Division
Brigham and Women's Hospital
Harvard Medical School
Boston, MA, USA

Gautham Kalahasty, MD
Associate Professor of Medicine
Division of Cardiology
Section of Cardiac Electrophysiology
Medical College of Virginia/VCU School of Medicine
Richmond, VA, USA

Suraj Kapa, MD, FACC
Assistant Professor
Mayo Clinic
Rochester, MN, USA

Karoly Kaszala, MD, PhD, FACC, FHRS
Director, Cardiac Electrophysiology Laboratory
Hunter Holmes McGuire VA Medical Center;
Associate Professor of Medicine
Medical College of Virginia/VCU School of Medicine
Richmond, VA, USA

Paul Khairy, MD, PhD, FRCPC
Canada Research Chair, Electrophysiology and Adult Congenital Heart Disease
Director, Adult Congenital Heart Centre
Montreal Heart Institute;
Associate Professor
University of Montreal
Montreal, QC, Canada

Fadi Mansour, MD, FRCPC
Electrophysiology Service
Centre Hospitalier Université de Montréal
University of Montreal
Montreal, QC, Canada

Joseph E. Marine, MD, MBA, FACC, FHRS
Associate Professor of Medicine
Associate Director of Electrophysiology
Associate Chief of Cardiology for NCR
Section Chief for Cardiology, Johns Hopkins Community Physicians
Johns Hopkins University School of Medicine
Baltimore, MD, USA

Jeffrey S. Osborn, MD, FACC, CCDS
Cardiac Device Director
Intermountain Heart Institute
Intermountain Medical Center
Murray, UT, USA

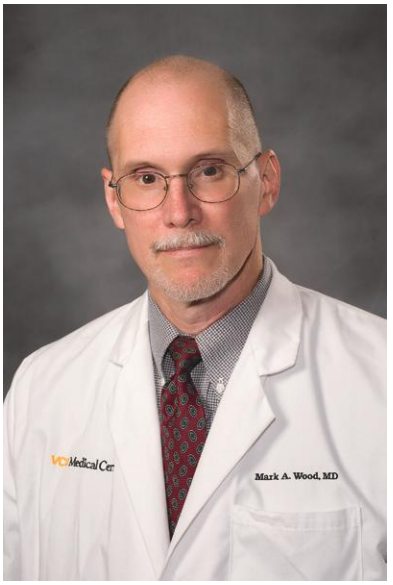
Mark H. Schoenfeld, MD, FACC, FAHA, FHRS
Clinical Professor of Medicine
Yale University School of Medicine;
Director, Cardiac Electrophysiology and Pacemaker Laboratory
Yale-New Haven Hospital
New Haven, CT, USA

Bruce S. Stambler, MD
Professor of Medicine
Case Western Reserve University
Cleveland, OH, USA

Charles Swerdlow, MD, FACC, FAHA, FHRS
Clinical Professor of Medicine
Cedars Sinai Medical Center
David Geffen School of Medicine at UCLA
Los Angeles, CA, USA

Niraj Varma, MA, DM, FRCP
Staff Cardiologist
Cardiac Electrophysiology and Pacing
Heart and Vascular Institute
Cleveland Clinic
Cleveland, OH, USA

In Memoriam
Dr Mark Allen Wood



It is our great sadness to say goodbye to our colleague and great friend, Mark Wood, who lost a long battle against cancer before the current edition reached beyond the planning stage. Mark received his medical degree from the University of Tennessee Center for the Health Sciences and completed residency and fellowship training at the Medical College of Virginia and the University of Virginia. He was co-director of the Department of Cardiac Electrophysiology at MCV Hospital and served on the medical faculty for 25 years, most recently as Professor of Medicine and Cardiology.

He had a very impressive scientific career. Mark had a key role as author and co-editor in previous editions of this book and contributed, over 300 scientific articles and numerous book chapters in the field of cardiology and electrophysiology. He also co-edited a highly respected cardiac electrophysiology book. He was an exceptionally caring physician and talented teacher. He was adored by his patients. He received numerous teaching awards from medical students, residents, and fellows. He had the ability to motivate his students and explain the most complex concepts with simplicity and ease. In the 1990s, he helped to initiate a Cardiac Electrophysiology Program in Beijing, China and for his humanitarian efforts he received the title of Honorary Professor at Beijing University Hospital. His gentle and respectful approach to his patients and their family members, as well as his enduring friendships with colleagues, earned him the title of MCV Clinician of the Year in 2011.

Mark has been an exceptional individual and we are honored to have known him, worked with him and learned from him. His departure at such a young age is a great loss for our program and the electrophysiology community. He is sorely missed.

Kenneth A. Ellenbogen and Karoly Kaszala

Preface

Understanding the basic function of pacemakers and implantable defibrillators (ICD) is more relevant today than ever. The number of patients with implantable cardiac devices continues to increase due to evolving new indications and increased life expectancy of patients with implantable devices. In the new edition of the book, we continue to provide comprehensive material for the beginner and intermediate level cardiovascular providers that helps to build a basic foundation, but also serves as a reference for a more comprehensive understanding of device therapy and management. We hope that this edition of the book will attract all levels of learners ranging from medical students to house officers, cardiology and cardiac surgery fellows and the vast array of nurses, technicians, engineers and representatives from industry who play a vital role in the delivery of care to our patients. Many readers have found this book invaluable for preparing for examinations in this field.

As the complexity of devices, device programming and new scientific information evolves, we offer a fresh update with thoroughly revised chapters on the most relevant information. Every chapter has undergone major revision and most have been completely rewritten by new authors. We have incorporated new information on biventricular pacemaker technology and device indications and updated the information on lead technology and recent lead advisories. There is exciting new information about ICDs, ranging from device programming to battery design. The hemodynamic section is even more comprehensive and thoroughly updated and a completely re-written pacemaker timing cycle section includes a very broad review of currently available pacemaker algorithms. The troubleshooting sections are updated to relevant problems with illustrative tracings from currently implanted devices. It goes without saying that this book would not be here without the tremendous work by all the contributors and we would like to thank them here again for all the hard work they have put into the current edition.

As we reflect on our previous editions, it is inevitable to remember our dear friend and colleague, Dr. Mark Wood, who was involved from the very early phases of the preparation of this edition as well. Although his untimely passing did not allow him to actively participate in the writing and editing, for all of us who knew him, his thoughtful teachings still shine through this book.

Kenneth A. Ellenbogen, MD
Karoly Kaszala, MD, PhD

1

CHAPTER 1

Indications for permanent and temporary cardiac pacing

Roy M. John
Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA

Introduction

Defects of cardiac impulse generation and conduction can occur at various levels in the cardiac conduction system. In general, intrinsic disease of the conduction system is often diffuse. For example, normal atrioventricular (AV) conduction cannot necessarily be assumed when a pacemaker is implanted for a disorder seemingly localized to the sinus node. Similarly, normal sinus node function cannot be assumed when a pacemaker is implanted in a patient with AV block. Conduction disorders that lead to important bradycardia or asytole may result from reversible or irreversible causes. Recognition of reversible causes is critical to avoid unnecessary commitment to long-term pacemaker therapy. This chapter reviews the common disorders that warrant cardiac pacing and lists the recommended indications set out by published guidelines.

Anatomy and physiology of the conduction system

For a complete understanding of rhythm generation, intracardiac conduction, and their pathology, a brief review of the anatomy and physiology of the specialized conduction system is warranted.

Sinus node

The sinus node or sinoatrial (SA) node is a crescent shaped sub-epicardial structure located at the junction of the right atrium and superior vena cava along the terminal crest. It measures 10–20 mm (with larger extension in some studies) and has abundant autonomic innervation and blood supply, with the sinus node artery commonly coursing through the body of the node. Endocardially, the crista terminalis overlies the nodal tissue, although the inferior aspect of the node has a more subendocardial course. Histologically, the sinus node is comprised of specialized nodal cells (P cells) packed within a dense matrix of connective tissue. At the periphery, these nodal cells intermingle with transitional cells and the atrial working myocardium, with radiations extending toward the superior vena cava, the crista terminalis, and the intercaval regions.[1,2] The absence of a distinct border and the presence of distal fragmentation explain the lack of a single breakthrough of the sinus node excitatory wavefront. The radiations of the node, although histologically distinct, are not insulated from the atrial myocardium. Hence, a clear anatomical SA junction is absent. The sinus node is protected from the hyperpolarizing effect of the surrounding atria, probably by its unique structure wherein electrical coupling between cells

Cardiac Pacing and ICDs, Sixth Edition. Edited by Kenneth A. Ellenbogen and Karoly Kaszala.
© 2014 John Wiley & Sons, Ltd. Published 2014 by John Wiley & Sons, Ltd.

and expression of ion channels vary from the center of the node to the periphery. The pacemaker cells at the center of the node are more loosely coupled, while those at the periphery are more tightly coupled with higher density I_f (funny current; a slow sodium current) and I_{Na} currents.[2]

The SA node has the highest rate of spontaneous depolarization (automaticity) in the specialized conduction system and is responsible for the generation of the cardiac impulse under normal circumstances, although normal human pacemaker activity may be widely distributed in the atrium. The unique location of the sinus node astride the large SA nodal artery provides an ideal milieu for continuous monitoring and instantaneous adjustment of heart rate to meet the body's changing metabolic needs. Impulse generation in the sinus node has been extensively studied in mammalian hearts, but remains incompletely understood. Sinus nodal cells have a low resting membrane potential of −50 to −60 mV. Spontaneous diastolic (phase 4) depolarizations are probably triggered by several currents, including I_f. T type calcium current is activated early during the diastolic depolarization, followed by the L type calcium current that triggers a "slow" action potential. Differential sensitivity to adrenergic and vagal inputs exists along the nodal pacemaker cells, such that superior sites tend to dominate during adrenergic drive while the inferior sites predominate during vagal stimulation.[3] Interventions including premature stimulation, autonomic stimulation, and drugs have been shown to induce pacemaker shifts (due to multicentric origins) with variable exit locations.[4]

Atrioventricular node

The compact AV node is a sub-endocardial structure situated within the triangle of Koch and measuring 5–7 mm in length and 2–5 mm in width.[5,6] On the atrial side, the node is an integral part of the atrial musculature, in contrast to the AV bundle which is insulated within the central fibrous body and merges with the His bundle. Based on action potential morphology in rabbit hearts, atrial (A), nodal (N), and His (H) cells have been defined. Intermediate cell types such as AN and NH define areas toward the atrial and His bundle ends of the compact node, respectively. Histologically, the mid nodal part has densely packed cells in a basket-like structure interposed between the His bundle and the loose atrial approaches to the node. The AN cells are comprised primarily of transitional cells. Distinct electrical and morphological specialization is seen only in the progressively distal His fibers. Rightward and leftward posterior extensions of the AV node were described by Inoue and Becker.[7] These extensions have clinical implications for defining re-entrant circuits that act as a substrate of AV nodal re-entrant tachycardia.

The AV node has extensive autonomic innervation and an abundant blood supply from the large AV nodal artery, a branch of the right coronary artery, in 90% of patients, and from the left circumflex artery in 10% (Figure 1.1). AV nodal conduction is mediated via "slow" calcium-mediated action potential and demonstrates decremental conduction due to post repolarization refractoriness as a result of delayed recovery of the slow inward currents. AV nodal tissue closer to the His bundle (NH

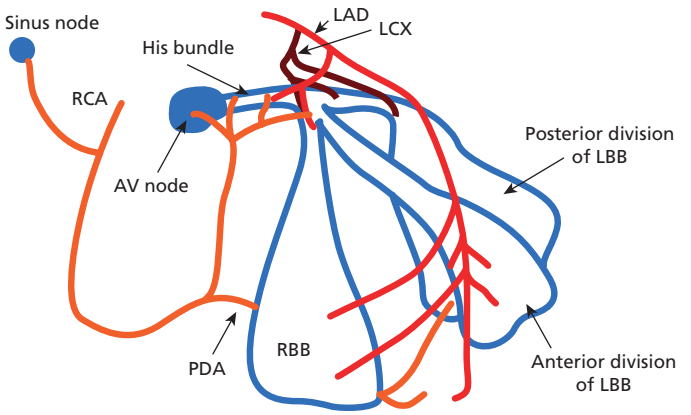


Figure 1.1 Schematic of the conduction system with arterial supply shown. LAD, left anterior descending coronary artery; LBB, left bundle branch; LCX, left circumflex coronary artery; RBB, right bundle branch; RCA, right coronary artery.

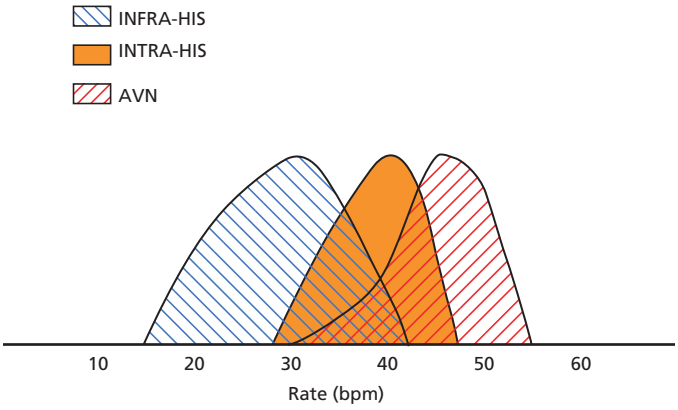


Figure 1.2 Rate of escape rhythm from various areas of the conduction system. AVN, atrioventricular node; Infra-His, below the bundle of His; Intra-His, within the His bundle.

and proximal His bundle area) generates junctional escape rhythms (Figure 1.2). Escape rates are dependent on the site of dominant pacemaker activity. Isoproterenol stimulation, for example, accelerates junctional escape and shifts the dominant activity to the transitional cells in the AN region and posterior extensions of the node.[8–10]

His–Purkinje system

Purkinje fibers emerging from the area of the distal AV node converge gradually to form the His bundle, a narrow tubular structure that runs through the membranous septum to the crest of the muscular septum, where it divides into the bundle branches. The His bundle has relatively sparse autonomic innervation, although its blood supply is quite ample, emanating from both the AV nodal artery and the septal branches of the left anterior descending artery (Figure 1.1). Longitudinal strands of Purkinje fibers, divided into separate parallel compartments by a collagenous skeleton, can be discerned by histological examination of the His bundle. Relatively sparse P cells can also be identified, embedded within the collagen. The rapid conduction of electrical impulses across the His–Purkinje system is responsible for the almost simultaneous activation of the right and left ventricles.

The bundle branch system is a complex network of interlaced Purkinje fibers that varies greatly among individuals. It generally starts as one or more large fiber bands that split and fan out across the ventricles until they finally terminate in a Purkinje network that interfaces with the myocardium (Figure 1.1). In some cases, the bundle branches clearly conform to a tri- or quadrifascicular system. In other cases, however, detailed dissection of the conduction system has failed to delineate separate fascicles. The right bundle is usually a single, discrete structure that extends down the right side of the interventricular septum to the base of the anterior papillary muscle, where it divides into three or more branches. The left bundle more commonly originates as a very broad band of interlaced fibers that spread out over the left ventricle, sometimes in two or three distinct fiber tracts. There is relatively little autonomic innervation of the bundle branch system, but the blood supply is extensive, with most areas receiving branches from both the right and left coronary systems.

Indications for permanent pacemakers

Permanent pacing is considered in a number of clinical situations, some of which are unambiguous whereas others require a higher level of expertise for determination of potential benefit. However, two major factors determine the need for cardiac pacing: (1) symptoms associated with a bradyarrhythmia and (2) the site of conduction abnormality in the conduction system. In addition, the determination will depend on whether the conduction disease is likely to be permanent or reversible, such as due to a drug effect or acute inflammatory or ischemic process. A permanent pacemaker is generally a life-long commitment for a patient; the

need for a generator changes and surgical revisions for malfunction become important considerations in younger patients. Hence, the decision to implant a pacemaker is not to be taken lightly.

A joint committee of the American College of Cardiology (ACC) and the American Heart Association (AHA) was formed in the 1980s to provide uniform criteria for pacemaker implantation. These guidelines were first published in 1984 and most recently revised in 2008 in conjunction with the Heart Rhythm Society (HRS).[11] A task force for cardiac pacing and cardiac resynchronization therapy published similar guidelines in 2007.[12] A recent focused update to the ACC/AHA/HRS guidelines of 2008 was published in 2012.[13] It is recognized that there will be occasional cases that cannot be categorized based on these guidelines. Nevertheless, these guidelines have received wide endorsement and are periodically updated to incorporate important emerging data. A recent publication addressed the important issue of mode selection for cardiac pacing.[14] This subject is discussed in detail in Chapter 3.

All guideline recommendations are subdivided into three classes to reflect the magnitude of treatment effect (Table 1.1). A class I indication pertains to a condition in which the procedure or intervention confers definite benefits. A class III indication is one where the intervention is not helpful and potentially harmful, and hence, not recommended.

Table 1.1 Classes of guideline recommendations

Class I	Conditions for which there is evidence and/or general agreement that a pacemaker implantation is beneficial, useful, and effective
Class II	Conditions for which there is conflicting evidence and/or a divergence of opinion about the usefulness/efficacy of pacemaker implantation
Class IIa	Weight of evidence/opinion in favor of efficacy
Class IIb	Usefulness/efficacy less well established by evidence/opinion
Class III	Conditions for which there is evidence and/or general agreement that a pacemaker is not useful/effective and in some cases may be harmful

Additionally, the ACC/AHA Committee ranked evidence supporting its recommendations by the following criteria:

- *Level A:* Data derived from multiple randomized trials involving a large number of patients.
- *Level B:* Data derived from a limited number of trials involving a relatively small number of patients or from well-designed analyses of non-randomized studies or data registries.
- *Level C:* Recommendations derived from the consensus of experts.

Some class I indications will necessarily lack support from level A evidence due to early non-randomized studies documenting clear benefits such that randomized trials become unethical.

Sinus node dysfunction

Disorders of the sinus node can be divided into those primarily due to intrinsic pathology of the node and surrounding atrium, or extrinsic factors such as autonomic stimulation or drug effects. The terms sinus node disease (SND), sick sinus syndrome, and SA disease are often used interchangeably. All these refer to a broad range of abnormalities in the sinus node and atrial impulse formation and propagation (Table 1.2). They include persistent sinus bradycardia and/or chronotropic incompetence without identified cause, intermittent or persistent sinus arrest, and SA exit block. Frequently, atrial arrhythmias and sinus nodal dysfunction co-exist and cause symptomatic sinus pauses at cessation of an atrial arrhythmia (Figure 1.3). The term tachy–brady syndrome is applied because of the frequent need for bradycardia support with pacing to allow antiarrhythmic therapy for the tachycardia.

Pathology intrinsic to the sinus node is quite common, and its incidence increases with advancing age. Several patterns have been identified: A diffuse or localized atriopathy has been suggested. Electrophysiological studies have shown structural remodeling, particularly along the long axis of the crista terminalis, and associated with a more caudal migration of the atrial pacemaker activity.[8] Progressive down-regulation of the I_{CaL} channel and loss of connexin-43 expression are features in the guinea pig model.[15] In humans, such atriopathy is also associated with atrial arrhythmias, particularly

Table 1.2 Manifestations of sinus node dysfunction and their diagnosis

Sinus bradycardia	Sinus rates persistently <60 bpm and associated with symptoms. Prolonged sinus node recovery time (following atrial pacing) is helpful in diagnosing sinus node disease but has low sensitivity
Chronotropic incompetence	Sinus rate does not increase with exertion. Diagnosis made with exercise test or ambulatory ECG monitoring
Sinoatrial (SA) block	Sinus beats are "dropped" in a regular pattern (e.g.2:1 SA block, 3:2 SA Wenckebach, etc.) due to blocking of impulses in the perinodal area between the sinus node and atrial muscle (by disease, medications, etc.). Diagnosis is made by the use of continuous ECG monitoring
Sinoatrial pause	Failure of impulse formation in the sinus node due to pathology, medications, etc. The diagnosis is made electrocardiographically by an absence of sinus P waves that occurs without any discernible pattern
Tachy–brady syndrome	The diagnosis is made electrocardiographically by alternating periods of sinus bradycardia and tachycardia (most commonly atrial fibrillation or flutter). The bradycardia is often manifested by periods of prolonged sinus arrest that often occur at termination of tachycardia

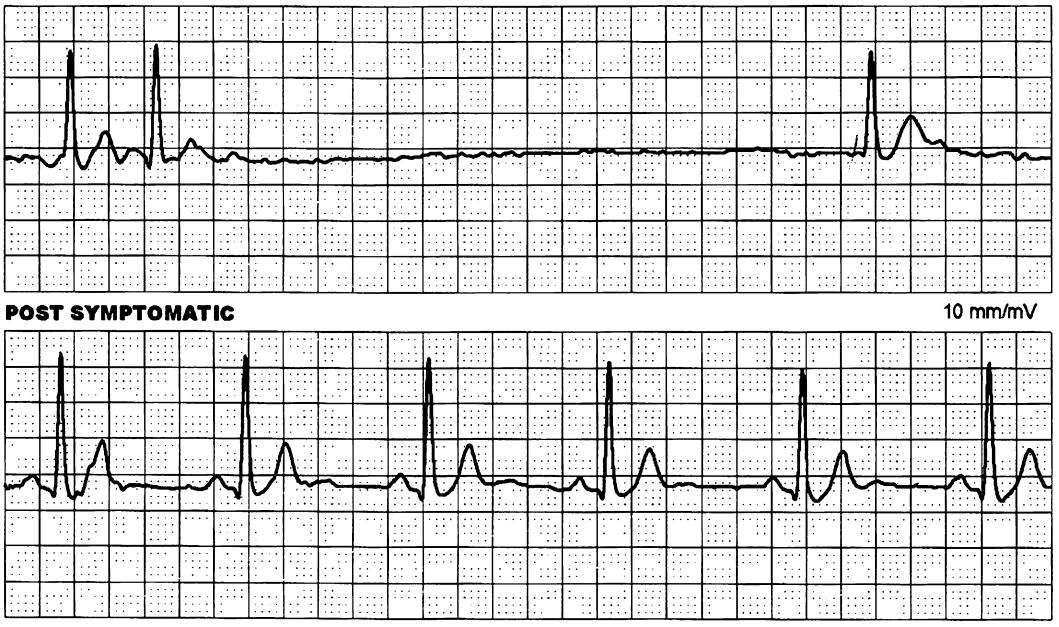


Figure 1.3 Tachy–brady syndrome due to sinus arrest at termination of atrial fibrillation. Patient-triggered event recording during presyncope in a 56-year-old male with paroxysmal atrial fibrillation shows an asystolic pause in excess of 4 s at termination of fibrillation. The sinus offset pause is intercepted by a junctional escape beat before resumption of normal sinus rhythm.

atrial fibrillation that develops in 50% of patients with SND. Atrial arrhythmias further aggravate SND and catheter ablation of fibrillation, and flutter has been shown to reverse some of the adverse electrical remodeling of the sinus node.[16] Atrophic or hypoplastic sinus node has been described in association with congenital anomalies. A familial form of SND is also recognized. Finally, idiopathic SND without any detectable morphological abnormality can occur and may be related to abnormal neural innervation.

In patients with sinus node dysfunction, the correlation of symptoms with bradyarrhythmias is *critically* important. This is because there is a great deal of disagreement about the absolute heart rate or length of pause required before pacing is indicated. If the symptoms of SND are dramatic (e.g. syncope, recurrent dizzy spells, seizures, or severe

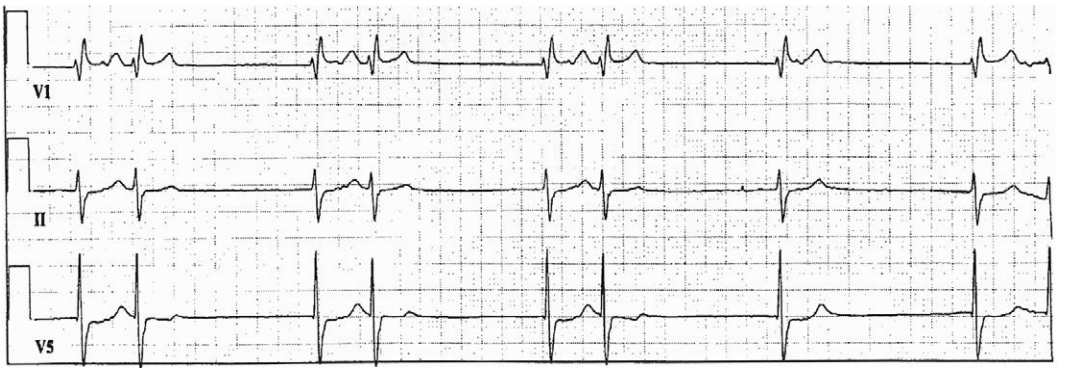


Figure 1.4 A 69-year-old male had been started on atenolol 75 mg/day for treatment of hypertension approximately 2 weeks earlier. He was seen in the emergency room complaining of feeling weak and lightheaded. The ECG shows a slow junctional escape rhythm followed by a sinus beat in a pattern termed "escape–capture bigeminy." Discontinuation of atenolol resulted in return of normal sinus rhythm within 36 h. Patients with sinus node dysfunction may be dependent upon sympathetic stimulation, and β-blockers, even in low doses, may result in profound bradycardia.

heart failure), then the diagnosis may be relatively easy. However, symptoms are often non-specific (e.g. easy fatigability, depression, listlessness, early signs of dementia) and may be easily misinterpreted in the elderly. Electrophysiological studies have a low sensitivity for detection of SND and ambulatory monitoring with symptom correlation has the best diagnostic yield.

Essential drugs used for co-existing conditions can accentuate SND (Figure 1.4). If cessation of a drug is anticipated to cause deterioration of the primary condition, permanent pacing may be needed to allow continuation of medical therapy in some patients. A group of patients has been identified who have a relatively fixed heart rate during exercise; this condition is referred to as chronotropic incompetence and can result in marked exercise intolerance in some patients. Heart rate response to exercise compared with that of an age- and gender-matched population is often necessary for clear diagnosis, although no specific parameter has been established as a diagnostic standard.

Patients with SND may have associated disease in the AV node and His–Purkinje conduction system. However, the rate of lone SND progressing to AV block is low. The mean annual incidence of complete AV block developing in patients implanted with AAI pacemakers for SND is 0.6% (range 0–4.5%) with an overall prevalence of 2.1% (range 0–11.9%).[11] The natural history of untreated SND is highly variable. Syncope resulting from sinus arrest tends to be recurrent and may result in falls and significant orthopedic injuries, especially in the elderly. The incidence of sudden death is low and SND very rarely affects survival regardless of whether or not it is treated with a pacemaker.

Indications for permanent pacing in sinus node dysfunction

Class I indications

1 Sinus node dysfunction with documented symptomatic bradycardia or sinus pauses. (Level of evidence: C)

2 Symptomatic chronotropic incompetence. (Level of evidence: C)

3 Sinus node dysfunction as a result of essential long-term drug therapy of a type and dose for which there are no acceptable alternatives. (Level of evidence: C)

Class IIa indications

1 Sinus bradycardia with a heart rate of less than 40 bpm when a clear symptom correlation has not been established with documented bradycardia. (Level of evidence: C)

2 Syncope of unexplained origin when clinically significant abnormalities of sinus node function are detected or provoked during electrophysiological studies. (Level of evidence: C)

Class IIb indications

1 In minimally symptomatic patients with persistent bradycardia with a heart rate of less than 40 bpm during awake hours. (Level of evidence: C)

Class III (permanent pacing not indicated)

1 Permanent pacing is not indicated in asymptomatic patients with SND. (Level of evidence: C)

2 Sinus node dysfunction in patients with symptoms suggestive of bradycardia that are clearly documented as not associated with a slow heart rate.

3 Sinus node dysfunction with symptomatic bradycardia due to non-essential drug therapy.

Acquired atrioventricular block

In the majority, sclerodegenerative changes account for progressive conduction system disease. However, in a significant proportion, AV block is secondary to other causes that are potentially reversible or associated with progressive heart disease with added risk of ventricular arrhythmias such that an implantable cardioverter–defibrillator (ICD) should be considered as a means of providing pacing therapy. In a recent review of unexplained heart block in patients under 55 years of age, cardiac sarcoidosis or giant cell myocarditis accounted for 25% of cases and these patients had a high incidence of sudden death, ventricular tachycardia, or need for cardiac transplantation.[17] In younger patients presenting with advanced conduction system disease, further evaluation with cardiac magnetic resonance (CMR) imaging or positron emission tomography (PET) is useful for detection of pathology that merits the use of an ICD as opposed to provision of cardiac pacing alone.

Based on electrocardiography (ECG) characteristics, AV block is classified as first, second, and third degree. Anatomically, block can occur at various levels in the AV conduction system; above the His bundle (supra-His), within the His bundle (intra-His), and below the bundle of His (infra-His). First-degree AV block is defined as abnormal prolongation of the PR interval to greater than 200 ms and is commonly due to delay in the AV node irrespective of QRS width. Type I second-degree heart block refers to progressive PR prolongation before a non-conducted beat and a shorter PR interval after the first blocked beat. This is the classical Wenckebach type AV block usually seen in conjunction with narrow QRS complexes, implying a more proximal level of block, usually in the AV node (Figure 1.5). Type II second-degree heart block is characterized by fixed PR intervals before and after blocked beats, and is usually associated with a wider QRS complex, indicating distal levels of block in the conduction system. Type II second-degree AV block is usually below the level

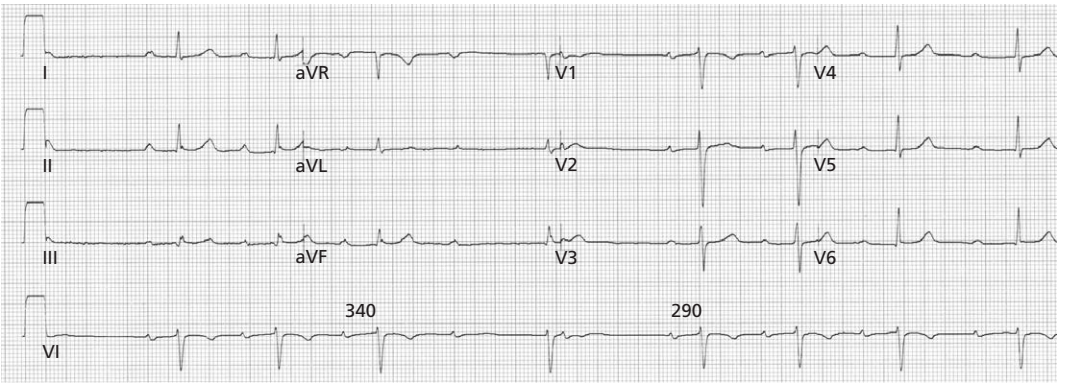


Figure 1.5 Type 1 second-degree atrioventricular (AV) block associated with Lyme disease. This 32-year-old male presented with complaints of palpitation due to heart beat irregularity. He had features of Lyme disease several weeks previously. There is progressive PR prolongation before the fourth P wave fails to conduct. The fourth QRS complex is a junctional escape beat. The sixth P wave that conducts has a shorter PR interval (290 ms) compared to the last conducted beat before block occurred (340 ms).

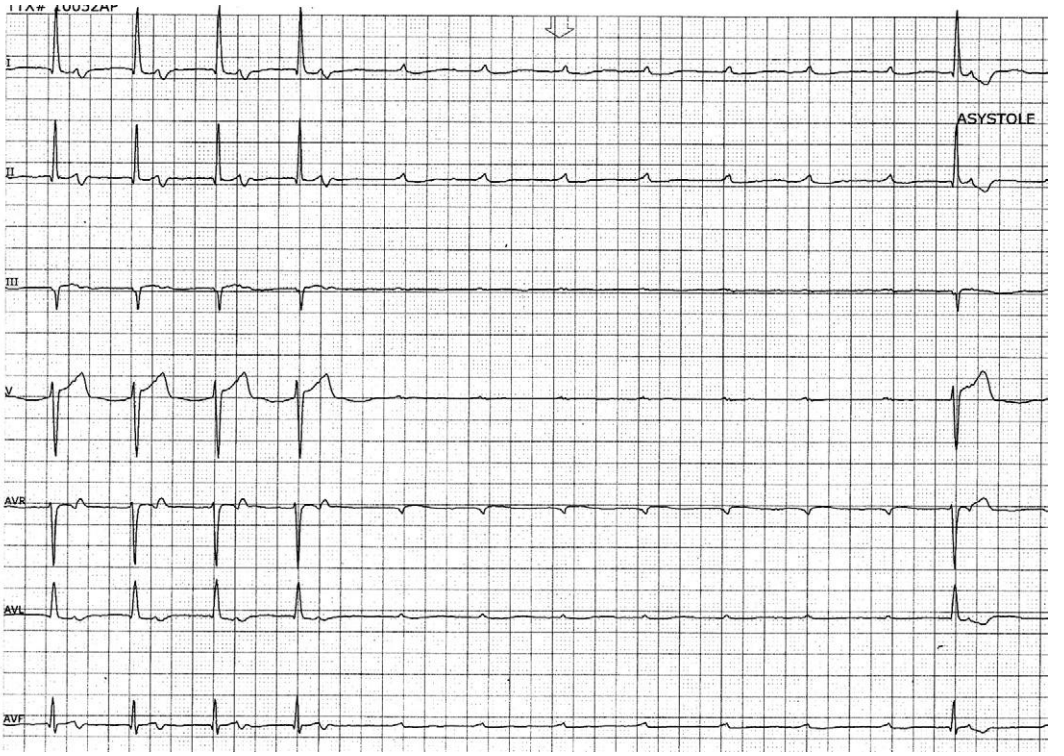


Figure 1.6 High-grade atrioventricular (AV) block. This 60-year-old female with hypertension and coronary artery disease presented with syncope. Baseline ECG showed marked first-degree AV block and voltage changes of left ventricular hypertrophy. Telemetry recorded abrupt interruption of AV conduction with multiple non-conducted P waves with spontaneous recovery. Her β-adrenergic blockers were continued as essential treatment for coronary artery disease and a permanent pacemaker was implanted.

of the AV node (within or below the His bundle); symptoms and progression to complete AV block are common. AV conduction in a 2:1 pattern can be due to proximal or distal block, although the width of the QRS can help differentiate these based on the above principle. Advanced second-degree block or "high-grade" AV block refers to two or more non-conducted sinus P waves, but with resumption of conducted beats suggesting preservation of some AV conduction (Figure 1.6). In the setting of atrial fibrillation or flutter, a prolonged pause (e.g. >5 s) is often due to advanced second-degree AV block. Third-degree AV block is defined as the absence of AV conduction. In the case of atrial fibrillation, complete AV block often manifests as a regularized slow ventricular rate.

The site of AV block will to a great extent determine the adequacy and reliability of the underlying escape rhythm (Figure 1.7 and Figure 1.8). While ECG characteristics are helpful in defining levels of block, they are not always reliable and occasionally, an electrophysiological study is required. Type I second-degree block, for example, can occasionally be infranodal, even with a narrow QRS, and may warrant the consideration of pacing.[18] Certain clinical maneuvers may be helpful in determining the level of block. Increased AV conduction with exercise and atropine generally indicate block at the AV nodal level, while maneuvers that slow the atrial rate, such as carotid massage, improve His–Purkinje conduction by allowing for recovery from refractoriness (Table 1.3).

There is considerable variation in the symptomatic manifestation of AV block, ranging from an asymptomatic status to syncope and sudden death. First-degree AV block and asymptomatic type I second-degree AV block are in general benign and not an indication for cardiac pacing. However,

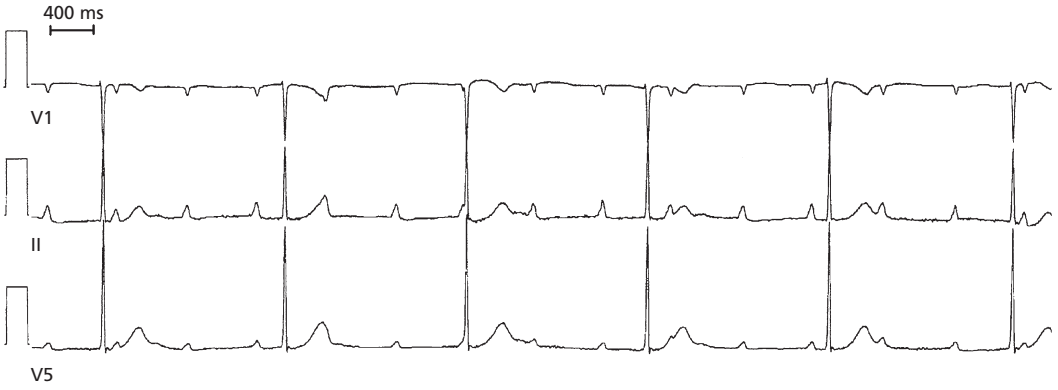


Figure 1.7 Complete heart block with narrow QRS escape rhythm. This 70-year-old male presented with fatigue. Rhythm strips reveal complete AV block and a slow junctional escape rhythm with narrow QRS complexes. A permanent dual chamber pacemaker completely relieved his symptoms.

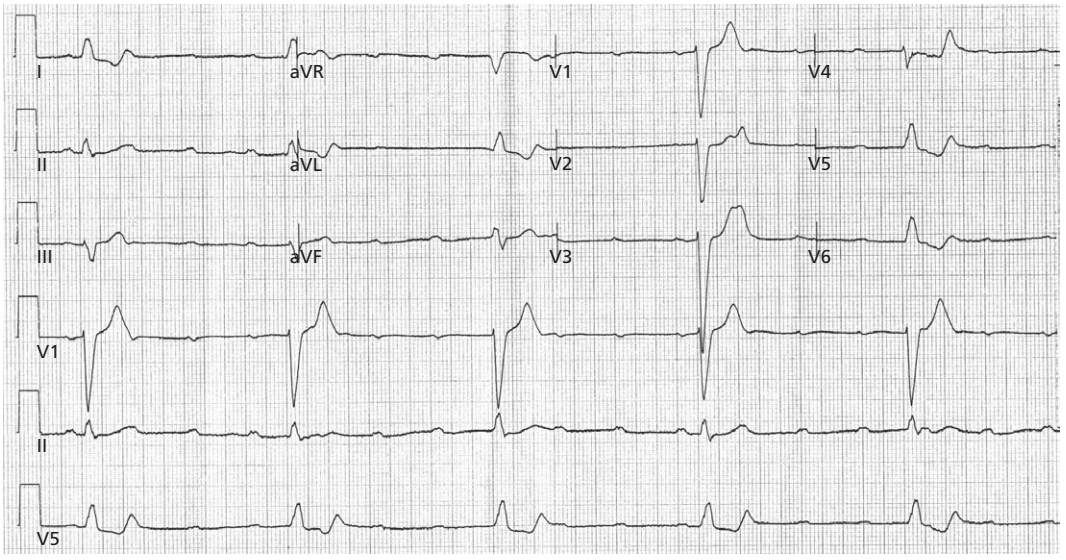


Figure 1.8 Complete AV block with wide QRS escape rhythm. This 77-year-old male presented with syncope without warning and sustained facial injuries. The slow ventricular escape rhythm at 30 bpm likely originates from the right bundle branch. Intermittent asystole due to unstable escape rhythm was the most likely cause of syncope.

Table 1.3 Responses to maneuvers to identify level of block in patients with 2:1 atrioventricular (AV) block

	Block above AV node	*Block below AV node*
Exercise	+	± or −
Atropine	+	± or −
Carotid sinus massage	−	+ or ±
Isoproterenol	+	− or ±

+, improved AV conduction; −, worsened AV conduction.

rarely, first-degree block with marked PR prolongation can potentially cause atrial systole to occur in close proximity to the preceding ventricular systole and give rise to symptoms similar to those of a pacemaker syndrome.[19] Prolongation of the PR interval is particularly important in patients with left ventricular (LV) dysfunction as marked PR prolongation in excess of 250–300 ms can lead to impaired LV filling, increased pulmonary capillary wedge pressure, and decreased cardiac output.[20]

Similar consequences can ensue in patients with type I second-degree AV block even in the absence of bradycardia-related symptoms.

Type II second-degree AV block is important as it has a high rate of progression to third-degree AV block. It usually reflects diffuse conduction system disease and often warrants permanent pacing even in the absence of symptoms. Third-degree AV block with a wide QRS escape rhythm, often present with fatigue, dyspnea, pre-syncope or frank unheralded syncope. Rarely, ventricular fibrillation and torsades de pointes ventricular tachycardia (VT) can result from marked bradycardia and prolonged pauses. Permanent cardiac pacing should be strongly considered even if the escape rate is greater than 40 bpm, because it is not necessarily the escape rate that determines a safe and reliable heart rhythm but the site of origin of the escape rhythm. Infra-His escape rhythms are more likely associated with prolonged asystole, syncope, and death (Figure 1.8).

AV block, usually with 2:1 AV conduction, can be provoked by exercise (Figure 1.9). Patients typically complain of exertional dyspnea and dizziness. The abnormality is often reproducible by exercise testing. Once ischemia is excluded as a cause, permanent pacing is remarkably effective for symptom relief. Without pacing, these patients have a poor prognosis because the site of conduction block is below the AV nodal level.[21]

A distinct form of paroxysmal AV block associated with syncope has been described in patients without structural heart disease or evidence for conduction disturbance on ECG.[22] Patients present with abrupt syncope associated with abrupt onset of high-grade AV block and prolonged asystole, with recovery of normal AV conduction soon afterward. Electrophysiological studies do not indicate the presence of His–Purkinje disease. The majority tends to have an exaggerated response to intravenous adenosine, raising the possibility of a variant of reflex syncope (see "Reflex syncope"). However, the classical sinus slowing prior to onset of AV block that is typical of vagally-mediated AV block, is usually absent in this group of patients.

In general, the presence of symptoms documented to be due to AV block is an indication for permanent pacing regardless of the site of the block (e.g. above the His bundle as well as below the His bundle). However, it is important to recognize potentially reversible causes of AV block despite their presentation with symptoms. Important examples include acute myocarditis (particularly that associated with Lyme carditis), AV block related to drug toxicity, transient vagotonia, and hypoxic events. Many of these conditions tend to resolve with disease-specific treatment and although temporary pacing may be required, permanent pacing is seldom necessary. One exception is drug-related AV block that may not always resolve completely on cessation of the medication and may need permanent pacing (see "Temporary pacing indications"). The indications for permanent pacing of heart block due to acute myocardial infarction (MI), congenital AV block, and increased vagal tone differ and are discussed in "Reflex syncope," "Congenital complete AV block," and



Figure 1.9 Exercise-induced atrioventricular (AV) block. This 68-year-old male presented with exertional dyspnea. His baseline ECG showed sinus rhythm with first-degree AV block and left anterior hemiblock. With gentle leg elevation exercise in the examination room while connected to the ECG, 2:1 AV block developed as the PP intervals shortened from 860 ms to 800 ms. This finding is typical of block below the AV node. Permanent dual chamber cardiac pacing relieved his symptoms.

"Permanent pacing after acute myocardial infarction."

Indications for permanent pacing in acquired AV block

Class I indications

1 Third-degree and advanced second-degree AV block at any anatomical level, associated with any one of the following conditions:

- **a** Bradycardia with symptoms (including heart failure) presumed to be due to AV block. (Level of evidence: C)
- **b** Arrhythmias and other medical conditions requiring drugs that result in symptomatic bradycardia. (Level of evidence: C)
- **c** Documented periods of asystole of 3.0 s or longer, any escape rate of less than 40 bpm or with any escape rhythm below the AV node in awake, symptom-free patients. (Level of evidence: C)
- **d** Atrial fibrillation and bradycardia with one or more pauses of at least 5 s or longer in awake, symptom-free patients. (Level of evidence: C)
- **e** Following catheter ablation of the AV junction. (Level of evidence: C)
- **f** Postoperative AV block that is not expected to resolve after cardiac surgery. (Level of evidence: C)
- **g** Neuromuscular diseases with AV block, such as myotonic muscular dystrophy, Kearns–Sayre syndrome, Erb muscular dystrophy, and peroneal muscular atrophy, with or without symptoms, because there may be unpredictable progression of AV conduction disease. (Level of evidence: B)

2 Second-degree AV block regardless of type or site of block, with associated symptomatic bradycardia. (Level of evidence: B)

3 Third-degree AV block with evidence for cardiomegaly or LV dysfunction. (Level of evidence: B)

Class IIa indications

1 Persistent third-degree AV block with an escape rate of greater than 40 bpm in asymptomatic adult patients without cardiomegaly. (Levels of evidence: C)

2 Asymptomatic type II second-degree AV block at intra-His or infra-His levels found at electrophysiological study. (Level of evidence: B)

3 First- or second-degree AV block with symptoms similar to those of pacemaker syndrome or hemodynamic compromise. (Level of evidence: B)

4 Asymptomatic type II second-degree AV block with narrow QRS. Note that when type II second-degree AV block occurs with wide QRS, including isolated right bundle branch block (RBBB), pacing becomes a class I indication. (Level of evidence: B)

Class IIb indications

1 Neuromuscular diseases such as myotonic muscular dystrophy, Kearns–Sayre syndrome, Erb muscular dystrophy, and peroneal muscular atrophy with any degree of AV block (including first-degree AV block), with or without symptoms, because there may be unpredictable progression of AV conduction disease. (Level of evidence: B)

2 AV block in the setting of drug use and/or toxicity when the block is expected to recur even after the drug is withdrawn. (Level of evidence: B)

Class III (not indicated)

1 Asymptomatic first-degree AV block. (Level of evidence: B)

2 Asymptomatic type I second-degree AV block at the AV nodal level or not known to be intra- or infra-Hisian. (Levels of evidence: C)

3 AV block expected to resolve and/or unlikely to recur (e.g. drug toxicity, Lyme disease, or transient increases in vagal tone or during hypoxia in sleep apnea syndrome in the absence of symptoms). (Level of evidence: B)

Chronic bifascicular block

In bifascicular block, the ECG shows evidence of conduction delay in both bundles such as complete RBBB with anterior or posterior hemiblock or complete left bundle branch block (LBBB) alone. The term alternating bundle branch block (BBB; or bilateral BBB) refers to evidence for impaired conduction in the right bundle and both fascicles of the left bundle on successive ECGs. In strict terms, evidence for disease in all three fascicles should justify the term trifascicular block. However, the term trifascicular block has also been loosely applied to bifascicular block with first-degree AV block where the block may actually be due to either

or a combination of AV nodal and infra-His conduction disease.

The prevalence of BBB increases with age (approximately 1% in middle age and rising to 17% at age 80).[23] LBBB is less common but its presence is associated with a higher incidence of structural heart disease. In bifascicular block, the risk of progression to advanced heart block is related to the presence of symptoms. Syncope is the sole predictor. In the absence of syncope, the annual incidence is 0.6–0.8%, whereas syncopal patients have a 5–11% annual risk of progression to AV block.[24,25] The finding of an His–ventricular (HV) interval of greater than 100 ms or the demonstration of intra- or infra-Hisian block during incremental atrial pacing at a rate of less than 150 bpm is highly predictive for the development of high-grade AV block (Figure 1.10), but their prevalence is low and hence, sensitivity is low.[26,27] Care has to be exercised during atrial pacing so as not to misinterpret physiological AV block that is often seen with long–short intervals. The majority of patients with bifascicular block who undergo electrophysiological studies will have normal or mildly prolonged HV intervals. However, in patients with BBB and normal electrophysiological study, implantable loop monitors have shown that recurrent syncope is often due to a bradyarrhythmia, most commonly sudden onset paroxysmal AV block.[28] Hence, unexplained syncope is a better indicator of the need for pacing than electrophysiological studies.

Because chronic bifascicular block is associated with other forms of heart disease, pacing alone, although successful for symptom relief, has not been shown to improve mortality. In the presence of ventricular dysfunction, ventricular tachycardia is an alternative mechanism for syncope and sudden death. Programmed stimulation of the ventricle may demonstrate inducibility for ventricular arrhythmia, necessitating the consideration of an ICD.

Indications for pacing in chronic bifascicular block

Class I indications

1 Advanced second-degree AV block or intermittent third-degree AV block. (Level of evidence: B)
2 Type II second-degree AV block. (Level of evidence: B)
3 Alternating BBB. (Level of evidence: C)

Class IIa indications

1 Syncope not demonstrated to be due to AV block and when other likely causes have been

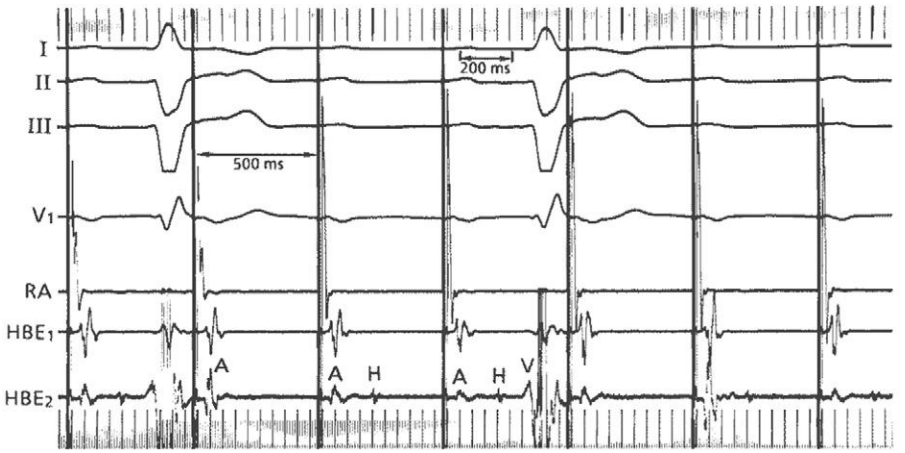


Figure 1.10 Infra-His atrioventricular (AV) block induced with atrial pacing. A 68-year-old male was admitted complaining of recurrent dizziness and syncope. His baseline 12-lead ECG showed a PR interval of 0.20 s and a right bundle block QRS morphology. With decremental atrial pacing, block below the His bundle was demonstrated at 500 ms (120 bpm). These findings are indicative of severe diffuse conduction system disease. A permanent dual chamber pacemaker was implanted, and the patient's symptoms resolved. From top to bottom: I, II, III, and V_1 are standard ECG leads; intracardiac recording from the right atrial appendage (RA) and His bundle (HBE_1 for the proximal His bundle and HBE_2 for the distal His bundle). A, atrial depolarization; H, His bundle depolarization; V, ventricular depolarization.

excluded, specifically ventricular tachycardia. (Level of evidence: B)
2 Incidental finding at electrophysiology study of markedly prolonged HV interval (≥100 ms) in asymptomatic patients. (Level of evidence: B)
3 Incidental finding at electrophysiology study of pacing-induced infra-His block that is not physiological. (Level of evidence: B)

Class IIb indications

1 Neuromuscular diseases such as myotonic muscular dystrophy, Kearns–Sayre syndrome, Erb muscular dystrophy, and peroneal muscular atrophy with any degree of fascicular block with or without symptoms, because there may be unpredictable progression of AV conduction disease. (Level of evidence: C) (*Note that this is a class IIa indication in European guidelines.*)

Class III (not indicated)

1 Fascicular block without AV block or symptoms. (Level of evidence: B)
2 Fascicular block with first-degree AV block without symptoms. (Level of evidence: B)

Reflex syncope

Reflex syncope includes a group of conditions that are neurally mediated and result in a common cardiovascular response of vasodilation and/or bradycardia. Cerebral hypoperfusion results in loss of consciousness. Any one of the two components of the reflex may predominate. The cardioinhibitory response with predominant bradycardia results from increased parasympathetic tone and is characterized by sinus slowing, sinus arrest (Figure 1.11), prolongation of the PR interval, and less commonly, AV block that occurs alone or in combination. The vasodepressor response is secondary to a reduction in sympathetic activity and marked by loss of vascular tone and hypotension. This effect is independent of heart rate changes.

The two most common types of reflex syncope are neurocardiogenic (vasovagal) and carotid sinus syndrome. The other types are generally referred to as situational syncope because they are generally associated with a particular stimulus (Table 1.4). Several forms are recognized based on the triggering mechanism, although the triggers may vary considerably in and between individual patients. The classical vasovagal syncope is most common in young patients and occurs as isolated episodes. Generally, patients experience a distinct prodrome of dizziness, nausea, diaphoresis, and visual changes, followed by loss of consciousness. Recovery is fairly rapid and it is unusual to experience post-ictal states. However, a third of patients (commonly older adults) may have minimal or no prodromal symptoms and syncope can be sudden with bodily injuries. When vasovagal syncopal spells begin at an older age, they may be an expression of a pathological process heralding early autonomic failure.[29]

Table 1.4 Types of neurally-mediated syncope (Source: Adapted from Taskforce 2009.[29] Reproduced with permission of Oxford University Press.)

Vasovagal	Mediated by emotional stress such as fear, pain, sight of blood, instrumentation
	Mediated by orthostatic stress
Carotid sinus syncope	
Situational	Cough, sneeze
	Gastrointestinal stimulation: swallow, defecation, visceral pain
	Micturition syncope
	Post exercise
	Post prandial
Other	Triggered by increased intrathoracic pressure, e.g. laughing, playing brass instruments, weightlifting
Atypical forms	No identified precipitant

Reflex syncope becomes important when frequent syncope alters quality of life, occurs with a very short prodrome exposing patients to risk of trauma, or occurs during high-risk activity such as driving, flying, or heavy machine operation. Non-pharmacological measures such as avoidance measures, physical counter-pressure maneuvers, and tilt training are useful initial interventions for control of vasovagal syncope.[30] Pharmacological interventions predominantly address the vasodepressor component and may occasionally be effective for individual patients, but randomized trials have not proven clear benefit from any particular drug. Observational studies suggest that β-adrenergic blockers may be effective in patients over the age of 40 years by alleviating the



Figure 1.11 Marked cardioinhibitory response to neurally-mediated syncope. This 45-year-old female presented with syncope preceded by nausea while wearing an event monitor. There was gradual sinus slowing with prolonged sinus arrest resulting in syncope. Intense vagal stimulation can suppress junctional escape rhythms.

hyperadrenergic initial response that often precedes vasovagal syncope.[31]

The role of cardiac pacing in vasovagal syncope has been evaluated in multiple clinical trials with varying results. Meta-analysis of these studies suggested a 17% non-significant reduction in syncope in double-blind studies when both the paced and unpaced groups received pacemaker implants (thereby eliminating a placebo effect). More recent trials using implantable loop recorders (ILRs) to document asystole during vasovagal syncope have been more favorable toward permanent cardiac pacing for symptom relief. The ISSUE 3 study randomized patients aged 40 years or older, with three

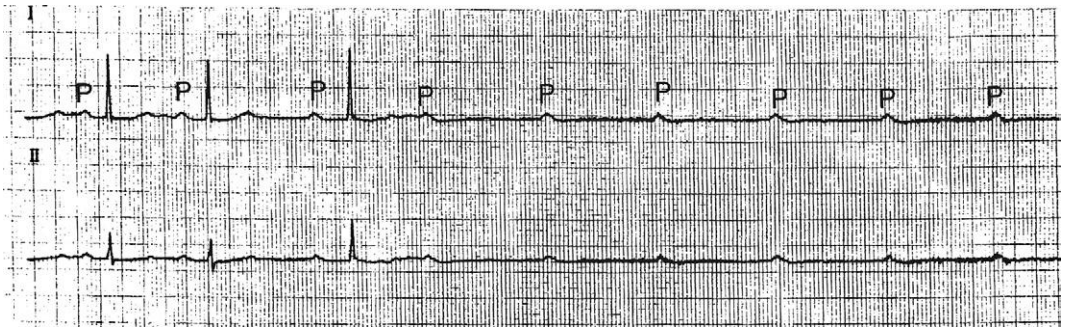


Figure 1.12 Response to gentle carotid massage in carotid hypersensitivity syndrome. A 49-year-old male complained of near-syncope, which typically occurred while shaving or turning his neck. Carotid sinus massage was performed shortly before the second QRS complex. Note that the sinus rate slows prior to the third QRS complex, followed by complete heart block with ventricular asystole.

or more syncope episodes and documentation of syncope with greater than 3-s asystole or 6s asystole without syncope, to pacing-activated or -inactivated modes after implantation. The study showed a significant reduction in recurrent syncope at 2 years from 57% in the pacing inactivated group to 25% in the paced group.[32] However, it should be noted that 511 patients with highly symptomatic vasovagal syncope underwent implantation of an ILR in order to identify 89 (17%) patients with important asystole.

In the presence of predominantly cardioinhibitory responses, cardiac pacing tends to be effective for attenuation of symptoms and is a reasonable consideration in the older patients. Because the cardioinhibitory and vasodepressor components can variably manifest in the same patient during different episodes, patients should be warned of the possibility of recurrence relating to hypotension. In younger patients, however, simple measures should be exhausted before considering commitment to life-long pacemaker therapy. In the ISSUE 3 study, pacemaker implantation was associated with complications in 6%. Longer-term complications of pacemaker generator changes and lead malfunction are more pertinent to younger patients.

One variant of neurally-mediated syncope is the hypersensitive carotid sinus syndrome. A mildly abnormal response to vigorous carotid sinus massage may occur in up to 25% of patients, especially if co-existing vascular disease is present. Some patients with an abnormal response to carotid sinus massage may have no symptoms suggestive of carotid sinus syncope. On the other hand, the typical history of syncope such as blurred vision and lightheadedness or confusion in the standing or sitting position, especially during movement of the head or neck, should suggest the diagnosis. Classical triggers of carotid sinus syncope are head turning, tight neckwear, shaving, and neck hyperextension. Syncopal episodes are generally reproducible in a given patient. Because of the predominantly bradycardic (cardioinhibitory) response to carotid hypersensitivity, permanent pacing has a high success rate for alleviating symptoms (Figure 1.12).

Indications for pacing in neurally-mediated syncope and hypersensitive carotid sinus syndrome

Class I indications

1 Recurrent syncope caused by spontaneous carotid sinus stimulation; carotid sinus pressure induces ventricular asystole of greater than 3-s duration. (Level of evidence: C)

Class IIa indications

1 Recurrent syncope without clear, provocative events and with a hypersensitive cardioinhibitory response of 3 s or longer. (Level of evidence: C)

Class IIb indications

1 Significantly symptomatic and recurrent neurocardiogenic syncope associated with bradycardia documented spontaneously or at the time of tilt table testing. (Level of evidence: B)

The 2007 European guidelines state that recurrent severe vasovagal syncope with prolonged asystole during ECG recording or tilt table testing, after failure of medical therapy, is a class IIa indication in patients aged over 40 years and a class IIb indication in patients under 40 years.

Class III (not indicated)

1 A hyperactive cardioinhibitory response to carotid sinus stimulation in the absence of symptoms or in the presence of vague symptoms.

2 Situational vasovagal syncope in which avoidance behavior is effective and preferred.

The European guidelines recommend avoidance of pacing in patients with vasovagal symptoms in whom significant bradycardia cannot be documented.[12]

Idiopathic orthostatic hypotension

Idiopathic orthostatic hypotension is a related neurocirculatory disorder that may respond to permanent pacing. Small single-center studies have documented a beneficial response to atrial or AV sequential pacing in a small number of patients with idiopathic orthostatic hypotension refractory to salt and steroid therapy.[33,34] A potential mechanism for benefit includes increased cardiac output from pacing at higher rates (the lower rate in these series varied from 80 to 100 bpm), and consequent vasoconstriction. The therapy, while beneficial in some, has significant variability in response from patient to patient. There are currently no class I or class II indications for permanent pacing for idiopathic orthostatic hypotension.

Specific conditions associated with cardiac conduction disease

Chronic neuromuscular disorders

A number of neuromuscular disorders are associated with cardiomyopathy and a high incidence of sudden death. In general, the direct consequence of the neuromuscular defects, such as respiratory failure, limits life span. However, in some of these conditions, cardiac disease may be responsible for greater morbidity and mortality. Most often, bradyarrhythmias in neuromuscular disorders are due to direct involvement of the specialized AV conduction system. The relatively small numbers of patients involved and the absence of randomized, placebo-controlled clinical trials make it difficult to provide definitive guidelines for pacemaker implantation. Since mortality and the incidence of sudden cardiac death are high in this group of disorders, and because conduction system disease tends to be unpredictable, the development of second- or third-degree AV block, even in the absence of symptoms, is considered a class I indication for permanent pacing. In addition, suggestive symptoms such as syncope should be promptly and aggressively investigated. Some authorities recommend yearly ECGs and 24-h ambulatory recordings for patients with one of these disorders to facilitate early recognition of AV block. It should also be realized, however, that life-threatening ventricular arrhythmias are also fairly common in this population, especially when LV function is impaired or complicated by hypertrophic cardiomyopathy (HCM), so use of a permanent pacemaker will not necessarily prevent sudden cardiac death.

The neuromuscular disorders most frequently associated with symptomatic conduction system disease are as follows.

Myotonic muscular dystrophy

The type 1 form (Steinert disease) is the most common adult form of neuromuscular disease and is inherited as an autosomal dominant disorder that usually becomes clinically manifest in the third decade. A third of deaths are sudden and related to heart block or ventricular tachyarrhythmias.[35,36] Permanent pacemakers are warranted for second- or third-degree AV block, even in the absence of symptoms. A recent large nonrandomized study of type 1 myotonic dystrophy patients compared an invasive electrophysiological evaluation when PR interval exceeded 200 ms and/or QRS was prolonged in excess of 100 ms with a non-invasive clinical approach. The invasive group who underwent pacemaker implantation based on the finding of an HV interval greater than 70 ms had a significant reduction in sudden death.[37]

Duchenne muscular dystrophy

This progressive X-linked disease usually becomes clinically apparent in the mid-teens and is fatal by the end of the third decade. The ECG typically

shows prominent R waves in V1 with deep narrow Q waves in the lateral precordial leads. Although cardiac involvement is almost universal, the incidence of arrhythmias is variable, with many patients dying from heart failure. In the absence of definitive data, it seems prudent to recommend permanent pacemaker implantation in patients who develop second-degree or higher degrees of AV block, especially in the setting of a wide QRS complex.

Becker muscular dystrophy

This is an X-linked condition closely related to Duchenne muscular dystrophy. It has similar electrocardiographic abnormalities, but progresses more slowly. The severity of cardiac involvement does not parallel the severity of neuromuscular disease. Although there is less experience with this disorder, the indications for permanent pacing are similar to those for patients with Duchenne muscular dystrophy.

Emery–Dreifuss muscular dystrophy

This is a slowly progressive X-linked muscular dystrophy with a high incidence of conduction system disease and arrhythmias. Sudden cardiac death due to bradyarrhythmias has been well documented, and permanent pacemakers are often necessary.

Limb girdle muscular dystrophy

This is a heterogeneous group of disorders that usually begin with weakness in the upper legs and pelvic musculature. Cardiac involvement is variable, although there is a familial form with a high incidence of conduction system disease. Patients with a family history of heart block or sudden death should be considered for permanent pacing relatively early in the course of their disease.

Kearns–Sayre syndrome

This is a multisystem mitochondrial disorder characterized by progressive external ophthalmoplegia, pigmentary retinal degeneration, and AV block. Involvement of the distal conduction system is the rule and high-degree AV block is common. Although definitive data are lacking, it seems prudent to implant a permanent pacemaker prophylactically when marked first-degree AV block becomes manifest.

Indications for pacing in the chronic neuromuscular disorders

These are included under "Acquired atrioventricular block."

Infiltrative and inflammatory disorders

The infiltrative cardiomyopathies are characterized by deposition of abnormal substances that commonly lead to stiffening of the ventricular myocardium, causing diastolic dysfunction. Many of these diseases increase wall thickness, and may present with small ventricular volume and occasional LV outflow tract (LVOT) obstruction so as to mimic HCM. Some may have minimal structural abnormalities by echocardiography but involve the conduction system early such that initial presentation may be with heart block or ventricular arrhythmias. Infiltrative and inflammatory cardiomyopathies particularly prone to manifest cardiac conduction disease include sarcoidosis, giant cell myocarditis, amyloidosis, Wegener's granulomatosis, metabolic diseases such as hemochromatosis, primary oxaluria, and hematological malignancies and cardiac tumors. Some metabolic diseases such as Fabry disease and the glycogen storage diseases (e.g. Danon disease) demonstrate frequent cardiac involvement. AV block, although rare, is well recognized in these conditions. In South American countries, Chagas disease is a common cause of bradyarrhythmias requiring cardiac pacing.

The prognosis of many of these disorders is usually more closely related to the underlying disease, although the actual cause of death may be cardiac. For example, malignancies involving the heart, especially "solid" tumors, tend to have a uniformly poor prognosis. Nonetheless, infiltrative disorders may directly affect the conduction system and cause life-threatening bradyarrhythmias and tachyarrhythmias. In these situations, permanent pacemakers or defibrillators can be life saving.

Sarcoidosis

This is a relatively common disorder of unknown etiology and is characterized by formation of noncaseating granulomas in various organs, including the myocardium. After an early stage of granulomatous inflammation, sarcoidosis may resolve completely or progress with end organ fibrosis.

Cardiac involvement is common in autopsy studies but infrequently recognized clinically, and is a common cause of death. Approximately 5% of patients will have cardiac-predominant disease without evidence for other organ involvement.[38] Granulomas typically involve the basal septum and posterior wall, resulting in conduction system disease, localized LV aneurysms, and ventricular tachycardia. Definitive diagnosis requires demonstration of cardiac granulomas, but patchy myocardial involvement reduces yield from cardiac biopsy to a low 25–30%. Imaging with fluorodeoxyglucose (^{18}F-FDG) and PET or CMR can identify inflammation and has better diagnostic accuracy compared with older techniques.[39]

Although conduction abnormalities are the most common cardiac presentation, the risk of sudden death from ventricular arrhythmias is high in the presence of significant cardiac involvement. Hence, once a diagnosis of cardiac sarcoidosis is established, it is common to consider an ICD.[11] Treatment with corticosteroids has been shown in retrospective studies to stabilize LV function, but has no significant impact on conduction disease or ventricular arrhythmias.[40]

Amyloidosis

The amyloidoses are a group of multisystem diseases characterized by deposition of the extracellular proteinaceous material, amyloid. These deposits occur as a result of misfolding of a precursor protein.[41] The most common clinical amyloidoses that involve the heart are those due to deposition of light chains (AL amyloid), and a hepatically expressed protein, transthyretin (TTR). A rarer form of wild-type TTR infiltration is seen in men aged older than 70 years and is termed senile amyloidosis. Cardiac involvement is the most common cause of death in amyloidosis and manifests as marked wall thickening due to infiltration in all anatomical distributions, including the atria, ventricles, and perivascular space. Because the infiltration is extracellular, despite the appearance of increased wall thickness on echocardiography, the voltage on surface ECG will be low and is a clue to the diagnosis. Perivascular fibrosis can affect the specialized conduction system, causing SND, intraventricular conduction defects, or AV block. Patients with senile cardiac amyloidosis most commonly progress to heart block. Permanent pacing is helpful in alleviating symptoms, but has not been demonstrated to provide a survival benefit.[42]

Collagen vascular diseases

Several systemic inflammatory diseases can involve the heart and vascular structures, resulting in pericarditis, myocarditis, and vasculitis, including coronary artery disease. Arrhythmias are not common, but fibrosis of the conduction system has been reported to cause AV block, particularly in Wegener granulomatosis, and polymyositis. An acute inflammatory AV block that reverses with treatment has been reported with Wegener granulomatosis. Congenital heart block associated with the transmission of anti-SS A Ro-antibodies from the mother occurs in systemic lupus erythematosis and to a lesser extent in primary Sjögren syndrome (see "Pacing for children and adolescents").[43]

Chagas disease

This chronic inflammatory disease, caused by the protozoa *Trypanosoma cruzi*, is largely restricted to endemic areas in Central and South America. The acute phase of the infection usually goes unrecognized and is rarely life threatening. Approximately 20% of patients will develop chronic Chagas disease several years (10–20 years) after the initial infection. Conduction system disease precedes other manifestations, such as localized cardiac aneurysms, thromboembolism, and a diffuse cardiomyopathy with marked cardiomegaly. Sinus bradycardia, atrial fibrillation, AV block, and ventricular arrhythmias are common. Even the early phases of conduction abnormalities, such as RBBB and fascicular block, are associated with an increased risk of sudden death.[44]

Genetic cardiomyopathies

Familial or genetic cardiomyopathies account for 20–30% of disease originally diagnosed as idiopathic dilated cardiomyopathy. These cardiomyopathies share some management strategies. Once the proband is identified, evaluation of family members can identify clinically silent cardiomyopathy and allow for early interventions. Genetic

testing can be helpful in some diseases, especially if the pathogenic mutation is identified.[45]

Dilated cardiomyopathy

Cardiomyopathies resulting from mutations in the genes coding for the nuclear envelope protein lamina A and C (*LMNA*) and mutations in the *SCN5A* gene are particularly associated with conduction system disease and ventricular arrhythmias.[45] Mutations in *LMNA* associated with cardiomyopathy are highly penetrant, with most carriers demonstrating some evidence of cardiac involvement by 65 years of age. Initial manifestations may be first-degree AV block with gradual progression to compete heart block. Associated atrial arrhythmias are common. Cardiomyopathy usually follows the development of conduction system disease by several years and risk of ventricular arrhythmias is highest when significant systolic dysfunction is present.[40] The diagnostic possibility of an inherited cardiomyopathy has two implications for the relatively young patient presenting with complete heart block: (1) a cardiac evaluation is warranted prior to permanent pacemaker implantation and (2) periodic assessment of LV function is essential after cardiac pacing for early detection of LV dysfunction. Indications for pacing in dilated cardiomyopathy are discussed under "Pacing for systolic heart failure."

Hypertrophic cardiomyopathy

This is a common disease entity caused by autosomal dominant mutations in genes encoding protein components of the sarcomere and its constituent myofilament elements. It is characterized by excessive myocardial hypertrophy without cavity dilatation, but varying degrees of phenotypic expressions exist. The disease may manifest with LVOT obstruction, diastolic dysfunction, mitral regurgitation, myocardial ischemia, arrhythmias including atrial fibrillation, and sudden death. The distinction between the obstructive and non-obstructive varieties is important because management strategies are largely dependent on symptoms of obstruction. LVOT obstruction is well recognized to be dynamic. Although initially attributed to systolic contraction of the hypertrophied basal ventricle encroaching on the outflow tract, recent studies emphasize the importance of drag forces on an abnormally positioned mitral apparatus that push the leaflets into the outflow tract during systole.[46]

In HCM with significant LV outflow obstruction, atrial synchronized RV apical pacing results in decrease in outflow gradient and symptomatic improvement in a subset of patients. The exact mechanism of improvement is unclear, but may be related to paradoxical septal movement during systole, although alternate or additional mechanisms such as ventricular dilatation and chronic remodeling may play a part.

Initial enthusiasm for dual chamber pacing in obstructive HCM was tempered by randomized trials that eliminated a placebo effect. In three randomized cross-over trials of continuous DDD pacing compared with AAI pacing, the overall reduction in outflow tract gradient with DDD pacing was modest (20–40%), with substantial variation among individual patients, and symptomatic improvement was no different from that in AAI paced patients.[46] Acute hemodynamic studies and echocardiographic LV morphology do not predict long-term benefit from dual chamber pacing. One subgroup that appears to derive most benefit is patients over the age of 65 years.[47] When pacing is performed to relieve outflow tract obstruction in HCM, it is important to optimize AV delay to allow ventricular pre-excitation, but not to compromise ventricular filling with too short a delay. In addition, rate adaptive AV delay is necessary to maintain ventricular pre-excitation during exercise. The position of the ventricular lead should be such that it provides distal apical capture.

Permanent pacing is currently not considered an early mode of intervention for symptomatic obstructive HCM. Surgical myomectomy or alcohol septal ablation has been shown to provide more reliable and consistent clinical improvement. Pacing is therefore considered only for patients who are not candidates for these interventions or for those with pre-existing dual chamber pacing devices. Approximately 10–20% of patients will develop persistent complete heart block following alcohol septal ablation and will require permanent cardiac pacing. The risk of ventricular arrhythmias following septal ablation ranges in various reports from 2% to 5% per year. The choice of pacemaker

versus ICD should be based on current guideline recommendations.[46]

Indications for permanent pacing for hypertrophic cardiomyopathy (adapted from guidelines published in 2011[46])

Class I indications

1 Class I indications for sinus node dysfunction or AV block as previously described. (Level of evidence: C)

Class IIa indications

1 In patients with HCM who have had a dual chamber device implanted for non-HCM indications, it is reasonable to consider a trial of dual chamber AV pacing from the RV apex for the relief of symptoms attributable to LVOT obstruction. (Level of evidence: B)

Class IIb indications

1 Permanent pacing may be considered in medically refractory symptomatic patients with obstructive HCM who are suboptimal candidates for septal reduction therapy. (Level of evidence: B)

Class III (not indicated)

1 Permanent pacing implantation for the purpose of reducing gradient should not be performed in patients with HCM who are asymptomatic or whose symptoms are medically controlled. (Level of evidence: C)

2 Permanent pacing implantation should not be performed as a first-line therapy to relieve symptoms in medically refractory symptomatic patients with HCM and LVOT.

Pacing for systolic heart failure

Early studies suggested that dual chamber pacing, especially with a short AV delay, improved hemodynamics by optimizing ventricular filling or reducing diastolic mitral regurgitation. However, randomized studies failed to confirm these beneficial effects. In contrast, there is considerable evidence that the use of biventricular pacing, by providing cardiac resynchronization therapy (CRT), reduces heart failure symptoms and lowers heart failure mortality with or without an ICD.[11] CRT has been well studied in randomized trials involving over 6000 patients and has demonstrated favorable structural remodeling with improved LV function and reduced mitral regurgitation in 70% of patients. Recent trials of less symptomatic patients (NYHA class I and II) show a reduction in composite end points of heart failure hospitalization and death, but mortality reduction is limited to class II patients.[48,49] All but one trial of CRT involved the use of an ICD as opposed to a CRT pacemaker. Consequently, it is common practice to incorporate defibrillator therapy when CRT pacing is indicated. However, CRT pacing alone has a significant impact on improving quality of life and functional status, and is a reasonable choice in older patients when prolongation of life is not the primary consideration. In addition, for patients who demonstrate a cardiomyopathy as a result of dyssynchrony induced by RV pacing, addition of a LV pacing lead to provide biventricular pacing alone may result in adequate reversal of cardiomyopathy and avoid the need for an ICD.

CRT device implantation is more difficult than placement of a non-CRT pacemaker or ICD and complication rates are greater, usually related to the additional manipulations required for the lead and its delivery systems. Lead dislodgement requiring revision is particularly more common.[50] Appropriate patient selection for this therapy is therefore crucial for ensuring benefit. In *post-hoc* subgroup analyses of clinical trials, factors associated with the most benefit from CRT include non-ischemic dilated cardiomyopathy, the presence of LBBB, and QRS duration of 150 ms or longer.[51] The recent 2012 focused update guideline of the ACC/AHA/HRS limits the class I indication for CRT to patients with LBBB and a QRS duration of 150 ms or longer.[13]

The role of biventricular pacing in atrial fibrillation is less well established. As the purpose of pacing is to correct LV dyssynchrony, adequate heart rate control in atrial fibrillation is essential to allow for consistent biventricular pacing. Often, this requires AV nodal ablation.[52]

Indications for pacing in heart failure and impaired LV systolic function

Class I indications

1 Class I indications for sinus node dysfunction or AV block as previously described. (Level of evidence: C)

2 CRT pacing in patients with an LV ejection fraction (LVEF) of 35% or less, sinus rhythm, LBBB, and QRS duration of150 ms or longer, and NYHA class II, III, or ambulatory IV symptoms on guideline directed medical therapy (GDMT). (Level of evidence: A for NYHA III/IV and B for NYHA class II) Most of these patients will qualify for ICD therapy. The choice between a biventricular pacemaker and a biventricular ICD should be made based upon the patient's preference and other clinical factors.

Class IIa indications

1 CRT pacing can be useful in patients with an LVEF of 35% or less, sinus rhythm, LBBB with a QRS duration of 120–149 ms and NYHA class II, III or ambulatory IV symptoms on GDMT. (Level of evidence: B)

2 CRT can be useful in patients with a LVEF of 35% or less, sinus rhythm, non-LBBB pattern with a QRS duration of 150 ms or longer, and NYHA class III or ambulatory IV symptoms on GDMT. (Level of evidence A)

3 CRT can be useful in patients with atrial fibrillation and an LVEF of 35% or less on GDMT if:

a the patient requires ventricular pacing or otherwise meets CRT criteria and

b AV nodal ablation or pharmacological rate control will allow near 100% ventricular pacing with CRT. (Level of evidence: B)

4 CRT can be useful in patients on GDMT who have an LVEF of 35% or less and are undergoing device placement or replacement with anticipated requirement for significant (>40%) ventricular pacing. (Level of evidence: C)

Class IIb indications

1 CRT may be considered for patients who have an LVEF of 35% or less, ischemic etiology for heart failure, sinus rhythm, LBBB with a QRS duration of 150 ms or longer, and NYHA class 1 symptoms on GDMT. (Level of evidence: C)

2 CRT maybe considered for patients who have an LVEF of 35% or less, sinus rhythm, non-LBBB pattern with a QRS duration 120–149 ms, and NYHA class III/ambulatory class IV symptoms on GDMT. (Level of: B)

3 CRT maybe considered for patients who have an LVEF of 35% or less, sinus rhythm, non-LBBB pattern with a QRS duration of 150 ms or longer, and NYHA class II symptoms on GDMT. (Level of evidence: B)

Class III (not indicated)

1 CRT pacing is not recommended for patients with NYHA class I or II symptoms and a non-LBBB pattern with a QRS duration of less than 150 ms. (Level of evidence: B)

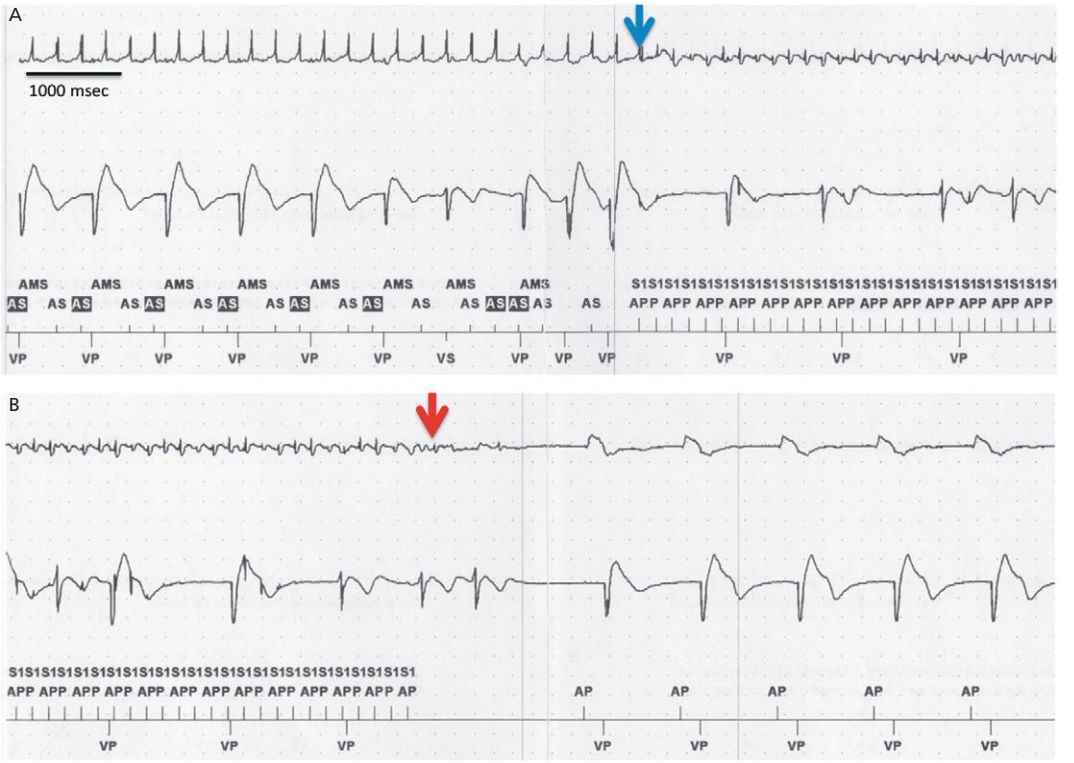
2 CRT is not indicated in patients whose functional status and life expectancy are limited predominantly by chronic non-cardiac conditions. (Level of evidence: C)

Pacing to prevent or terminate tachycardias

Pacing techniques may terminate arrhythmias that depend on a re-entrant mechanism. For supraventricular tachycardias (SVTs) and atrial arrhythmias, antiarrhythmic drugs or catheter-based ablation is often effective in preventing recurrence and hence, in contemporary practice, the use of cardiac pacing is limited to patients who have associated bradyarrhythmias. Rarely, a patient who fails on or is unsuitable for drugs or ablation may benefit from antitachycardia pacing if reliable and repetitive termination of the arrhythmia can be demonstrated without pro-arrhythmic effects (Figure 1.13). Such devices for pacing without defibrillation capability are limited to the atrium. Ventricular antitachycardia pacing is currently only available with ICDs.

Ventricular arrhythmias may be pause dependent and pacing prevents prolonged pauses and can prevent the arrhythmia in some patients. Typically, the onset of torsades de pointes VT in patients with a prolonged QT interval is preceded by long RR intervals (Figure 1.14). Pacing combined with β-adrenergic blockers has been shown to reduce the occurrence of sudden cardiac death in patients with the congenital long-QT syndrome.[53] In patients with long-QT syndrome at high risk for sudden death however, such pacing is usually provided via an ICD.

Several modes of permanent pacing therapy have been tested for prevention of atrial fibrillation. However, none of the special pacing techniques, such as dual site atrial pacing, biatrial pacing, alternative sites for atrial pacing in the region of the


A
1000 msec
AMS AMS AMS AMS AMS AMS AMS AMS
AS AS AS AS AS AS AS AS AS AS AS AS AS
VP VP VP VP VP VP VS VP VP VP
S1S1S1

Class IIa indications

1 Permanent pacing is reasonable for high-risk patients with congenital long-QT syndrome. (Level of evidence: C) (Note that most of these patients will qualify for an ICD.)

2 Symptomatic recurrent SVT that is reproducibly terminated by pacing in the unlikely event that catheter ablation and/or drugs fail to control the arrhythmia or produce intolerable side effects. (Level of evidence: C)

Class IIb indications

1 Prevention of symptomatic, drug-refractory recurrent atrial fibrillation in patients with co-existing sinus node dysfunction. (Level of evidence: B)

Class III (not indicated or recommended)

1 The presence of accessory pathways with the capacity for rapid anterograde conduction whether or not the pathway(s) participate in the mechanism of the tachycardia.

2 Frequent or complex ventricular ectopic activity without sustained VT in the absence of the long-QT syndrome.

3 Torsades de pointes VT due to reversible causes.

Pacing for children and adolescents (including all patients with congenital heart block)

There are no randomized clinical trials of permanent pacing in pediatric patients and those with congenital heart disease. Hence, the level of evidence for most recommendations is consensus based. The general indications for pacing in children and adolescents are similar to those for adults but with several additional considerations. The diagnosis of important bradycardia in children is age dependent. Whereas a heart rate of 45 bpm would be considered normal for an adult, the same rate would indicate profound bradycardia in a newborn or infant with marked hemodynamic consequences. In addition, the abnormal cardiovascular physiology resulting from palliative surgery for congenital heart diseases can place postsurgical patients at risk for decompensation from bradycardia or loss of AV synchrony that may have been well tolerated by patients with normal physiology. Further, the risk of paradoxical embolism from thrombus on endocardial leads is a consideration in patients with significant intracardiac shunts. Finally, the technical challenges of vascular access and long-term consequences of endovascular leads in children often prompt the consideration of epicardial systems at early ages. While this may be appropriate for children weighing less than 10–15 kg, in larger children, the risk of thoracotomy and the higher rate of epicardial lead failures have to be balanced against vascular occlusions from endovascular lead placement. Long-term RV pacing can lead to ventricular dysfunction and periodic assessment by echocardiography is helpful in the detection of early LV dysfunction, especially in patients with congenital heart disease and genetic cardiomyopathies.

The common indications for pacing in children, adolescents, and patients with congenital heart disease can be broadly divided into: (1) sinus bradycardia, (2) tachy–brady syndrome, and (3) congenital or postsurgical advanced second- or third-degree AV block. SND is rare in pediatric patients but when present, may be associated with mutations in the *SCN5A* gene.[55] Pacing is usually reserved for situations where symptoms such as syncope can be correlated with bradyarrhythmias (<40 bpm or >3-s pause). It should be recognized that apnea, seizures, and neurocardiogenic mechanisms might cause concurrent bradycardia. Correction of the primary abnormality is more effective than long-term pacing for these conditions.

The common form of tachy–brady syndrome seen in children follows surgery for congenital heart disease. Intra-atrial re-entrant tachycardia with loss of sinus node function can manifest as recurrent palpitation, hemodynamic compromise, and prolonged sinus pauses at termination of the atrial tachycardia. Although permanent atrial-based pacing, including antitachycardia pacing to terminate intra-atrial re-entry, is a potential treatment option, catheter-based ablation of these arrhythmias is optimal if it can be achieved successfully.

Congenital complete AV block is a rare anomaly that results from abnormal embryonic development of the AV node and is not associated with structural heart disease in 50% of cases. Patients

can be broadly divided into antibody (maternal anti-SS/Ro and/or anti-SSb/La antibodies) positive and antibody negative groups. When anti-SSA/Ro antibodies are present in the sera of mothers with connective tissue disease, the incidence of congenital heart block in live births has been reported to be 1–2%.[56] The antibodies cross the placenta and damage the conduction system; heart block develops *in utero* and in the early neonatal stage. Less commonly, late postnatal development of heart block has been described. The antibody negative group tends to present at a later stage and heart block is progressive.

Most children with isolated congenital complete AV block have a stable escape rhythm with a narrow complex. The indications for pacing continue to evolve. Pacing is generally indicated in symptomatic children with complete heart block or if the heart rate in the neonate is less than 55 bpm. In the asymptomatic child or adolescent with complete congenital AV block, several criteria, including average heart rate, pauses in intrinsic rate, associated structural heart disease, QT interval, and exercise tolerance, have been suggested as indications for pacing.[57,58]

Congenital heart diseases such as corrected transposition of the great arteries, ostium primum atrial septal defects, and ventricular septal defects may be associated with complete heart block. Patients who develop permanent postsurgical complete AV block have a poor prognosis without cardiac pacing. Hence, advanced AV block that persists for longer than 7–10 days postoperatively is considered a class 1 indication for pacing.

Indications for permanent pacing in children and adolescents

Class I indications

1 Advanced second- or third-degree AV block associated with symptomatic bradycardia, ventricular dysfunction, or low cardiac output. (Level of evidence: C)

2 Sinus node dysfunction with correlation of symptoms during age-inappropriate bradycardia. The definition of bradycardia varies with the patient's age and expected heart rate. (Level of evidence: B)

3 Postoperative advanced second- or third-degree AV block that is not expected to resolve or persists for at least 7 days after cardiac surgery. (Levels of evidence: B)

4 Congenital third-degree AV block with a wide QRS escape rhythm, complex ventricular ectopy, or ventricular dysfunction. (Level of evidence: B)

5 Congenital third-degree AV block in the infant with a ventricular rate of less than 55 bpm or with congenital heart disease and a ventricular rate of less than 70 bpm. (Levels of evidence: C)

Class IIa indications

1 Patients with congenital heart disease and sinus bradycardia for prevention of recurrent episodes of intra-atrial re-entrant tachycardia; SND may be intrinsic or secondary to antiarrhythmic treatment. (Level of evidence: C)

2 Congenital third-degree AV block beyond the first year of life with an average heart rate of less than 50 bpm, abrupt pauses in ventricular rate that are two or three times the basic cycle length, or associated with symptoms due to chronotropic incompetence. (Level of evidence: B)

3 Sinus bradycardia with complex congenital heart disease and a resting heart rate of less than 40 bpm or pauses in ventricular rate of longer than 3 s. (Level of evidence: C)

4 Patients with congenital heart disease and impaired hemodynamics due to sinus bradycardia or loss of AV synchrony. (Level of evidence: C)

5 Unexplained syncope in a patient with prior congenital heart surgery complicated by transient complete heart block with residual fascicular block after a careful evaluation to exclude other causes of syncope. (Level of evidence: B)

Class IIb indications

1 Transient postoperative third-degree AV block that reverts to sinus rhythm with residual bifascicular block. (Level of evidence: C)

2 Congenital third-degree AV block in asymptomatic children or adolescents with an acceptable heart rate, narrow QRS complex, and normal ventricular function. (Level of evidence: B)

3 Asymptomatic sinus bradycardia after biventricular repair of congenital heart disease with resting heart rate of less than 40 bpm or pauses in ventricular rate longer than 3 s. (Level of evidence: C)

Class III (not indicated)

1 Transient postoperative AV block with return of normal AV conduction in the otherwise asymptomatic patient. (Level of evidence: B)

2 Asymptomatic postoperative bifascicular block with or without first-degree AV block in the absence of prior transient complete AV block. (Level of evidence: C)

3 Asymptomatic type I second-degree AV block. (Level of evidence: C)

4 Asymptomatic sinus bradycardia in the adolescent with longest RR interval of less than 3 s and minimum heart rate of greater than 40 bpm. (Level of evidence: C)

Permanent pacing after the acute phase of myocardial infarction

Bradyarrhythmias and conduction defects are relatively common after acute myocardial infarction (MI). They are the result of both autonomic stimulation and ischemia or necrosis of the conduction system. In a large randomized trial of thrombolysis in acute MI, AV block occurred in approximately 7%.[59] The location of the infarction influences the type of conduction defect; AV block associated with inferior wall MI is often at the AV nodal level with narrow QRS escape rhythms, is usually transient, and has a good prognosis. Permanent pacing is rarely required. AV block in association with an anterior MI is most often due to extensive myocardial necrosis that includes the conduction tissue, tends to be infranodal with unstable wide QRS escape, and carries a high mortality, although acute revascularization strategies have improved outcomes in these patients (Figure 1.15 and Figure 1.16). Intraventricular conduction defects (IVCDs) after acute MI occur transiently in up to 18.4% of patients and in a permanent form in 5.3%.[60] The incidence of AV block is higher in post MI patients who develop transient AV block associated with a persisting peri-infarct IVCD other than isolated left anterior fascicular block.

Although temporary pacing is often necessary in the acute phase of infarction, the need for permanent pacing is less common and mostly dictated by the presence of IVCDs and not necessarily by the presence of symptoms. The long-term prognosis for patients who develop AV block and an IVCD is strongly influenced by the extent of myocardial injury and hemodynamic status (Figure 1.15). The need for temporary pacing in the acute stages of infarction is not by itself an indication for permanent pacing. Patients who have an indication for permanent pacing after ST elevation MI and severe LV dysfunction should be evaluated for an ICD indication if recovery of ventricular function is not anticipated.

Indications for permanent pacing following acute myocardial infarction

Class I indications

1 Persistent second-degree AV block in the His–Purkinje system with alternating BBB or third-degree AV block within or below the His–Purkinje system after ST segment elevation MI. (Level of evidence: B)

2 Transient advanced (second- or third-degree) infranodal AV block and associated BBB. If the site of block is uncertain, an electrophysiology study may be necessary. (Level of evidence: B)

3 Persistent and symptomatic second- or third-degree AV block. (Level of evidence: C)

Class IIb indications

1 Persistent second- or third-degree AV block at the AV node level even in the absence of symptoms. (Level of evidence: B)

Class III (not indicated)

1 Transient AV block in the absence of IVCDs. (Level of evidence: B)

2 Transient AV block in the presence of isolated left anterior fascicular block. (Level of evidence: B)

3 New BBB or fascicular block in the absence of AV block. (Level of evidence: B)

4 Persistent first-degree AV block in the presence of BBB or fascicular block. (Level of evidence: B)

Pacing after cardiac surgery and transcatheter aortic valve implantation

Approximately 3–5% of patients will develop persistent bradyarrhythmias after open heart surgery, with a higher incidence following repeat surgery. Sinus node dysfunction may result from right atrial cannulation for cardiopulmonary bypass, but

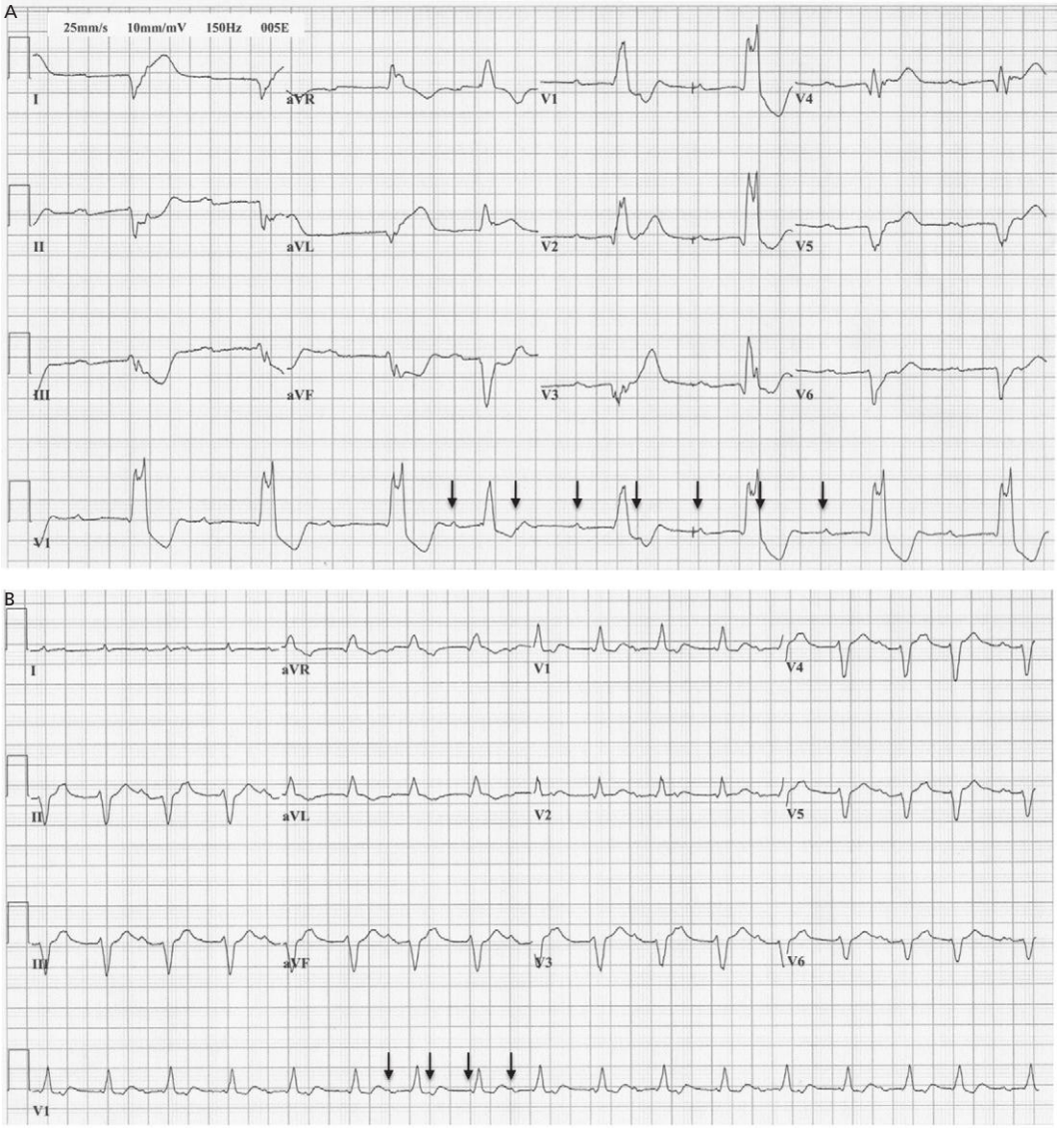


Figure 1.15 Acute anterior myocardial infarction complicated by complete atrioventricular (AV) block. This 82-year-old male presented with acute left main coronary artery occlusion in cardiogenic shock. (A) The initial ECG shows complete AV block with wide complex escape and evidence of ST elevation MI. The fourth and probably also the fifth complexes are conducted beats. P waves are indicated by arrows. He underwent temporary pacing, percutaneous intervention for acute revascularization and hemodynamic support with a percutaneous LV assist device. (B) ECG on the following day shows persistent complete AV block and an accelerated junctional rhythm with RBBB and left anterior hemiblock. Although the conduction abnormalities are indications for pacing, the associated myocardial damage and hemodynamic compromise limit prognosis. This patient succumbed to progressive multiorgan failure.

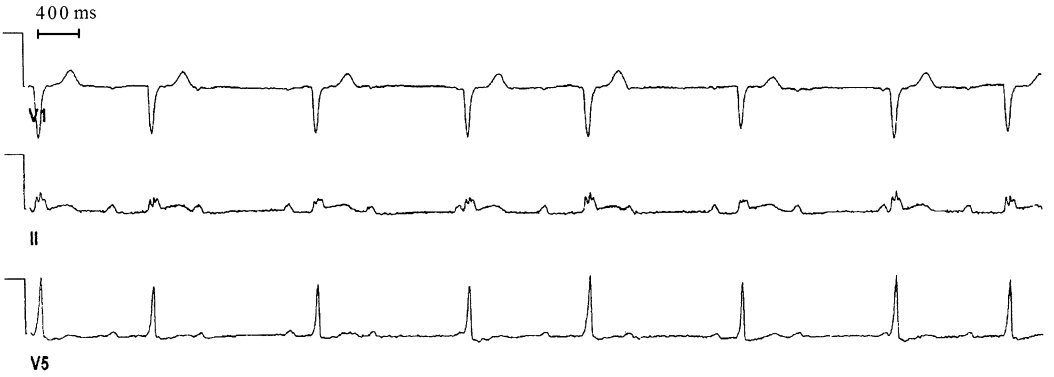


Figure 1.16 AV block associated with acute inferior myocardial infarction. Rhythm strips recorded from a 63-year-old female with an acute inferior wall myocardial infarction showing high-grade AV block with junctional escape beats. The second, fourth, and sixth QRS complexes are conducted with a prolonged PR interval (note shortening of the RR interval with the conducted beats). The presence of junctional escape beats precludes typical Wenckebach conduction. Because the patient was asymptomatic, no therapy was administered. Normal AV conduction resumed the following morning.

mostly resolves within a week. The development of paroxysmal atrial arrhythmia in conjunction with SND can be particularly troublesome to treat without temporary pacing support. However, once sinus node function recovers, antiarrhythmic drugs can often be employed safely for postoperative atrial arrhythmias.

In adults, persistent AV block is most common after valvular surgery, particularly tricuspid valve replacement. Risk is higher with multivalvular surgery.[61] In one large retrospective study, preexisting RBBB was more predictive than LBBB, but preoperative PR prolongation, repeat surgery, and age over 70 years were all predictors for the need for permanent pacing.[61] Because the majority of patients who develop bradyarrhythmias following cardiac surgery recover, it is customary to wait 7–10 days before consideration of permanent pacing. In the absence of the above risk factor and if there is evidence for continued improvement in sinus node function or AV conduction, longer waiting times may be justified. Patients who ultimately undergo permanent cardiac pacing tend to have a good prognosis and only about 40% remain dependent on pacing in the longer term.[62]

Transcatheter aortic valve implantation (TAVI) is rapidly evolving as an effective alternative to valve surgery for non-surgical patients with aortic stenosis. Unlike in the surgical procedure where the valve is excised prior to replacement, the calcified valve remains *in situ* in TAVI. Transcatheter placement of a valve prosthesis and balloon dilatation within this calcified valve produce a mass effect in the region of the membraneous septum and adjoining conduction system. This potential mechanism leads to persistent heart block requiring cardiac pacing in a fifth of patients.[63] New LBBB occurs in 5–6% of patients, but does not necessarily progress to heart block.[64] A third of cases of new AV block may be related to the acute balloon dilatation during the procedure and recover during the first 24 hours. QRS duration of less than 120 ms was predictive of recovery.[65] The risk of persistent AV block appears to be specific to the type of prosthestic valve used (27–33% for the Corevalve and 4–12% for the Edwards Sapiens valve). A valve prosthesis oversized for the native annulus was a risk factor in one series.[63]

Indications for temporary cardiac pacing

Temporary cardiac pacing is utilized for:

1 Treating a reversible condition causing bradycardia for which permanent pacing is unlikely to be necessary.

2 An interim measure while awaiting further assessment and implantation of a permanent system.

3 Prophylaxis against asystole during interventions expected to worsen a pre-existing conduction abnormality.
4 Overdrive pacing to terminate re-entrant supraventricular, atrial, and ventricular arrhythmias.
5 Suppression of bradycardia-dependent tachycardias such as torsades de pointes VT.

Acute myocardial infarction

Acute myocardial ischemia and infarction can precipitate sinus node dysfunction, AV block and IVCDs (see "Permanent pacing after the acute phase of myocardial infarction"). In the era of primary coronary interventions or thrombolysis, the need for temporary pacing is rare, although the incidence of IVCDs has not altered significantly compared with the prethrombolytic area. Abnormalities of sinus and AV nodal tissues are more common with inferior–posterior infarction because their blood supply is derived from the right coronary artery or left circumflex coronary artery and these are commonly involved in an inferior MI. Another potential reason is chemically-mediated activation of receptors on the posterior left ventricular wall; these receptors stimulate vagal afferent fibers, resulting in marked vagotonia and bradyarrhythmias.

Sinus bradycardia is the most common arrhythmia in inferior MI, occurring in 40% of patients in the initial 2 h. Half of these resolve by the end of the first day. Sinus node dysfunction occurring later in the course of acute MI might be secondary to atrial or sinus node ischemia. Treatment of sinus bradycardia is not usually necessary, unless symptoms such as worsening myocardial ischemia, heart failure or hypotension are documented. If bradycardia is prolonged and severe, or is not responsive to atropine, temporary cardiac pacing is indicated. A special circumstance to bear in mind involves sinus arrest with junctional rhythms that can occur in the context of a large right ventricular (RV) infarction. Here, maintenance of AV synchrony with AV sequential or atrial pacing is often necessary for maintenance of hemodynamic stability.

AV block can be progressive in the early phases of an acute inferior MI. A third of patients with first- or second-degree AV block can progress to complete AV block. However, block is located at the AV nodal level above the His bundle in 90% of patients with a stable junctional escape rhythm that responds to intravenous atropine. Hence, even complete AV block may not require temporary pacing if the patient is hemodynamically stable. Pacing is instituted only in the event of persisting heart block associated with hemodynamic compromise. Recovery is expected in 5–7 days. On the rare occasions that heart block persists, concomitant involvement of the left coronary system is likely with poor collateralization of the infarct region.

In contrast to inferior wall infarction, high-grade AV block complicating an anterior wall infarction is usually located within the His–Purkinje system. The transition from the first non-conducted P wave to high-grade AV block is often abrupt, and the resulting escape rhythm is typically slow and unreliable. Conducted beats usually have a wide QRS complex. In general, an interruption of the blood supply to the anterior wall and the interventricular septum severe enough to cause AV block usually causes severe LV dysfunction and results in high mortality. Emergency temporary pacing and prophylactic pacing are indicated, although survival may not be significantly improved because of the associated extensive myocardial damage.

New BBB is three times more likely during anterior infarction than during inferior infarction, because the left anterior descending coronary artery provides the major blood supply to the His bundle and the bundle branches (Figure 1.1). As with anterior MI and complete heart block, new BBB reflects extensive myocardial damage and is associated with a four-fold increase in risk of progression to high-grade AV block (an increase from 4% to 18%). Both in-hospital and out-of-hospital mortality are higher for patients presenting with BBB during acute infarction. Development of RBBB tends to carry a worse prognosis than LBBB. The effect of thrombolytic and early interventional therapies on the subsequent development of high-grade AV block in patients presenting with acute infarction and IVCD has been poorly studied.

Indications for temporary transvenous pacing in acute myocardial infarction[66]

Class I indications
1 Asystole.
2 Symptomatic bradycardia (includes sinus bradycardia with hypotension and type I

second-degree AV block with hypotension not responsive to atropine).
3 Bilateral BBB [alternating BBB or RBBB with alternating left anterior fascicular block (LAFB)/left posterior fascicular block (LPFB)] (any age).
4 New or indeterminate age bifascicular block (RBBB with LAFB or LPFB, or LBBB) with first-degree AV block.
5 Mobitz type II second-degree AV block.

Class IIa indications
1 RBBB and LAFB or LPFB (new or indeterminate).
2 RBBB with first-degree AV block.
3 LBBB, new or indeterminate.
4 Incessant VT, for atrial or ventricular overdrive pacing.
5 Recurrent sinus pauses (>3 s) not responsive to atropine.

Class IIb indications
1 Bifascicular block of indeterminate age.
2 New or age-indeterminate isolated RBBB.

Class III (not indicated)
1 First-degree heart block.
2 Type I second-degree AV block with normal hemodynamics.
3 Accelerated idioventricular rhythm.
4 BBB or fascicular block known to exist before acute MI.

Temporary pacing for procedural interventions
Cardiac catheterization
During catheterization of the right side of the heart, manipulation of the catheter may induce a transient RBBB in up to 10% of patients. This block generally lasts for seconds or minutes, but can occasionally last for hours or days. Trauma induced by RV endomyocardial biopsy also may result in temporary, or rarely long-lasting, RBBB. This is a problem only in patients with pre-existing LBBB, in whom complete heart block may result. A temporary transvenous pacing wire is therefore recommended in patients who are undergoing right heart catheterization or biopsy in the presence of previously known LBBB. Catheterization of the left side of the heart in patients with known pre-existing RBBB only rarely gives rise to complete heart block because of the short length and more diffuse nature of the left bundle branch. Significant bradycardia and asystole can occur during injection of the right coronary artery. This complication is extremely rare, and the placement of a temporary pacing catheter does not alter the morbidity or mortality of catheterization. The bradycardia usually resolves after several seconds. The same comments apply in general to placement of a temporary pacing wire during angioplasty.

Temporary pacing prior to non-cardiac surgery
Both surgeons and anesthesiologists frequently ask about the need for a preoperative temporary pacing catheter in patients with bifascicular block. Several studies have suggested a low incidence of intraoperative and perioperative complete heart block. Hence, there is minimal benefit from preoperative prophylactic pacemaker insertion. Even in patients with first-degree AV block and bifascicular block, there is a very low incidence of perioperative high-grade heart block.

However, in patients who have bifascicular block and also type II second-degree AV block or a history of unexplained syncope or presyncope, the risk of development of high-grade AV block is higher, and temporary pacing is warranted. The appearance of new bifascicular block in the immediate postoperative period should also lead to consideration of temporary pacing and raise suspicion of an intraoperative MI. The general availability of transcutaneous pacing may make it an acceptable alternative to temporary transvenous pacing in lower risk individuals, although low patient tolerance is often a limitation.

Temporary pacing following cardiac surgery
This is usually achieved via epicardial wires placed at the time of surgery. Occasionally, epicardial wires may not have been placed or the existing epicardial wires fail to capture. In such situations, transvenous pacing is often implemented while awaiting recovery of sinus node function or AV conduction, or until a decision regarding permanent pacing is made (see earlier).

Drug-induced bradycardia
A number of medications may produce transient bradycardia that may require temporary pacing until the effect of the drug dissipates. These drugs

may cause sinus node dysfunction and/or AV block; if drugs are used in combination, their effects may become more potent and exacerbate mild or latent conduction system disease. If long-term therapy with these agents is necessary for an underlying disorder and a substitute cannot be found, permanent pacing may be required (Figure 1.6). Drug-induced AV block might not always resolve after discontinuation of the potentially offending drug. In one series, approximately half of patients who developed heart block in the context of therapy with an AV nodal blocking agent required permanent pacing for persistent or recurrent AV block.[67] Cessation of digoxin therapy has the best chance of recovery of AV nodal conduction, but β-adrenergic blocker therapy often unmasks underlying conduction disease.[68]

Other indications for temporary pacing

Temporary pacing is indicated in patients with new AV or BBB in the setting of *acute bacterial endocarditis*. The development of a new conduction system abnormality generally suggests that there is a perivalvular (ring) abscess that has extended to involve the conduction system near the AV node and/or the His bundle. The endocarditis generally involves the non-coronary cusp of the aortic valve. In one study, high-grade or complete heart block developed in 15% of patients with aortic valve endocarditis.[69] Patients who develop a new AV block or BBB, especially in the setting of aortic valve endocarditis, should be considered for temporary pacing while cardiac evaluation is in progress.

Treatment of *tumors* of the head and/or neck or around the carotid sinus may in some circumstances give rise to high-grade AV block. Temporary pacing may be required during surgical treatment, radiation therapy, or chemotherapy. If the tumor responds poorly, permanent pacing may be necessary in some cases. The long-term risk for recurrent heart block due to tumor recurrence is unknown.

Lyme disease, a tick-borne spirochete infection, causes a systemic infection with arthritis, skin lesions, myalgias, meningoencephalitis, and cardiac involvement in 5–10% of patients. Lyme disease is epidemic in the summer months in the northeastern USA. Carditis typically occurs relatively late in the course of the illness, usually 4–8 weeks after the onset of symptoms. AV block is the most common manifestation of carditis and tends to be transient. Block is most common at the level of the AV node, and fluctuation between first-degree and higher degrees of AV block is frequent. Temporary cardiac pacing may be required, but the conduction disturbances usually resolve spontaneously, especially with antibiotic treatment, so permanent cardiac pacing is rarely necessary. Similar conduction disturbances can occasionally be seen in patients with viral myocarditis, as well as with other tick-borne infections.

Rarely, temporary pacing may be required during periods of *acidosis and hyperkalemia* until the metabolic derangements are corrected. The bradycardia that is associated with *hypothyroidism* rarely warrants pacing unless concomitant QT prolongation leads to torsades de pointes VT (see next section).

Temporary pacing for tachycardias

Temporary cardiac pacing has been used for the termination and/or prevention of a variety of arrhythmias. Type I atrial flutter can be successfully pace terminated, especially after cardiac surgery. Due to the development of radiofrequency catheter ablation techniques, there is currently less interest in pace termination of atrial flutter outside of the postoperative situation. Similarly, the most common varieties of paroxysmal SVT are usually pace terminable, but tend to be equally amenable to radiofrequency ablation. Recurrent torsades de pointes VT can sometimes be suppressed with pacing, especially if there is underlying bradycardia. Pacing to increase the heart rate will shorten the QT interval. Intravenous magnesium, correction of other metabolic derangement, and cessation of any offending drugs should be performed in conjunction with pacing.

Summary

In patients with symptomatic and potentially life-threatening bradyarrhythmias, cardiac pacing is a cost-effective intervention to relieve symptoms and prevent death. However, the possible complications and the potentially complex longer-term management of permanent pacemaker systems require

that careful consideration be given to the indications before implantation.

Acknowledgment

The author would like to acknowledge Robert W. Peters, Pugazhendhi Vijayaraman and Kenneth A. Ellenbogen for use of figures from the Fifth Edition.

References

1 Sanchez-Quintana D, Cabrera JA, *et al*. Sinus node revisited in the era of electroanatomical mapping and catheter ablation. *Heart* 2005; 91: 189–194.
2 Boyett MR, Honjo H, Kodama I. The sinoatrial node, a heterogenous pacemaker structure. *Cardiovasc Res* 2000; 47: 658–687.
3 Boyett MR, Honjo H, Yamamoto M, *et al*. Regional differences in the effects of 4-aminopyridine within the sinoatrial node. *Cardiovasc Res* 1998; 39: 360–372.
4 Opthof T. The mammalian sinoatrial node. *Cardiovasc Drugs Ther* 1988; 1; 573–597.
5 Mazgalv TN, Ho SY, Anderson RH. Anatomic-electrophysiological correlation concerning the pathways for atrioventricular conduction. *Circulation* 2001; 103: 2660–2667.
6 Lee PC, Chen SA, Hwang B. Atrioventricular nodal anatomy and physiology: implications for ablation of atrioventricular nodal re-entrant tachycardia. *Curr Opin Cardiol* 2009; 24: 105–112.
7 Inoue S, Becker AE. Posterior extensions of the human compact atrioventricular node: A neglected anatomic feature of potential clinical significance. *Circulation* 1998; 97: 188–193.
8 Sanders P, Morton JB, Kistler PM, *et al*. Electrophysiological and electroanatomic characterization of the atrial in sinus node disease: evidence for diffuse atrial remodeling. *Circulation* 2004; 109: 1514–1522.
9 Fedorov VV, Ambrosi CM, Kostecki G, *et al*. Anatomic locations and autonomic modulation of AV junctional rhythm in failing human hearts. *Circ Arrhythm Electrophysiol* 2011; 4: 515–525.
10 Dobrzynski H, Nikolski VP, Sambelashvili AT, *et al*. Site of origin and molecular substrates of atrioventricular junctional rhythm in the rabbit heart. *Circ Res* 2003; 93: 1102–1110.
11 Epstein AE, DiMarco JP, Ellenbogen KA, *et al*. ACC/AHA/HRS 2008 Guidelines for Device-Based Therapy of Cardiac Rhythm Abnormalities. *J Am Coll Cardiol* 2008; 51: 1–62.
12 Vardas PE, Auriccio A, Blanc J, *et al*. Guideline for cardiac pacing and cardiac resynchronization therapy of the European Society of Cardiology. Developed in collaboration with the European Heart Rhythm Association. *Eur Heart J* 2007; 28: 2256–2295.
13 Epstein AE, Darbar D, DiMarco JP, *et al*. 2012 ACCF/AHA/HRS focused update of the 2008 guideline for device based therapy for cardiac rhythm abnormalities. *J Am Coll Cardiol* 2012; 60: 1297–1313.
14 Gillia AM, Russo AM, Ellenbogen KA, *et al*. HRA/ACCF Expert Consensus Statement on Pacemaker Device and Mode Selection. *Heart Rhythm* 2012; 9: 1344–1365.
15 Jones SA, Boyett MR, Lancaster MK. Declining into failure: the age-dependent loss of the L-type calcium channel within the sinoatrial node. *Circulation* 2007; 115: 1183.
16 Hocini M, Sanders P, Deisenhofer I, *et al*. Reverse remodeling of sinus node function after catheter ablation of atrial fibrillation in patients with prolonged sinus pauses. *Circulation* 2003; 108: 1172.
17 Kandolin R, Lehtonen J, Kupari M. Cardiac sarcoidosis and giant cell myocarditis as cause of atrio-ventricular block in young and middle aged adults. *Circ Arrhythm Electrophysiol* 2011; 4: 303–309.
18 Zipes DP. Second-degree atrioventricular block. *Circulation* 1979; 60: 465–472.
19 Kim YH, O'Nunain S, Trouton T, *et al*. Pseudo-pacemaker syndrome following inadvertent fast pathway ablation for atrioventricular nodal reentrant tachycardia. *J Cardiovasc Electrophysiol* 1993; 4: 178–182.
20 Brecker SJ, Xiao HB, Sparrow J, Gibson DJ. Effects of dual chamber pacing with short atrioventricular delay in dilated cardiomyopathy. *Lancet* 1992; 340: 1308–1312.
21 Chokshi SK, Sarmiento J, Nazari J, Mattioni T, Zheutlin T, Kehoe R. Exercise-provoked distal atrio-ventricular block. *Am J Cardiol* 1990; 66: 114–116.
22 Brignole M, Deharo J, De Roy L, *et al*. Syncope due to idiopathic paroxysmal atrioventricular block: long term follow-up of a distinct form of atrioventricular block. *J Am Coll Cardiol* 2011; 58: 167–173.
23 Eriksson P, Hansson PO, Eriksson H, Dellborg M. Bundle branch block in a general male population: the study of men born 1913. *Circulation* 1998; 98: 2494–2500.
24 McAnulty JH, Rahimtoola SH, Murphy E, *et al*. Natural history of 'high risk' bundle branch block: final report of a prospective study. *N Engl J Med* 1982; 307: 137–143.
25 Scheinman MM, Peter RW, Morady F, *et al*. Electrophysiological studies in patients with bundle branch block. *Pacing Clin Electrophysiol* 1983; 6: 1157–1165.
26 Dhingra RC, Palileo E, Strasberg B, *et al*. Significance of the HV interval in 517 patients with chronic bifascicular block. *Circulation* 1981; 64: 1265–1271.
27 Petrac D, Radic B, Birtic K, *et al*. Block induced by atrial pacing in the presence of chronic bundle branch block. *Pacing Clin Electrophysiol* 1996; 19: 784–792.

28 Birgnole M, Menozzi C, Moya A, *et al*. International Study on Syncope of Uncertain Etiology (ISSUE) Investigators. Mechanism of syncope in patients with bundle branch block and negative electrophysiological test. *Circulation* 2001; 104: 2045–2050.

29 Task Force for the Diagnosis and Management of Syncope, European Society of Cardiology (ESC), European Heart Rhythm Association (EHRA), *et al*. Guidelines for the diagnosis and management of syncope (version 2009). *Eur Heart J* 2009; 30: 2631.

30 Krediet CT, van Dijk N, Linzer M, van Lieshout JJ, Wieling W. Management of vasovagal syncope: controlling or aborting faints by leg crossing and muscle tensing. *Circulation* 2002; 106: 1684–1689.

31 Sheldon RS, Morillo CA, Klingenheben T, Krahn AD, Sheldon A, Rose S. Age-dependent effect of beta blockers in preventing vasovagal syncope. *Circ Arrhythm Electrophysiol* 2012; 5: 920–926.

32 Brignole M, Menozzi C, Moya A, *et al*. Pacemaker therapy in patients with neurally-mediated syncope and documented asystole. Third International Study on Syncope of Uncertain Etiology (ISSUE-3): A randomized trial. *Circulation* 2012; 125: 2566–2571.

33 Weissmann P, Chin MT, Moss AJ. Cardiac tachypacing for severe refractory idiopathic orthostatic hypotension. *Ann Intern Med* 1992; 116: 650.

34 Tse HF, Lau CP, Park E, *et al*. Transient overdrive pacing upon standing prevents orthostatic hypotension in elderly pacemaker patients with chronotropic incompetence. *Pacing Clin Electrophysiol* 2007; 30: 188–192.

35 Groh WJ, Groh MR, Saha C, *et al*. Electrocardiographic abnormalities and sudden death in myotonic dystrophy type 1. *N Engl J Med* 2008; 358: 2688–2697.

36 Lazarus A, Varin J, Babuty D, *et al*. Long-term follow-up of arrhythmias in patients with myotonic dystrophy treated by pacing. *J Am Coll Cardiol* 2002; 40: 1645–1652.

37 Wahbi K, Meune C, Porcher R, *et al*. Electrophysiological study with prophylactic pacing and survival in adults with myotonic dystrophy and conduction system disease. *JAMA* 2012; 307: 1292–1301.

38 Douglas AR, Williams BR. Cardaic sarcoidosis. *Heart* 2006; 92: 282–288.

39 Buckley O, Doyle L, Padera R, *et al*. Cardiomyopathy of uncertain etiology: complimentary role of multimodality imaging with cardiac MRI and (18^{F}) FDG PET. *J Nucl Cardiol* 2010; 17: 328–332.

40 Lakdawala NH, Givertz MM. Dilated cardiomyopathy with conduction disease and arrhythmia. *Circulation* 2010; 122: 527–534.

41 Merlini G, Bellotti V. Molecular mechanisms of amyloidosis. *N Engl J Med* 2003; 349: 583–596.

42 Falk RH. Cardiac amyloidosis: A treatable disease often overlooked. *Circulation* 2011; 124: 1079–1085.

43 Knockaert DC. Cardiac involvement in systemic inflammatory diseases. *Eur Heart J* 2007; 28: 1797–1804.

44 Bern C, Montgomery SP, Herwaldt BL, *et al*. Evaluation and treatment of Chagas disease in the United States: a systematic review. *JAMA* 2007; 298: 2171–2181.

45 Ackerman MJ, Prior SG, Willems S, *et al*. HRS/EHRA expert consensus statement on the state of genetic testing for the channelopathies and cardiomyopathies. *Europace* 2011; 13: 1077.

46 Gersh BJ, Maron BJ, Bonow RO, *et al*. 2011 ACCF/AHA guideline for the diagnosis and treatment of hypertrophic cardiomyopathy. *J Am Coll Cardiol* 2011; 58: e212–e260.

47 Maron BJ, Nishimura RA, McKenna WJ, *et al*. For the M-PATHY Study Investigators. Assessment of permanent dual-chamber pacing as a treatment for drug-refractory symptomatic patients with obstructive hypertrophic cardiomyopathy: a randomized double-blind crossover study. *Circulation* 1999; 99: 2927–2933.

48 Tang ASL, Wells GA, Talajic M, *et al*. Cardiac-resynchronization therapy for mild to moderate heart failure. *N Engl J Med* 2010; 363: 2385–2395.

49 Moss AJ, Hall WJ, Cannon DS, *et al*; for the MADIT-CRT Trial Investigators. Cardiac resynchronization therapy for the prevention of heart failure events. *N Engl J Med* 2009; 361: 1329–1338.

50 van Rees JB, de Bie MK, Thijssen J, Borleffs CJ, Schalij MJ, van Erven L. Implantation-related complications of implantable cardioverter-defibrillators and cardiac resynchronization therapy devices: a systematic review of randomized clinical trials. *J Am Coll Cardiol* 2011; 58: 995–1000.

51 Zareba W, Klein H, Cygankiewicz I, *et al*. Effectiveness of cardiac resynchonization therapy by QRS morphology in the multicenter automatic defibrillator trial—cardiac resynchronization therapy (MADIT-CRT). *Circulation* 2011; 123: 1061–1072.

52 Gasparini A, Auricchio A, Regoli F, *et al*. Four-year efficacy of cardiac resynchronization therapy on exercise tolerance and disease progression: the importance of performing atrio-$\leq$ventricular junction ablation in patients with atrial fibrillation. *J Am Coll Cardiol* 2006; 48: 734–743.

53 Eldar M, Griffin JC, Van Hare GF, *et al*. Combined use of beta-adrenergic blocking gents and long-term cardiac pacing for patients with the long QT syndrome. *J Am Coll Cardiol* 1992; 20: 830–837.

54 Ellenbogen KA. Pacing therapy for prevention of atrial fibrillation. *Heart Rhythm* 2007; 4: S84–S87.

55 Lei M, Zhang H, Grace AA, Huang CL. SCN5A and sinoatrial node pacemaker function. *Cardiovasc Res* 2007; 74: 356–365.

56 Costedoat-Chalumeau N, Amoura Z, Villain E, Cohen L, Piette J. Anti-SSA/Ro antibodies and the heart: more than complete congenital heart block? A review of electrocardiographic and myocardial abnormalities and of treatment options. *Arthritis Res Ther* 2005; 7: 69–73.

57 Villain E, Costedoat-Chalumeau N, Marijon E, Boudjemline Y, Pietre JC, Bonnet D. Presentation and prognosis of complete atrioventricular block in childhood, according to maternal antibody status. *J Am Coll Cardiol* 2006; 48: 1682–1687.

58 Michaelsson M, Jonzon A, Riesenfeld T. Isolated congenital complete atrio-ventricular block in adult life. A prospective study. *Circulation* 1995; 92: 442–449.

59 Meine TJ, Al-Khatib SM, Alexander JH, *et al*. Incidence, predictors and outcomes of high degree atrioventricular block complicating acute myocardial treated with thrombolytic therapy. *Am Heart J* 2005; 149: 670–674.

60 Newby KH, Pisano E, Krucoff MW, *et al*. Incidence and clinical relevance of the occurrence of bundle-branch block in patients treated with thrombolytic therapy. *Circulation* 1996; 94: 2424–2428.

61 Koplan BA, Stevenson WG, Wpstein LM, Aranki SF, Maisel WH. Development and validation of a simple risk score to predict the need for permanent pacing after cardiac valve surgery. *J Am Coll Cardiol* 2003; 41: 795–801.

62 Riaza SS, LI JM, John R, *et al*. Long-term mortality and pacing outcomes of patients with permanent pacemaker implantation after cardiac surgery. *Pacing Clin Electrophysiol* 2011; 34: 331–338.

63 Bleiniffer S, Ruge H, Horer J, *et al*. Predictors of new-onset complete heart block after transcatheter aortic valve implantation. *J Am Coll Cardiol* 2010; 3: 525–530.

64 Sinhal A, Altwegg L, Pasupati S, *et al*. Atrioventricular block after transcatheter balloon expandable aortic valve implantation. *J Am Coll Cardiol Interv* 2008; 1: 305–309.

65 Roten L, Stortecky S, Scarcia F, *et al*. Atrioventricular conduction after transcatheter aortic valve implantation and surgical valve replacement. *J Cardiovasc Electrophysiol* 2012; 23: 1115–1122.

66 Ryan TJ, Antman EM, Brooks NH, *et al*. 1999 Update: ACC/AHA guideline for the management of patients with acute myocardial infarction. *Circulation* 1999; 100: 1016–1030.

67 Osmonov D, Erdinler I, Ozcan KS, *et al*. Management of patients with drug-induced atrioventricular block. *Pacing Clin Electrophysiol* 2012; 35: 804–810.

68 Zeltser D, Justo D, Halkin A, *et al*. Drug induced atrioventricular block: prognosis after discontinuation of the culprit drug. *J Am Coll Cardiol* 2004; 44: 105–108.

69 Graupner C, Vilacoasta I, San Roman J, *et al*. Periannular extension of infective endocarditis. *J Am Coll Cardiol* 2002; 39: 1204–1211.

2

CHAPTER 2

Components of a pacing and ICD system: basic concepts of pacing

Gautham Kalahasty,[1] Suraj Kapa,[2] and Joshua M. Cooper[3]

[1] Medical College of Virginia/VCU School of Medicine, Richmond, VA, USA
[2] Mayo Clinic School of Medicine, Rochester, MN, USA
[3] Hospital of the University of Pennsylvania, Philadelphia, PA, USA

Introduction

Modern day pacemakers serve the primary function of either maintaining a minimum heart rate to avoid symptomatic or potentially life-threatening bradyarrhythmias or offering resynchronization between the left and right ventricles in the setting of heart failure. However, multiple advances in device design, programming, sensor technology, and materials science have afforded the ability to offer an ever-widening range of devices with a variety of specialized features. In this chapter, we focus on the basic principles underlying cardiac pacing and then touch on several aspects of lead, device, and algorithm design.

Electrophysiological considerations

Electrical excitability of the cardiac myocyte

Excitability of biological tissues such as nerve and muscle refers to their ability to respond to a specific stimulus.[1,2] Myocytes at rest have a separation of charge across the cell membrane, resulting in an electrical transmembrane potential. This potential is created by differences largely in the concentration of sodium and potassium ions on the outside and inside of the cell (Figure 2.1). The phospholipid bilayer of myocardial cells is characterized by a high resistance to flow of ions through the cell membrane that may be overcome by the activation of a variety of transport pumps, including the Na^+/K^+-ATPase exchange pump and Na^+/Ca^{2+} transport mechanisms. Both of these transporters cause net exchange of three positive charges out of the cell in exchange for two positive charges into the cell, resulting in net polarization of the cell membrane with the inside of the cell maintained at a net negative charge relative to the outside (i.e. a net negative transmembrane potential). Maintaining this net negative potential requires energy expenditure in the form of adenosine triphosphate (ATP).

Excitable tissues have the ability not only to generate but subsequently to propagate a transmembrane action potential that depends on the opening and closing of a variety of membrane-based ion transporters. Once a threshold potential is reached, several transport mechanisms are activated, allowing for influx of sodium ions into the cell. This results in an initial upstroke of the action potential curve (phase 0). In addition to sodium channels, potassium, calcium, and chloride ion transporters are also activated for varying durations. At the end of phase 0, there is a short period where the transmembrane potential is positively

Cardiac Pacing and ICDs, Sixth Edition. Edited by Kenneth A. Ellenbogen and Karoly Kaszala.
© 2014 John Wiley & Sons, Ltd. Published 2014 by John Wiley & Sons, Ltd.

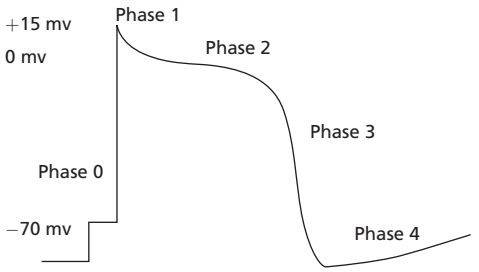


Figure 2.1 Action potential of a Purkinje fiber. The resting transmembrane potential is approximately −90 mV. Upon depolarization of the membrane to a threshold potential of −70 to −60 mV, the upstroke of the action potential is triggered (phase 0), carried predominantly by an influx of Na^+ ions into the cell. The transmembrane potential reaches approximately 15 mV (over-shoot potential) and is repolarized to approximately 0 mV during phase 1. The plateau phase of the action potential (phase 2) is produced by a complex interaction of inward Ca^{2+} and Na^+ currents, and outward K^+ currents. Repolarization of the cell occurs during phase 3, during which the cell regains the capability of responding to a polarizing electrical stimulus with another action potential. Phase 4 of the action potential is characterized by a slow upward drift in the transmembrane potential.

charged. During phase 1, the membrane potential partially repolarizes with the activation of the transient outward potassium current (Ito). Phase 2 is the plateau phase of the action potential. During this time, the myocyte is refractory to further electrical stimulation; the net membrane voltage is approximately 0 mV as inward sodium and calcium currents are balanced by slow, rapid, and ultrarapid outward potassium currents. After the plateau phase (which can last up to several hundred milliseconds), the cardiac cell begins to repolarize as outward currents exceed inward currents, resulting in regeneration of the resting membrane potential (phase 3). During this phase, there is net negative polarization of the inside of the cell and another action potential may be induced if the myocyte is challenged by an electrical stimulus of sufficient strength. After complete repolarization of the membrane, the cell enters a diastolic period (phase 4) during which it is fully excitable. Different myocytes may exhibit variable action potential profiles (e.g. cells capable of spontaneous automaticity exhibit gradual upward drifts in transmembrane potential until threshold is reached) (Figure 2.1).

Propagation of electrical stimuli

The response of excitable membranes to electrical stimuli is an active process, requiring delivery of a stimulus of sufficient strength to initiate the process of cellular depolarization. Signals initiated in one region of the heart are subsequently propagated from cell to cell via low-resistance intercellular connections termed gap junctions. Thus, the action potential at the site of stimulation results in the depolarization of neighboring myocytes. Propagation of the action potential away from the site of electrical stimulation also depends on the cable properties of the myocardium, including the axis of myofiber orientation and the geometry of the connections between fibers.[3] For example, a wavefront of depolarization will be conducted with a conduction velocity three to five times greater along the longitudinal axis of a myofiber than along the transverse axis. Such anisotropic conduction properties are further exaggerated in the presence of myocardial fibrosis, in which the intercellular collagen matrix is increased and there is decreased cell-to-cell communication. As the structure of cardiac tissue is affected by pathological conditions such as fibrosis or infarction, the physiological properties of conduction and excitability may be significantly altered. Thus, the location of pacing stimulus delivery may impact the strength of the stimulus required to achieve cardiac depolarization and the rapidity with which such a stimulus will achieve activation (e.g. pacing in an area of dense scar may require a longer time to ventricular activation than pacing in an area of healthy tissue).

Basic concepts of pacing

Cardiac myocytes may be "activated" by the delivery of an electrical pacing stimulus. This stimulus creates an electrical field that allows for the generation of a self-propagating wavefront of action potentials that may then advance from the stimulation site. However, if the stimulus is not of sufficient amplitude or duration, it may not initiate such a wavefront. The minimum amplitude and duration required to generate the self-propagating wavefront that results in cardiac activation is referred to as the *threshold*.

In order to provide for consistent myocardial stimulation, there needs to be a constant source of

energy for pulse delivery, which is provided by the pulse generator, a conductor that will deliver the stimulus from the source, which is the lead itself, an electrode at the end of the conductor that delivers the pulse, and underlying myocardium that is excitable. Failure at any of these points (e.g. due to fracture in the lead or loss of contact between the electrode and the underlying myocardium) will result in failure of myocardial stimulation.

When considering pacemaker stimulation of the myocardium, several important concepts need to be understood that define the stability and the integrity of the circuit responsible for myocardial stimulation. Generally, when evaluating proper pacemaker function, these concepts are enveloped by parameters evaluating sensing, impedance, and threshold. Subtle considerations need to be understood within the concept of each parameter, and how they may individually be affected over time or in the context of changes in physiological variables.

Currently available pacing systems comprise a pulse generator and one or more pacemaker leads with lead tips positioned in the cardiac chamber of interest. While leadless pacemaker systems are under development and being tested in early clinical studies, these are not currently available for clinical use and will not be further discussed. The lead in the traditional pacemaker system serves as the conduit of electrical signals between the myocardium and pacemaker generator. Depending on the individual components and programming, pacing and sensing may be accomplished in unipolar or bipolar configuration.

Bipolar versus unipolar sensing

Sensing of local electrograms (EGMs) is essential to the proper function of permanent pacemakers. Whether sensing takes place in a unipolar or bipolar system and despite the differences between the two, the principles of sensing remain the same. Two electrodes, a cathode and an anode, are required to complete the electrical circuit between the body and the pacemaker. In a bipolar system, both anode and cathode are located in the heart, whereas in a unipolar system only the cathode is located in the heart and the pacemaker generator can serve as the anode. Intracardiac electrical signals are produced by the movement of electrical current through the myocardium. An electrode that overlies a region of resting myocardium records from the outside of cardiac myocytes. As a wavefront of depolarization travels toward an endocardial electrode in contact with resting myocardium, the electrode becomes positively charged relative to the depolarized region. This is manifest in the intracardiac EGM as a positive deflection. As the wavefront of depolarization passes under the recording electrode, the outside of the cell suddenly becomes negatively charged relative to resting myocardium, and a brisk negative deflection is seen in the intracardiac EGM (Figure 2.2). The moment of myocardial activation at the site where the electrode is in contact with myocardium co-incides with the moment the negative deflection in the intracardiac EGM crosses the abscissa (bipolar EGM) or with the peak slope of the intrinsic negative deflection (unipolar EGM). The positive and negative deflections that precede and follow the intrinsic deflection represent activation in neighboring regions of myocardium relative to the recording electrode.

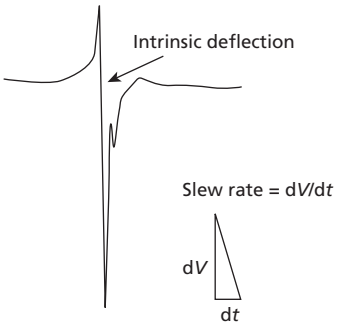


Figure 2.2 A typical bipolar ventricular electrogram (EGM) in a normal individual. The sharp downward deflection in the EGM represents the intrinsic deflection and indicates the moment of activation under the recording electrode. The slope of the intrinsic deflection (d*V*/d*t*) is expressed in volts per second and is referred to as the slew rate. For an EGM to be sensed by a sensing amplifier, the amplitude and slew rate must exceed the sensing thresholds.

Sensing of the intracardiac EGM is determined by the signal amplitude, measured in peak-to-peak voltage, and the slope of the intrinsic deflection of the electrogram.[4] This peak slope of the intrinsic deflection of the EGM is also termed the slew rate.

In general, the higher the slew rate of an EGM, the higher the frequency content. This frequency content is critical to the ability of the sense amplifier to properly process the signal, with most sense amplifiers being most sensitive to signals at a range of 30–40 Hz. Components of the EGMs below or above this frequency may not be properly sensed. However, the slew rate and peak-to-peak voltage are not always directly proportional. Thus, slow and broad signals with a low slew rate may not be sensed, even if the peak-to-peak amplitude of the EGM is large.

EGM amplitude is also dependent on the direction of the activation front. A bipolar EGM can be constructed by subtracting the absolute unipolar voltage recorded at the cathode (versus ground) from the unipolar voltage recorded at the anode (versus ground). Because the bipolar configuration represents the signal at the cathode minus the signal at the anode, the net EGM may be considerably different from that of either unipolar EGM alone. For example, if an advancing wavefront of depolarization is perpendicular to the interelectrode axis of a bipolar lead, each electrode will be activated at exactly the same time, and the instantaneous difference in voltage will be minimal. In this situation, the bipolar EGM will be markedly attenuated when compared with either unipolar EGM. In contrast, a wavefront of depolarization traveling parallel to the electrode axis of a bipolar lead will activate one electrode before the other, and the resulting bipolar EGM may have significantly greater amplitude than either unipolar EGM alone. Because unipolar EGMs have a broader field of view, extending from the lead tip to the can (30–50 cm in unipolar systems versus 3–5 cm in bipolar systems), the EGM in unipolar leads is less likely to be affected by such subtleties of ventricular activation. These potential differences in sensing in a bipolar versus unipolar mode are important to consider when EGM amplitude is assessed.[5] Change in the direction of local activation at a bipolar electrode (e.g. during a ventricular ectopic beat or new bundle branch block) may cause significant changes in sensing amplitude measurements. Differences in interelectrode distance between bipolar and unipolar leads have an important influence on sensing of "far-field" signals as well. Due to the much smaller field of view, bipolar electrodes tend to be minimally influenced by electrical signals that originate outside the heart, while unipolar leads may detect electrical signals that originate near the pulse generator pocket. Thus, unipolar sensing is more susceptible to interference from electrical signals originating in skeletal muscle (myopotentials), which can result in inappropriate inhibition of pacing (if sensed in the ventricular channel) or triggering of pacing output (if sensed in the atrial channel).[6] Thus, bipolar sensing is less prone to oversensing myopotentials, far-field cardiac signals, or electromagnetic interference from environmental sources. Shielding of the device and signal processing in the pacemaker circuitry, such as rectification and filtering of lower or higher frequency components, also help to attenuate recording of unwanted signals. Such signal processing is not perfect as there is overlap in the frequency spectrum of other non-cardiac signals, such as skeletal myopotentials. The almost exclusive use of bipolar sensing in modern devices has helped to minimize the risk of sensing far-field or non-cardiac signals. Despite all these advances, oversensing still remains a problem and needs to be considered when programming devices or reviewing intracardiac EGMs.

Bipolar versus unipolar stimulation

Modern lead design has largely eliminated any significant clinical difference between bipolar and unipolar stimulation, but some inherent differences remain. Historically, the unipolar threshold was lower than the bipolar threshold in the same system due to a markedly larger anode and resulting reduced impedance in the unipolar system. With the contemporary lead tip design, this difference is attenuated as impedance is mainly determined by the lead tip properties. The clinically important implication of unipolar pacing is that the pacemaker generator may cause pectoral muscle stimulation (muscle twitching) if implanted adjacent to the pectoral muscle. Because the distance between the cathode and anode is so much greater during unipolar pacing, the pacing stimulus on the surface electrocardiogram (ECG) is also much larger than during bipolar pacing. The increased size of the "pacer spike" may be visually helpful to determine proper pacemaker function

when interpreting cardiac telemetry recordings or trans-telephonic ECG tracings during remote pacemaker monitoring. Conversely, the larger amplitude signal from unipolar pacing is far more likely to interfere with appropriate sensing of the cardiac rhythm by an implantable cardioverter–defibrillator (ICD) in the rare instance that a patient has a separate pacemaker and ICD implanted. Specifically, a sensed large-amplitude unipolar pacing stimulus will result in subsequent under-detection of low-amplitude intracardiac signals, such as those that occur during ventricular fibrillation. It is for this reason that the use of bipolar pacing is critical when a separate pacemaker is present in an ICD patient. Bipolar pacing leads are also necessary for some rate-adaptive sensors, such as the minute-ventilation sensor, as well as for some types of automatic threshold algorithms, where the ring electrode is used to sense myocardial capture.

Pacing impedance

Impedance is defined as the overall opposition to flow of current across an electrical circuit. In direct current circuits, such as pacemaker generators that follow Ohm's law [i.e. voltage (V) = current flow (I) × resistance across the circuit (R)], the impedance and resistance are equivalent. The impedance (R) can be used to determine the current flow in the setting of constant voltage delivery. Higher impedances are associated with lower current flows in the setting of a constant voltage. Thus, pacing impedance has significant influence on battery longevity. Namely, the lower the resistance/impedance, the greater the current flow, and *vice versa*. Thus, the longevity of generators with a fixed amount of charge will in part be determined by the pacing impedance.

The determinants of total pacing impedance include the resistance across the lead conductor, the resistance to current flow from the lead electrode to the myocardium, and the charge of opposite polarity in the myocardium that develops at the electrode–tissue interface in the context of the stimulus delivery (polarization). The sum of these three factors equals the total impedance. However, while higher total impedance is of value to reducing current flow and thereby increasing battery life, ideally the highest impedance occurs at the electrode–myocardial interface rather than in the lead. The reason for this is that a higher resistance to flow across the lead conductor will result in a voltage drop and resultant conversion of a portion of the pacing impulse into heat, which does not contribute to myocardial stimulation. However, a high electrode resistance will help increase overall impedance and consequently minimize current flow and maximize battery life. The electrode resistance is determined by the size of the electrode (with a smaller electrode increasing resistance). Such smaller electrodes may also beneficially impact stimulation thresholds.

Routine use of leads with low intrinsic resistance but small electrode size has allowed for the creation of smaller implantable devices with greater battery longevity. A practical limitation of minimizing electrode size is impairment of contact stability, resulting in a greater risk of microdislodgement.

The polarization component of pacing impedance is related to movement of ions in the myocardium toward the cathode. Namely, the cathode attracts positively charged ions and repels negatively charged ions when an electrical current is applied to the myocardium. Thus, the cathode becomes surrounded by layers of hydrated sodium and H_3O^+ ions, while a layer of Cl^-, HPO_4^{2-}, and OH^- ions forms farther away. This movement of charged ions induces a current flow in the myocardium and essentially a functional capacitor develops, impeding further movement of charge. The capacitor effect of polarization increases over the course of stimulus application, peaking at the trailing edge of the stimulus and decaying exponentially after completion of stimulus delivery until the charged layers completely dissolve.

This polarization impedes movement of charge in the myocardium and increases the voltage requirement for stimulation. Polarization impedance directly relates to the duration of the stimulus and is minimized by using short pulse durations. In addition, polarization impedance is related to the surface area of the electrode, with a larger surface area allowing for minimization of the polarization effect. Given that a smaller surface area is desired for maximum electrode resistance, while a larger one is desired for minimum polarization effect, electrodes with small geometric radii but a complex, porous surface that increases the

microscopic surface area may be used.[7] In addition, various coatings (e.g. platinum or iridium oxide) may help minimize polarization.

The variable degree of polarization at different times in the period of stimulus delivery has an impact on measurement of impedance. When measured at the leading edge of the stimulus, there is minimal polarization, and thus the measured impedance reflects only the impedance of the lead conductor and electrode. However, measurements of impedance at the mid-point of the stimulus more accurately reflect total impedance because the polarization component will be at least partially factored in.

Sensing impedance

The intracardiac EGM is transmitted by the pacing lead from its source in the myocardium to the sensing amplifier of the pulse generator. The voltage drop that occurs from the origin of the electrical signal in the heart to the generator depends on the source impedance, which, similar to pacing impedance, includes the resistance between the electrode and the myocardium, the resistance of the lead conductor, and the effect of polarization. Unlike with pacing impedance, however, minimizing the impedance is ideal, and thus the smaller electrode area desired for increasing pacing impedance may conversely result in diminished sensing. For this reason, the trade-off in electrode size, impedance, and sensing needs to be considered in the design of any lead. Sensing impedance changes as seen in lead integrity failure (insulation damage or conductor fracture) may result in sensing abnormalities.

Stimulation threshold

Cardiac pacing involves the delivery of a polarizing electrical impulse from an electrode in contact with the myocardium, together with the generation of an electrical field of sufficient intensity to induce a propagating wave of cardiac action potentials. The stimulating pulse may be either anodal or cathodal in polarity, although the two types demonstrate different stimulation characteristics. The stimulation characteristics are related to the source of the stimulating pulse, with constant-voltage and constant-current generators exhibiting somewhat different stimulation properties. The minimum stimulus intensity and duration necessary to reliably initiate a propagated depolarizing wavefront from an electrode is defined as the stimulation threshold. The stimulation threshold is a fundamental concept that is crucial to programming and troubleshooting permanent pacemaker systems. Stimulation threshold may vary under different physiological conditions and over time. In this section, the factors that determine the stimulation threshold will be discussed.[8,9]

Strength–duration relationship

For a pacing stimulus to produce a wave of depolarization in a cardiac chamber ("capture"), the stimulus must exceed a critical amplitude (measured in volts or milliamperes) and must be applied for a sufficient duration. These factors of stimulus amplitude and duration interact so that the minimal amplitude that is required to capture the myocardium also depends on the duration of the stimulating pulse (pulse duration).[10] The stimulus amplitude for endocardial stimulation has an exponential relation to the duration of the pulse, with a rapidly rising strength–duration curve at pulse durations of less than 0.25 ms and a relatively flat curve at pulse durations of greater than 1.0 ms, as shown in Figure 2.3. A small change in pulse duration is associated with a significant change in the threshold amplitude at short pulse durations, but only a small change at longer pulse durations. Because of the exponential relationship between stimulus amplitude and pulse duration, the entire strength–duration curve can be described relatively accurately by two points on the curve: rheobase and chronaxie. The *rheobase* of a strength–duration curve is defined as the lowest stimulus voltage that will electrically stimulate the myocardium at any pulse duration. For practical purposes, the rheobase voltage is usually determined as the threshold stimulus voltage at a pulse duration of 1.5–2.0 ms. The *chronaxie* is defined as the threshold pulse duration at a stimulus amplitude that is twice the rheobase voltage. Using the rheobase and chronaxie points, Lapicque, in 1909, described the following mathematical equation, which can be used to derive the strength–duration curve for constant-current stimulation:

$$I = I_r(1 + t_C/t)$$

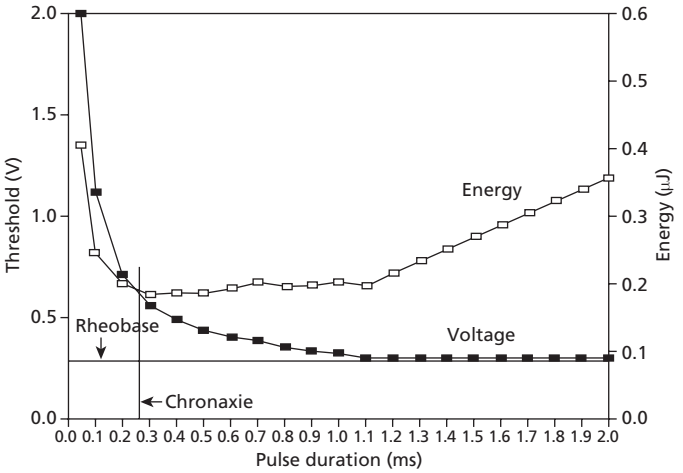


Figure 2.3 Strength–duration curve for constant voltage stimulation obtained at the time of permanent pacing lead implantation in a patient with complete atrioventricular block. The strength–duration relation is characterized by a steeply rising portion at short pulse durations and a relatively flat portion at pulse durations of greater than 1 ms. The stimulus energy at each point on the strength–duration curve is also demonstrated. The rheobase voltage of a constant voltage strength–duration curve is defined as the lowest stimulation voltage at any pulse duration. Because the curve is essentially flat at a pulse duration of 2 ms, rheobase can be accurately approximated as the threshold voltage at this point. Chronaxie, the threshold pulse duration at twice rheobase voltage, closely approximates the point of minimum threshold stimulation energy.

where I is the threshold current at pulse duration t, Ir is the rheobase current, and t_C is the chronaxie pulse duration. The relation of stimulus voltage, current, and pulse duration to stimulus energy is provided by the equation:

$$E = V^2/R \times t$$

where E is the stimulus energy, V is the stimulus voltage, R is the total pacing impedance, and t is the pulse duration. The chronaxie pulse duration is important in the clinical application of pacing, as it approximates the point of minimum threshold energy on the strength–duration curve. With pulse durations greater than the chronaxie, there is relatively little reduction in the threshold voltage. Rather, the wider pulse duration results in the wasting of stimulation energy without providing a substantial increase in safety margin. At pulse durations less than the chronaxie, there is a steep increase in threshold voltage and stimulation energy. Note from the equation relating the stimulus energy to the pulse duration and stimulus voltage that doubling the pulse duration results in a two-fold increase in stimulation energy, whereas doubling the stimulus voltage results in a four-fold increase, which has practical implications for the effect of programming pacing output on battery longevity.

An appreciation of the threshold strength–duration relation is important for the proper programming of the stimulus amplitude and pulse duration. Modern pulse generators offer two main methods for evaluating the stimulation threshold: either automatic decrement of the stimulus voltage at a constant pulse duration, or automatic decrement of the pulse duration at a constant stimulus voltage. To provide an adequate margin of safety, when the stimulation threshold is determined by decrementing the stimulus amplitude, the stimulus voltage is usually programmed to approximately twice the threshold value. Similarly, for pulse generators that determine threshold by automatically decrementing the pulse duration, the pulse duration is usually programmed to at least three times the threshold value. However, determination of the programmed output also has to take into consideration whether the voltage and pulse width

values are in the vicinity of the chronaxie or rheobase.

The threshold strength–duration curve is influenced by several factors, including the method of measurement, the nature of the electrode, the health of the tissue in contact with the electrode, the distance between the electrode and excitable myocardium, and how long the lead has been in place. Stimulation thresholds that are measured by decrementing the stimulus voltage until loss of capture are usually 0.1–0.2 V lower than when the stimulus intensity is gradually increased from sub-threshold until capture is achieved. This empiric observation, known as the Wedensky effect, must be considered when accurate measurements of the stimulation threshold are required.[11] The Wedensky effect may be greater at narrow pulse durations, potentially reaching clinical significance. When the pacing rate is maintained as a constant during experimental conditions, the Wedensky effect is of marginal significance. This suggests that this clinical phenomenon is probably explained by the effects of a varying cardiac rate during the gain or loss of capture as the stimulus amplitude is increased or decreased, respectively.

Strength–interval relationship

The stimulation threshold is influenced significantly by the coupling interval of electrical stimuli and the frequency of stimulation.[12] The stimulus intensity required to capture the ventricle remains quite constant at long extra-stimulus coupling intervals, but rises exponentially at shorter intervals. The rise in stimulation threshold at short coupling intervals is related to impingement of the stimulus on the relative refractory period of the ventricular myocardium. An electrical stimulus applied during the repolarization phase of the cardiac action potential will result in a propagated action potential only if it is of sufficient intensity. However, during the plateau phase of the action potential, electrical stimuli of any intensity will not be able to generate an action potential as the absolute refractory period is encountered.

The strength–interval relationship is particularly relevant when considering cathodal versus anodal stimulation.[13] Late diastolic stimulation thresholds are generally lower with cathodal than with anodal stimulation. However, at relatively short extra-stimulus coupling intervals, the anodal stimulation threshold may be less than the cathodal threshold. During the relative refractory period, the anodal threshold may actually decline ("dip") before abruptly rising at shorter coupling intervals. With bipolar cardiac pacing, the stimulation threshold is generally determined by the cathode. However, with short extra-stimulus coupling intervals, the bipolar stimulation threshold may actually be determined by the anode. If the stimulus intensity exceeds both the cathodal and anodal thresholds, bipolar pacing may result in stimulation at both electrode–myocardial interfaces (both anodal and cathodal stimulation).

Polarization

Following application of a polarizing pulse, an afterpotential of opposite charge may be induced in the myocardium at the interface with the stimulating electrode. This is due to an excess of positive charges that may surround the electrode after stimulation, which then exponentially decays to electrical neutrality (Figure 2.4). This positively charged afterpotential can be inappropriately sensed by the sensing circuit of the pulse generator with resulting inhibition or delay of the next pacing pulse. The amplitude of afterpotential is directly related to the amplitude and duration of the pacing stimulus, as well as the properties of the pacing electrode. Thus, afterpotentials are most likely to be sensed by particular leads, during conditions of maximum stimulus voltage and pulse duration, and when maximum sensitivity settings are programmed into the pulse generator. Inappropriate sensing of afterpotentials has been diminished by the use of blanking periods

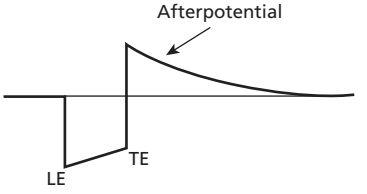


Figure 2.4 A constant voltage output pulse (downward deflection) and a resultant afterpotential of opposite polarity. LE, leading edge; TE, trailing edge.

following the pacing stimulus. However, for dual chamber pacing systems, polarization artifact of sufficient amplitude in one chamber may be sensed by the sensing amplifier in the other chamber (cross-talk). Atrioventricular (AV) cross-talk as a result of pacing is a very rare clinical problem in the current era of predominantly bipolar pacing and sensing, along with the design of pacing electrodes that minimize the polarization phenomenon.

Anodal stimulation

Ideally, myocardial stimulation occurs at the cathode. However, anodal stimulation is also possible in bipolar systems. Anodal stimulation is less likely because the anodal threshold is generally higher, the anode may not be in as direct contact with underlying myocardium, and it usually has a higher surface area than the cathode. However, if the programmed output or the pacing rate is high enough, it is possible to have both anodal and cathodal stimulation. Some animal studies have suggested that anodal stimulation may improve conduction velocity or mechanical performance. On the other hand, some data suggest increased pro-arrhythmia with anodal stimulation, but these findings are debated.

The implications of anodal stimulation may be most relevant in biventricular systems. Bipolar pacing from the left ventricular (LV) tip (cathode) to the right ventricular (RV) ring (anode) may cause simultaneous LV–RV pacing, resulting in an earlier activation of the RV due to anodal stimulation. In situations where an offset between the LV and RV is desired, this may prove deleterious (Figure 2.5).[14,15]

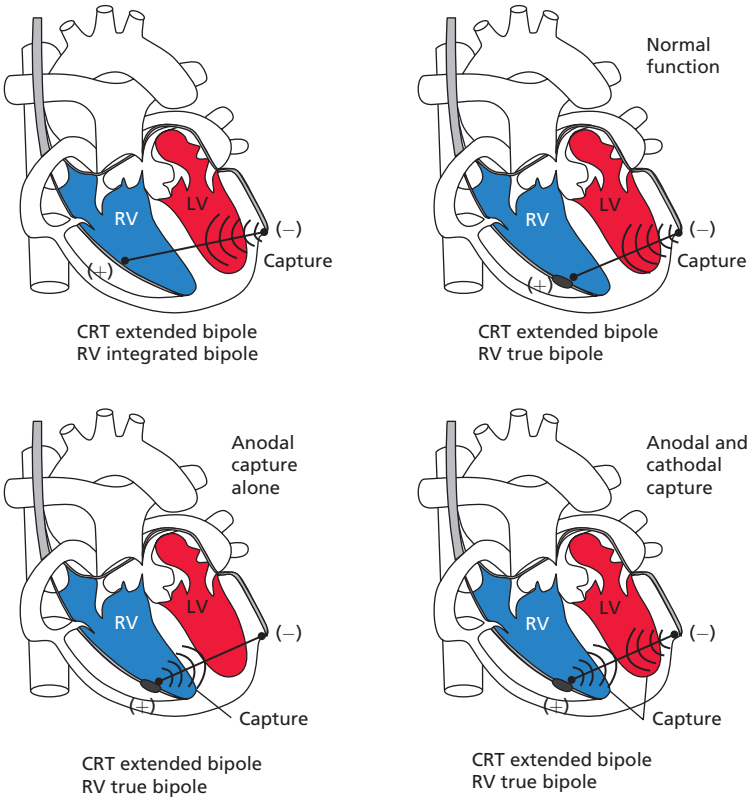


Figure 2.5 Schematic showing how anodal versus cathodal stimulation in biventricular pacing may impact the morphology of the QRS due to differences in the direction of depolarization. CRT, cardiac resynchronization therapy; LV, left ventricle; RV, right ventricle. (Source: Swerdlow CD, Friedman PA 2006.[14] Reproduced with permission of John Wiley & Sons Ltd.)

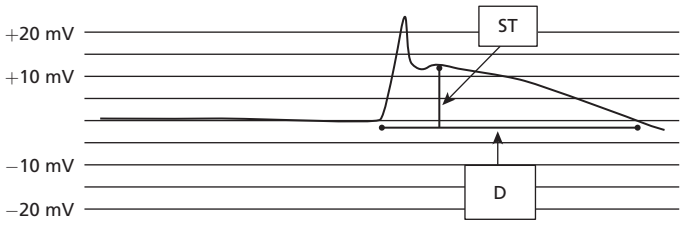


Figure 2.6 Current of injury recorded by a Medtronic model 2290 pacing system analyzer. This finding has been associated with adequate fixation. D, duration of injury current; ST, amplitude of injury current.

Electrode–myocardial interface maturation

The initial tissue reaction to the implantation of a permanent pacing lead involves acute injury to cell membranes. This damage is followed by the development of myocardial edema and coating of the electrode by platelets and fibrin. Infiltration of polymorphonuclear leukocytes and mononuclear cells then occurs, followed by acceleration of tissue injury around the electrode due to release of proteolytic enzymes and free oxygen radicals. The acute inflammatory response is followed by the accumulation of more macrophages and the influx of fibroblasts into the myocardium, which ultimately results in the creation of a fibrotic capsule around the distal electrode. Tissue fibrosis may improve lead stability at the electrode–myocardial interface, but at the same time several lead parameters may be negatively affected by an increased effective distal electrode size. Several advances in lead design, specifically in the development of steroid-eluting leads, have contributed to limiting the degree of fibrosis that occurs during the lead maturation process.

Current of injury

At the time of lead implantation, the intracardiac EGM will often demonstrate an injury current. This is due to the pressure exerted by the electrode on the underlying myocardium and may be seen with both active and passive leads. The lack of an injury current after lead implant may suggest poor contact between the distal electrode and endocardium, or scarring of the underlying myocardium. The manifestation of an injury current at the time of lead implantation is best appreciated as a change in the intracardiac EGM, characterized by widening of the EGM and pronounced "ST segment" elevation (Figure 2.6). Lead parameters, including sensing and threshold, may change over time after initial lead implant with reduction of the injury current. The injury current usually disappears within minutes to hours after initial implant. The effect of the injury current on acutely measured R waves may range from attenuation of the signal (especially in the case of active fixation leads) to slightly larger signals (as in the case of passive fixation leads). Ultimately, the value of the injury current lies in its ability to partially confirm adequate acute tissue–electrode contact.[16]

Time-dependent changes in sensing, impedance, and threshold

Sensing

With passive fixation leads, the amplitude of the intracardiac EGM typically declines abruptly within several days following implantation, followed by a gradual increase over 6–8 weeks back toward the initial value at the time of implant. The chronic amplitude of passive fixation electrodes has been shown to be approximately 85% of the acute value. However, modern corticosteroid-eluting leads have minimal deterioration of the EGM from implantation through regular follow-up assessments.

Active fixation leads may be associated with a different time course from passive fixation leads in the evolution of the sensed EGM. There may be more marked attenuation of the EGM amplitude immediately following lead positioning. Over the next 20–30 min, as the injury current dissipates, the EGM amplitude typically increases. It is likely that the trauma caused by extension of the screw helix

into the myocardium is responsible for this evolution of the sensed intracardiac EGM.

In general, active and passive fixation leads are associated with similar chronic EGM amplitudes despite the differences in the initial time course of sensing changes.

Impedance

Pacing impedance usually falls over the first 1–2 weeks following implantation. The chronic pacing impedance then rises to a stable value that is, on average, approximately 15% higher than that at implant. An abrupt change in impedance early after implant may indicate lead migration or improper lead pin connection. Serial measurements of pacing impedance are extremely valuable for the assessment of lead integrity. Generally, low impedance measurements reflect a failure of conductor insulation, and high values often suggest conductor fracture or a loose set-screw at the connector. For clinical purposes, serial assessments of impedance should use a consistent method of measurement as these may influence the impedance value.

Stimulation threshold

Myocardial stimulation thresholds may change dramatically between initial implantation and chronic values,[17] and it is important to understand the time course and properties of lead maturation with different leads and implantation techniques.

In active fixation leads, there may be acute variability in the stimulation threshold. Immediately following deployment of the screw helix, an increased stimulation threshold may be seen for several minutes that may correlate with the presence of an injury current. Both the injury current and the higher threshold decrease over several minutes. Thus, the threshold seen at the end of the implant procedure with an active fixation lead may be less than that seen upon initial deployment of the lead. Such an acute change is not generally seen with passive fixation leads.

There are differences in the time course of stimulation threshold changes in non–steroid-eluting versus steroid-eluting leads. Non–steroid-eluting leads generally exhibit a higher threshold within the first 24 h after implant, rising over the ensuing week, and then gradually decreasing over the following several weeks before reaching a stable value by 6 weeks. Final threshold is usually higher than that seen at initial implant, but less than the peak threshold. Several factors may modify this time course of events, including the electrode size, shape, chemical composition, surface structure, and other patient-specific factors.

Steroid-eluting leads, which reflect the majority of leads used in current endocardial procedures, rarely exhibit such marked changes in threshold over time. The stimulation threshold is much more constant, and the threshold at implant may be more reflective of the chronic threshold seen weeks or months after the procedure.

The difference in the threshold maturation process between steroid-eluting and non–steroid eluting leads is thought to be due to the greater growth of inexcitable capsules of fibrous tissue surrounding the electrode in the latter.[18] This fibrous capsule effectively increases the surface area of the electrode, thereby decreasing the intensity of the electrical field at the junction of the fibrous capsule and the normal, excitable myocardium. This will consequently result in a higher stimulation threshold. The use of steroid-eluting leads (e.g. by utilizing a reservoir of dexamethasone below the stimulating electrode that gradually elutes corticosteroid into the surrounding myocardium) attenuates early tissue reaction and formation of the fibrous capsule and, thus, allows for more stable stimulation thresholds over time.[19] The utility of steroid-eluting leads in decreasing long-term threshold values has been demonstrated in active and passive endo- and screw-in epi-myocardial leads.

Automated capture

The pacing output needs to be programmed to exceed the stimulation threshold by an adequate margin (termed the "safety margin") to reduce the risk of loss of capture during fluctuations in pacing threshold. On the other hand, the current drain on the battery has to be optimized in order to maximize battery longevity. A commonly used compromise to achieve these goals is to set the pulse amplitude at two to three times that of the pacing threshold close to the chronaxie pulse duration. Risks, however, are that patients may experience rises in stimulation threshold over time

that, in rare cases, may exceed the programmed output, or that a programmed output well in excess of the threshold may result in excessive early drain on the battery. Automatic capture algorithms in some devices allow the pacing threshold to be determined automatically and, in turn, automatically program the pacing output accordingly.

In current automatic capture algorithms, local myocardial capture is confirmed by detecting myocardial depolarization or "evoked response" following pacing. The key feature of automatic capture algorithms is the ability of the pacemaker to detect the presence or absence of an "evoked response," which is the electrical event that results from myocardial capture after an output pulse. Modern devices and leads have improved the ability to identify these signals and differentiate them from polarization artifact (Figure 2.7). The more frequently the pacing threshold is measured, the lower the necessary margin of safety may be programmed because of the reduced chance for an undetected rise in threshold. If capture is assessed with every beat, then pacing output need only be marginally higher than threshold, and a back-up, higher output pulse may be delivered with any detected non-capture event.

The algorithms used for automated capture vary somewhat between manufacturers and it is important to understand the limitations with each approach. The AutoCapture™ algorithm used in St. Jude pacemakers assures capture on a beat-to-beat basis. This algorithm first verifies that the evoked response can be differentiated from the polarization signal by delivering paired pulses, with the second pulse occurring in the absolute refractory period and thus causing only polarization artifact. Via this mechanism, the algorithm is able to set a reliable evoked response sensitivity. If there is insufficient difference between the evoked response signal and the polarization artifact, the algorithm may not function adequately because it runs the risk of oversensing polarization signal and under-estimating the threshold. In these cases, the automatic capture feature has to be turned off. After determination of the threshold, the pacemaker adjusts the output to stimulate at 0.3 V (for single chamber) or 0.25 V (for dual chamber) above the prevailing threshold. The algorithm works by reducing the pacing output in 0.25-V steps over consecutive pairs of beats until loss of capture occurs on two consecutive beats, with a 5-V back-up pulse delivered with each loss of capture event. The output is then increased in 0.125-V steps until two consecutive capture beats are seen, thereby defining capture threshold. The 0.25-V margin is then added to this threshold for subsequent pacing until loss of capture is seen or the next threshold test is performed. It is important to remember that capture confirmation occurs on a beat-to-beat basis. In several multicenter studies, the algorithm was found to be safe and effective and did not result in loss of capture, exit block, or other adverse events.[20,21] However, the algorithm requires use of a bipolar pacing lead with low polarization properties. Furthermore, patients with this feature turned "on" may exhibit unusual pacing behavior on telemetry or ECG when the device is performing automatic threshold testing.

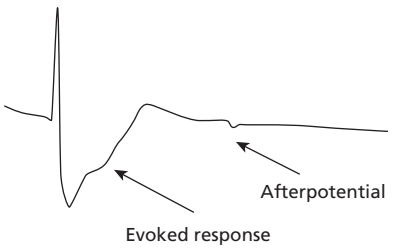


Figure 2.7 Schematic of how an evoked response (first potential) may be sensed as compared with the afterpotential due to polarization (second potential).

The Capture Control™ algorithm used in Biotronik pacemakers similarly depends on the use of a bipolar lead with low polarization characteristics. The differences from the St. Jude Medical algorithm include the absence of a back-up safety pulse during loss of capture and an output increase in 2-V steps if there is persistent loss of capture. Then, after a programmable length of time, the output is decreased to the original value to see if capture can be obtained with a lower output.

Other manufacturers use algorithms that deliver back-up pulses on a beat-to-beat basis or provide automatic determination of pacing threshold at programmed intervals during the day. Boston Scientific pacemakers make use of a coupling capacitor to "absorb" polarization energy, allowing their

beat-to-beat capture algorithm to be used with a wide range of pacing leads. The Ventricular Capture Management™ feature of Medtronic devices also works with a wide range of leads, but rather than looking for beat-to-beat capture, the algorithm performs a strength duration threshold test at programmable intervals (nominal is once per day). With this algorithm, the amplitude threshold is first determined at a fixed pulse duration (0.4 ms), and then the pulse amplitude is doubled and a pulse duration threshold is measured. The permanent ventricular stimulation amplitude is then automatically set using a pre-programmed amplitude safety margin (usually twice threshold, which is the nominal setting) or a programmable minimum amplitude (whichever is higher).

These automated capture algorithms may improve safety related to pacing by avoiding situations where loss of capture could occur due to a rise in the stimulation threshold, improve battery longevity by reducing the programmed safety margin in line with the stimulation threshold, or both.[22] However, the differences between manufacturers' algorithms should be understood before activating them, especially in a pacemaker-dependent patient. Furthermore, it is important to understand the differences in the types of leads with which each algorithm may work.

Automated sensing

The amplitude of the atrial and ventricular EGM can vary with the cardiac rhythm, patient activity, medications, or changes at the electrode–myocardial interface. Atrial EGMs, for example, are generally smaller in atrial fibrillation than in sinus rhythm, whereas the ventricular EGM amplitude can decrease in the setting of infarction or fibrosis of the myocardium near the ventricular electrode. In pacemakers, traditionally a fixed sensitivity setting is used, and EGMs that surpass this cut-off are sensed, and those of smaller amplitude fail to be sensed. Because the most common cause of anomalous pacemaker behavior relates to problems with sensing, several manufacturers have introduced pacemakers that regularly determine the amplitude of P and R waves, and automatically reprogram the atrial and ventricular sensitivity settings to maintain an acceptable sensing safety margin.

The clinical utility of an autosensitivity algorithm is highlighted by the observation that programming a 100% sensing safety margin based on a single P wave measurement provides reliable atrial sensing in only 72% of patients with dual chamber pacemakers. One example of autosensing is the Medtronic Sensing Assurance™ algorithm, which repeatedly measures the amplitude of P and R waves and classifies each as low, high, or adequate based on a non-programmable target safety margin. This feature reprograms the bipolar atrial sensitivity value so that the atrial EGM is maintained within a range that is 4.0–5.6 times the programmed sensitivity value, and the atrial unipolar lead and ventricular lead sensitivity value so that the target safety margin is 2.8–4.0 times the programmed sensitivity. Other manufacturers offer similar algorithms to ensure adequate sensitivity safety margin programming. In more recently introduced pacemaker platforms, sensing algorithms are similar to those used in ICDs with beat-to-beat variation in sensitivity or gain control.

Considerations of time-dependent changes in the context of device programming

Proper programming of the stimulus amplitude of a permanent pacemaker requires an understanding of these potential time-dependent changes in stimulation threshold and sensing. For example, the safety margin that is chosen for a particular patient must be based on an expected severity of symptoms if loss of effective pacing occurs. For patients judged to be highly pacemaker dependent, a higher stimulation safety margin may be desired. As an example, a patient with complete AV block with an unreliable ventricular escape rhythm may be more likely to develop symptoms with loss of ventricular capture than a patient with intermittent sinus node dysfunction. On the other hand, the patient with AV block is likely to be less dependent on atrial than ventricular capture. Thus, a higher safety margin may be needed for ventricular than atrial pacing.

One of the downsides to programming an excessive safety margin is the impact on battery longevity. Programming stimulus intensity to greater than 2.8 V results in a marked increase in current drain from the battery. Generally, a three-fold safety

margin may be employed at the time of initial implant, followed by reprogramming to a lower value at the 6–8-week follow-up visit. Determining the appropriate safety margin has to be considered in the context of the patient's other metabolic and pharmacological history as the resulting confounders may alter stimulation threshold.

Sensing may improve after resolution of acute current of injury and further significant changes are unusual in the subacute settings. Local scar formation or dislodgement may alter sensing parameters and reprogramming may be necessary during follow-up. Depending on the clinical circumstances and sensed signal amplitude, sensitivity in pacemakers is usually programmed between ½ to 1/5 of the peak signal amplitude.

Impact of clinical variables on pacing threshold

Several clinical variables, including metabolic and pharmacological factors, may impact pacing parameters, in particular the stimulation threshold[23] (Table 2.1). One example is the impact of faster pacing rates on pacing threshold. With increasing pacing rates, there is a shortening of the myocardial action potential, thus shortening the relative refractory period. In such situations, there may be a reduction in stimulation threshold. However, with very rapid pacing (rates above 250 bpm), stimulation may occur during the relative refractory period, thus necessitating higher stimulus output or duration. This is relevant to conditions under which antitachycardia pacing may be delivered (e.g. in defibrillators).

Table 2.1 Pharmacological and metabolic effects on stimulation threshold

	Increase threshold	*Decrease threshold*
Antiarrhythmic drugs	Class I Quinidine Procainamide Flecainide Propafenone	
Other drugs	β-blockers	Catecholamines Isoproterenol Corticosteroids
Metabolic conditions	Hyperkalemia Hyperglycemia Hypoxemia Hypercarbia Metabolic acidosis Metabolic alkalosis	
Activity/other conditions	Sleeping Eating Viral illness Vagal tone	Exercise Sympathetic tone

Other settings in which stimulation thresholds may change are myocardial infarction and endocardial ablation. Any condition that results in increased fibrosis or scarring close to the pacing lead may result in an increase in stimulation threshold or loss of capture.

Stimulation threshold shows a circadian variation, generally increasing during sleep and falling during waking hours. The changes in threshold likely reflect fluctuations in autonomic tone and circulating catecholamines. The stimulation threshold may also increase after eating, and during hyperglycemia, hypoxemia, hypercarbia, and metabolic acidosis or alkalosis. The stimulation threshold may increase during acute viral illnesses as well, especially in children. The concentration of serum electrolytes may also influence the stimulation threshold, as seen for example with a rise in the stimulation threshold in the setting of hyperkalemia.

Drugs may also influence the stimulation threshold. While medications like isoproterenol may decrease threshold, β-blocking drugs may increase threshold. Both oral and parenteral corticosteroids may produce a decrease in the stimulation threshold and alleviate the acute rise of threshold following implantation of an active fixation lead. Antiarrhythmic drugs also have prominent effects on stimulation threshold. Drugs that raise the stimulation threshold include the type I antiarrhythmic drugs quinidine, procainamide, flecainide, and propafenone. Virtually all antiarrhythmic drugs may influence the pacing threshold, though these changes are usually clinically important only at high serum concentrations of the drug.

Biventricular pacing

In the early days of cardiac resynchronization therapy (CRT) pacing, implantable devices were

not manufactured with separate pacing circuits for the RV and LV leads, and only unipolar leads were manufactured for LV pacing via a cardiac vein. In these older devices, the most common configuration involved electrically linking the tip electrodes of the RV and LV leads as a split cathode, and using either the RV ring electrode (if a bipolar RV lead was present) or the pulse generator as the common anode. Regardless of the configuration, the leads were linked to one another with a Y adaptor to achieve biventricular pacing. This configuration lent itself to multiple issues due to the leads essentially acting in parallel. Pacing output had to be programmed above the highest threshold of the two leads, resulting in increased current drain. It was also difficult to assess the parameters of individual leads and failure of a single lead could not be easily determined.

Modern CRT devices allow for separate pacing circuits for the RV and LV leads, and allow LV leads with unipolar, bipolar, and multipolar configurations. The ability to separately assess the RV and LV leads allows the clinician to program parameters separately, and simplifies lead assessment while simultaneously reducing current drain on the battery. Furthermore, separate programming of the LV and RV channels allows pacing with multiple LV configurations and with optional different timing between the two channels. Multiple LV configurations allow non-invasive programming options to avoid phrenic nerve capture or minimize current drain during LV pacing. For example, unipolar leads may be programmed as true unipolar (where the pacemaker generator is the anode; not available on all devices) or extended bipolar (where the RV ring electrode or the RV coil in the case of an ICD lead is programmed as the anode). Bipolar LV leads allow for the addition of several more pacing configurations beyond unipolar pacing from each electrode, including the ability to program true bipolar or an extended bipolar configuration with either the LV tip or LV ring as the cathode.

There have been recent advances in biventricular pacing beyond standard unipolar and bipolar configurations, though these require the use of unique leads and generators. One example is the quadripolar lead.[24] This lead has four poles which can act together in multiple configurations to allow for bipolar pacing (Figure 2.8). The addition of several poles that can act as the cathode along the body of the lead allows the identification of areas more proximally along the cardiac venous system where phrenic capture may be avoided or where placing a bipolar lead may be difficult due to issues with stability. For example, the tip of a quadripolar lead may be fixed in a distal position in a cardiac vein for stability, but a more proximal electrode may be used for pacing if local threshold or phrenic nerve capture may be limiting in other positions. However, this lead is slightly larger than the smallest LV leads, limiting the ability to access particularly small veins. In addition, only one device manufacturer currently provides the lead and currently it cannot be used with generators made by other manufacturers.

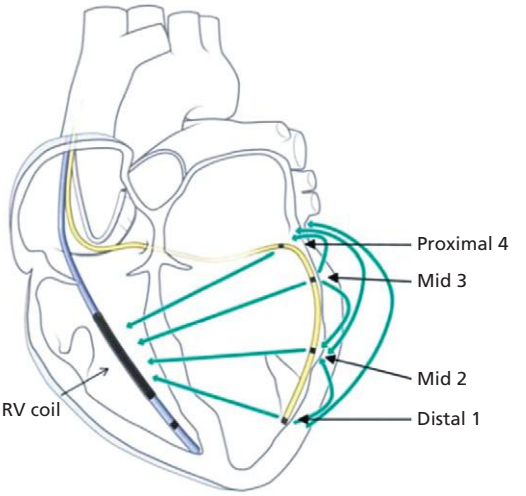


Figure 2.8 Poles available with a quadripolar lead. Ten vectors are available using the three ring electrodes, the distal tip of the lead, and the right ventricular (RV) coil: (1) distal 1 (D1) to mid 2 (M2); (2) D1 to proximal 4 (P4); (3) D1–RV coil; (4) M2–P4; (5) M2–RV coil; (6) mid 3 (M3) to M2; (7) M3–P4; (8) M3–RV coil; (9) P4–M2; and (10) P4–RV coil. (Source: St. Jude Medical, Inc. Reproduced with permission of St. Jude Medical, Inc.)

In some patients, endovascular LV lead placement may not be possible due to limitations of the cardiac venous anatomy. In such cases, placement of an epicardial LV lead may be considered. Currently, this requires placement in the operating room using thoracotomy. However, work is ongoing on developing percutaneous approaches to epicardial LV lead placement.

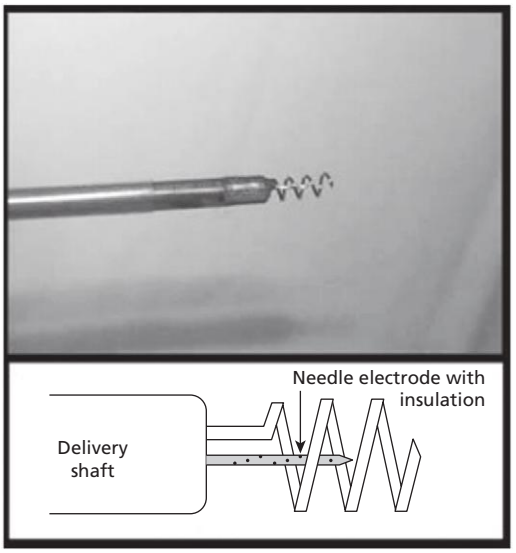


Figure 2.9 Novel intramyocardial pacing lead with the cathode wrapped around the anode in a spiral pattern. This formation allows for a complete intramyocardial position for both portions of the circuit. (Source: Biffi M *et al.* 2010.[22] Reproduced with permission of John Wiley & Sons Ltd.)

Additional research is exploring novel leads and pacing locations to achieve more physiological ventricular activation akin to biventricular pacing. One example is pacing via the AV septum that exists between the right atrium (RA) and LV.[25] For example, an intramyocardial pacing lead in which the cathode (a coil) surrounds the anode, such that both can be actively fixed together into the AV septum, may allow for pacing akin to His or para-Hisian pacing without crossing the tricuspid valve or accessing the cardiac venous system[25] (Figure 2.9).

Work has also been done on multisite pacing, or pacing from more than two sites. Limitations to this approach include the need for additional hardware. There is also a lack of sufficient clinical data to recommend routine clinical use of this modality at this time.

Generally, all LV pacing will be done from the cardiac venous system or an epicardially placed lead. Endocardial LV leads are not routinely used due to concern for thrombus formation and systemic embolization. However, some small studies on LV endocardial leads have suggested that they may be safely used and provide incremental benefits in some patients.[26,27]

Pacemaker hardware

A pacing system is comprised of the pulse generator and lead(s). The pulse generator is made up of the connector block (header) and device enclosure. Pacing systems have advanced tremendously in the last 40 years. They have become increasingly complex, while at the same time becoming smaller and more reliable, without compromising longevity. Even "simple" pacemakers have become so sophisticated that technologies developed for ICDs have found their way into pacemakers, especially in the areas of power sources and lead design. It is not possible for the clinician to be familiar with every design aspect of each pacing system. Device encyclopedias are published by all manufacturers and contain detailed specifications for pulse generators and leads. Furthermore, a product manual is available for each device and contains an even more comprehensive description of the device specifications and function. It is necessary for the clinician to have a fundamental knowledge of pacemaker design and function in order to select the appropriate hardware for a given patient and to evaluate new products as they are introduced.

Lead designs, materials, and functional characteristics

Pacing leads have five major components: electrodes, conductors, insulation, connector pin, and fixation mechanism. The design and functional characteristics of these components will be discussed together. With respect to these five components, the basic endocardial pacing lead has not undergone significant change in the last decade. Conversely, LV (coronary sinus) pacing leads have undergone a great deal of evolution in terms of shape, size, and fixation mechanism. There are now suitable leads for most coronary sinus (CS) anatomies, resulting in improved implant success rates.

Lead designs

Unipolar, bipolar, and multipolar pacing leads

Unipolar pacing leads have the simplest lead design of all leads. Once the only option for transvenous permanent pacing leads, unipolar leads have been

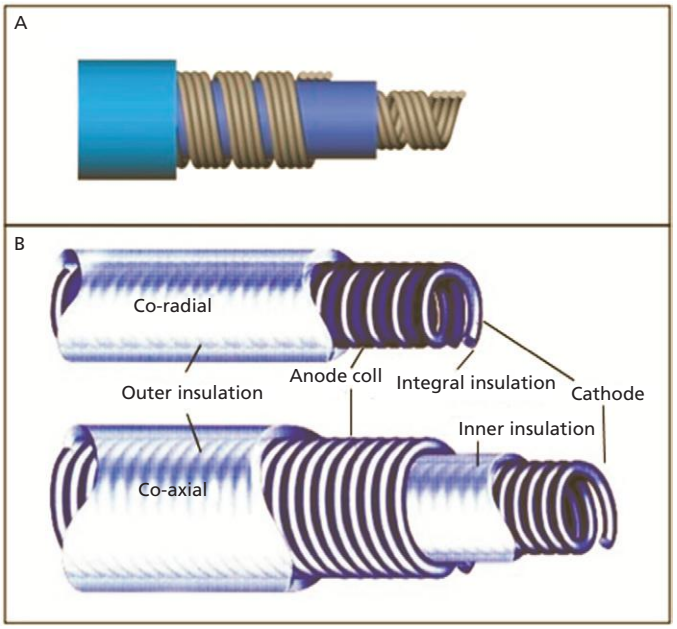


Figure 2.10 (A) Schematic of a typical co-axial lead design with an inner and outer conductor separated by a layer of insulation and then covered by another layer of insulation. (B) Comparative schematic of a co-radial (top) and co-axial (bottom) lead design. Note the two conductors are wound in parallel around a central lumen and each conductor is individually insulated.

largely replaced by bipolar lead designs for most endocardial applications. However, unipolar designs are still commonly used in CS branches for CRT.

Unipolar leads have only one conductor surrounded by insulation. The tip of the lead is the cathode and the pacemaker generator completes the circuit as the anode. Thus, pacing and sensing are accomplished as a bipolar circuit, but the lead is referred to as unipolar because only one electrode is in contact with the heart. Due to their relatively simple design, endocardial unipolar leads have demonstrated impressive longevity and many are still in service today.

With a bipolar pacing lead, the pulse generator is not part of the pace/sense circuit. Both the ring electrode (anode) and the tip electrode (cathode) are in contact with the myocardium. Bipolar leads can be used for endocardial, CS, and epicardial applications. There are two main bipolar lead designs: *co-axial* and *co-radial*. In a co-axial design, the inner conductor is arranged in a coil that extends to the tip of the lead (cathode) and has a central lumen to allow passage of a positioning stylet. A layer of insulation then covers the inner coil, electrically separating it from the outer coil that extends to the ring electrode. Another layer of insulation then covers the outer coil (Figure 2.10). These leads can be attached to the endocardium via an active or passive fixation tip. The active fixation mechanism is usually an *extendible/retractable* helix. The filar count of the inner and outer coils can be variable, depending on the goals of the manufacturer. The co-axial, four-layer design is an industry standard for most pacing leads, but this limits the minimum achievable lead diameter.

In the alternative co-radial configuration, two conductor strands are coiled in parallel around a central lumen (Figure 2.10). These strands terminate at the ring and tip electrodes, respectively, and are individually coated with a bonded layer of ethylene tetrafluoroethylene (ETFE) fluoropolymer insulation. The coils are then covered with an outer layer of insulation, usually polyurethane. This lead design allows for significantly smaller diameters ($<$6 Fr), but limits the fixation mechanism to a

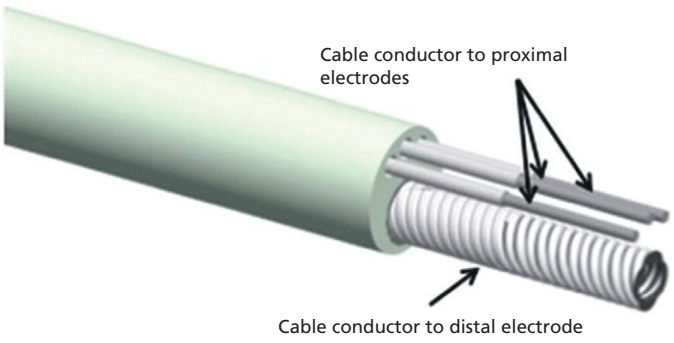


Figure 2.11 Schematic of a multipolar pacing lead. It is very similar in design to a high-voltage ICD lead, but the cable conductors are smaller.

passive tip or active fixed helix. The electrical performance and reliability of current leads using a co-radial design is comparable to those using a co-axial design.

ICD leads are more complex and require two, three, or four conductors. Co-axial designs were once used for ICD leads but resulted in large diameter leads. Multilumen designs are now the standard for ICD leads. The complex challenges of CRT systems have also resulted in the development of multipolar pacing leads. Engineers use a multilumen design for these leads (Figure 2.11). In this design, a central coil conductor extends to the tip, allowing for stylet or guidewire insertion. Conductors for the more proximal electrodes are cables arranged in parallel that terminate at their respective electrodes. Unlike ICD leads, the individual conductor elements can be smaller in diameter because they will not be conducting the high voltages needed for defibrillation. As such, the overall diameter of the lead can remain relatively small, allowing for stable positioning in the branches of the CS. The potential benefits of multipolar leads in CRT applications are significant. Since multiple pacing vectors are available, it may be possible to overcome phrenic nerve stimulation, pace from electrically more advantageous sites, or pace from sites with better pacing thresholds.

Fixation mechanisms

The chronic performance of permanent pacing leads is critically dependent on stable positioning of the electrode(s). Proper fixation to the endocardial surface is essential to lead performance. There

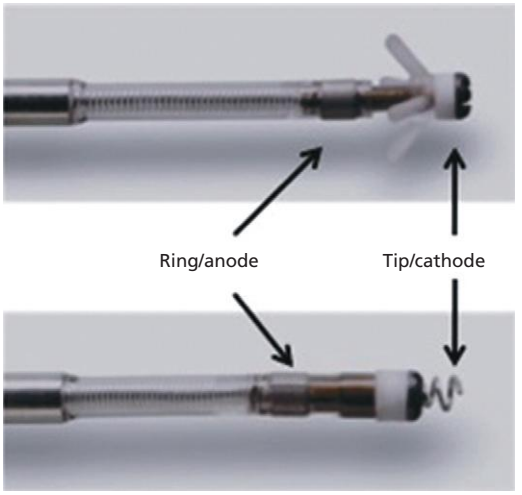


Figure 2.12 A passive fixation bipolar pacing lead (top) and an active fixation pacing lead (bottom). The ring and tip electrodes are indicated. Note: in most leads the fixation helix is the active tip electrode.

are two types of fixation mechanisms: *passive* and *active*. Passive fixation leads have tines (fins) near their tip, which are made of the same material as the insulation. The number (two, three or four), length, and stiffness of the tines are variable (Figure 2.12). Passive fixation leads become entrapped within the trabeculae of the RA appendage or RV apex immediately upon correct positioning of the lead. Effective fixation of the lead can be confirmed at the time of implantation by its gentle traction or rotation. Tines generally add minimal technical difficulty to the implantation procedure, although they may occasionally become entrapped in the

tricuspid valve apparatus. These leads are not suitable for placement in non-traditional locations such as the high RV septum or RV outflow tract. The passive fixation leads are rapidly covered by fibrous tissue, making removal of the lead by simple traction difficult or impossible in as short a time as 6 months. In general, passive fixation leads are more difficult to extract than active fixation leads.

Despite the overall low rates of dislodgement, passive fixation leads are not suitable for every patient. In the present generation of active fixation, endocardial leads have a fixed helix or extendable–retractable helix that in most cases also serves as a pacing electrode. However, not all leads have an electrically active helix. This fact is important to understand when attempting to electrically "map" the myocardium for suitable implant sites. In leads with a fixed helix design, the helix is coated with mannitol or polyethylene to facilitate introduction of the lead through the vasculature into the desired chamber. The coating dissolves within a few minutes, allowing the lead to be positioned with a stylet. Fixation is performed by rotation of the entire lead body and transmission of the torque to the distal tip. Repositioning is accomplished by reverse (counterclockwise) rotation of the lead. These leads have similar electrical performance characteristics to other designs with comparable rates of dislodgement. However, the implant technique may be unappealing for some implanters who prefer to use an extendable–retractable helix for fixation. The extendable–retractable design has become the most widely used active fixation mechanism because of its ease of implantation and because the fixation mechanism allows retraction long after implantation, thereby facilitating repositioning or extraction. Active fixation leads allow for stable positioning of the lead at many sites in either the atrium or the ventricle.

Although active fixation leads are easier to extract than passive fixation leads, the risk of myocardial perforation during and after implantation is higher. Historically, the chronic pacing thresholds of active fixation leads were higher than those of passive fixation leads. This difference has largely been eliminated with the routine use of corticosteroids in active fixation leads. Active and passive fixation leads tend to perform similarly overall.[28] The advantages of active fixation leads with regards to non-traditional positioning and repositioning need to be weighed against the risk of perforation.[29] The experience and comfort level of the implanter with a given lead is also a critical factor in the risk of dislodgement or perforation.

The shape of the lead is important to its function and stability. Passive fixation atrial leads have a preformed J shape, simultaneously allowing for and restricting positioning to the RA appendage. Some active fixation leads are available for use exclusively in the RA and have a preformed J shape. Most active fixation leads are straight and can be implanted in either the atrium or ventricle with the use of preformed or user-shaped stylets. In patients with prior cardiac surgery in whom the RA appendage may have been removed or modified, an active fixation lead (straight or preformed J shape) should be used.

Confirming adequate fixation is also important for acute stability and long-term lead function. Fixation to the myocardium causes injury to the tissue, known as the current of injury (see "Current of injury"). Most pacing system analyzers (PSAs) have the ability to display a filtered EGM to identify the current of injury (Figure 2.6). Saxonhouse *et al.* reported that the presence of an adequate current of injury at the time of active fixation of a pacing or defibrillation lead correlates with adequate fixation of the lead to the myocardium, and is associated with satisfactory acute pacing and sensing parameters.[16] The absence of a current of injury should prompt the implanter to reposition the lead. In addition, the morphology of the current of injury and time course of resolution have been studied. There is inadequate data to comment on the morphology, but rapid resolution of the current of injury may be associated with inadequate fixation.[30] Although the current of injury is usually observed with active fixation leads, it may also be observed briefly with passive fixation leads. The current of injury should be used in conjunction with other measured parameters (including slew rate, signal amplitude, pacing impedances, and thresholds) to guide implantation of leads. Finally, the implanter should be familiar with the fluoroscopic appearance of the lead tip with the helix extended.

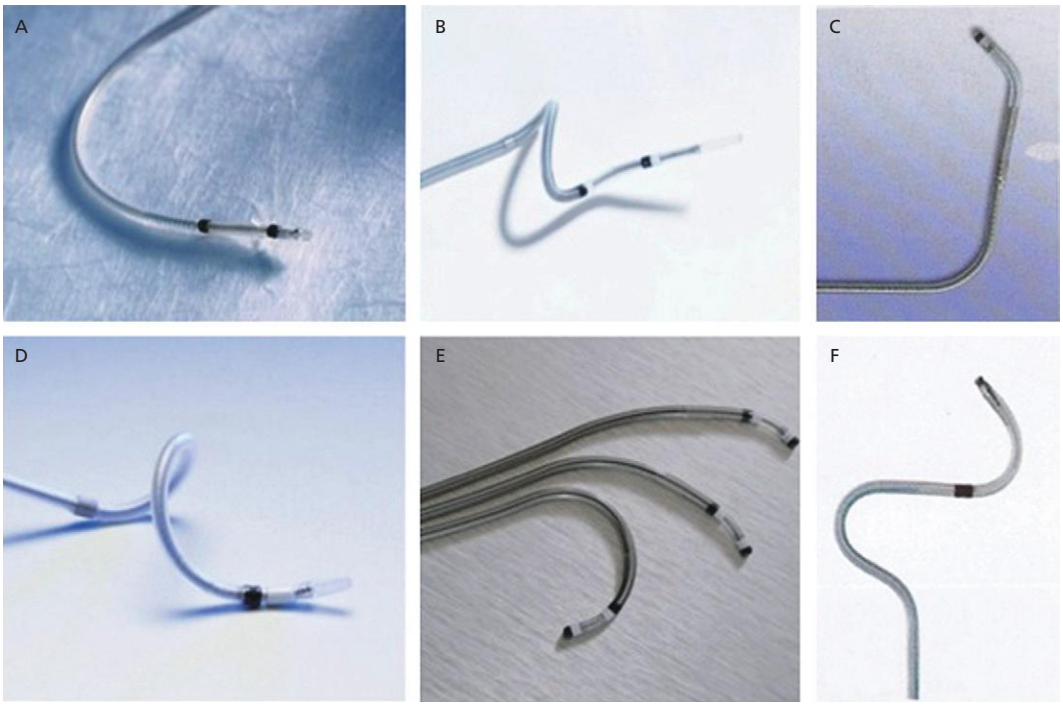


Figure 2.13 Examples of coronary sinus (CS) leads. (A) Bipolar lead with tines; (B) helical biased bipolar pacing lead; (C) bipolar pacing lead with can fixation; (D) helical biased, unipolar pacing lead; (E) bipolar pacing lead with curve fixation; (F) S-biased bipolar pacing lead. (Sources: (A, B, D, E) Boston Scientific Corporation. Reproduced with permission of Boston Scientific. (C) Medtronic, Inc. Reproduced with permission of Medtronic, Inc. (F) St. Jude Medical, Inc. Reproduced with permission of St. Jude Medical, Inc.)

Leads used in CRT deserve special consideration with respect to fixation and shape. CS branch anatomy is highly variable. Manufacturers offer a broad range of CS leads and it is up to the implanting physician to decide which lead is appropriate for a given patient. The implanter has to balance the frequently competing objectives of lead stability, electrical performance, avoidance of phrenic nerve capture, and resynchronization performance. Familiarity with a range of sizes, shapes, and fixation mechanisms of available leads is necessary for successful implantation. Lead diameters vary from 4 to 6 Fr. Another factor to consider is that some leads do not have isodiametric lead bodies. The ring and tip electrode may have larger diameters than the body of the lead. The tip diameter may then be the limiting factor when matching the lead to the anatomical target vessel. The terms active and passive fixation do not strictly apply when discussing CS leads. Most CS leads that are transvenously placed do not have a fixation helix or screw that embeds the lead to the myocardium. Most leads use friction and tension to maintain their position within the CS vasculature. Figure 2.13 shows some examples of CS leads of varying shape and size from the major manufacturers in the US. Most leads are bipolar, but some of the smaller diameter leads are unipolar. Some leads (Boston Scientific Easy Trak2®) are straight with tines that allow them to be wedged into a distal target vessel and help provide additional stability through frictional force. Other leads have multiple cants or curves that apply pressure to the vessel wall, again providing stability by frictional force. Alternatives to canted leads are leads with sigmoidal biasing in two dimensions (S shaped) or helical biasing in three dimensions (spiral). These leads also rely on the friction created both from wedging the distal tip in a branch and from the multiple contact points on the vessel walls. Despite the variety of available passive fixation CS leads, current passive leads often do not remain stable in the proximal

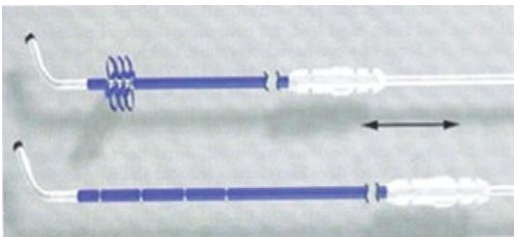


Figure 2.14 The Medtronic StarFix® lead with its fixation lobes deployed (top) and retracted (bottom).

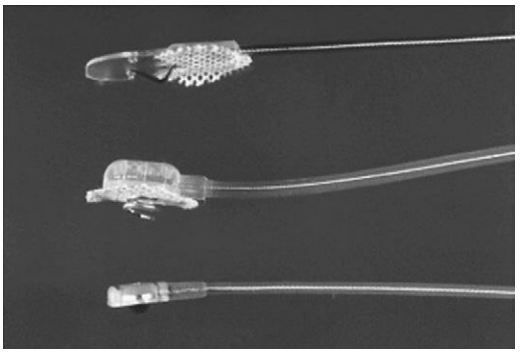


Figure 2.15 Examples of epimyocardial leads (see text for details). From top to bottom: fish hook type, screw-in helix type; and sew-on button type.

portion of the CS tributaries. If a distal branch cannot be engaged or is prohibited due to phrenic nerve or extracardiac stimulation, a proximal position can be targeted with a lead such as the Medtronic Attain 4195 StarFix® lead. This has a unipolar design with three lobes that are deployed by advancing the push tubing around the lead (Figure 2.14). While there is an expanding body of literature about extraction of passive fixation CS leads, valid concerns have been raised about the extractability of this lead.[31] Active fixation CS leads remain a niche application. The need for this type of lead may also be mitigated by the development of multipolar CS leads with alternate pacing vectors.

Epimyocardial leads

Permanent epicardial pacing leads are used when tricuspid valve abnormalities, central venous obstruction, congenital heart disease, or technical issues preclude transvenous lead placement. Epicardial leads may also be used when recurrent bloodstream infection is a concern, or when there is a need for lead implantation co-incident with another intrathoracic surgical procedure. Epicardial pacing leads are either sutured to the epicardial surface or screwed into the epimyocardium of the atrium or ventricle (Figure 2.15). Fixation mechanisms include a fishhook-shaped electrode that is stabbed into the atrial myocardium or a large screw helix that is rotated into the ventricular myocardium. These leads are typically unipolar and are frequently non-steroid eluting, with chronic stimulation thresholds that are higher than those of modern endocardial electrodes. A newer epicardial lead design has a steroid-eluting electrode, rests against the epicardium, and is sutured in place. This lead design, which is available in unipolar and bipolar models, has the advantage of lower chronic pacing thresholds and better long-term performance. It may require greater cardiac exposure and can be technically more difficult to place.

The presence of regions of epicardial fat can limit effective implant locations for all epicardial leads. Because epicardial leads have a higher rate of developing unacceptably high pacing thresholds, it is the practice of some cardiothoracic surgeons to implant two leads in a given cardiac chamber, with the second lead either connected to a different pacemaker port or left capped in the pacemaker pocket. If the initial lead fails, another is then available as a potential alternative. In the era of CRT, epicardial leads are also being used when a functional LV lead cannot be placed transvenously due to limitations imposed by the coronary venous anatomy.

Materials

Materials used in pacemaker leads and ICD leads are similar. The materials used in the construction of these leads and lead components are manufactured to very high industrial standards. Although the materials used by each manufacturer are similar, there are significant differences in how these materials are applied and in the construction of the leads. Some materials, such as co-polymer insulations, are unique to a specific manufacturer (i.e. Optim®, St. Jude Medical).

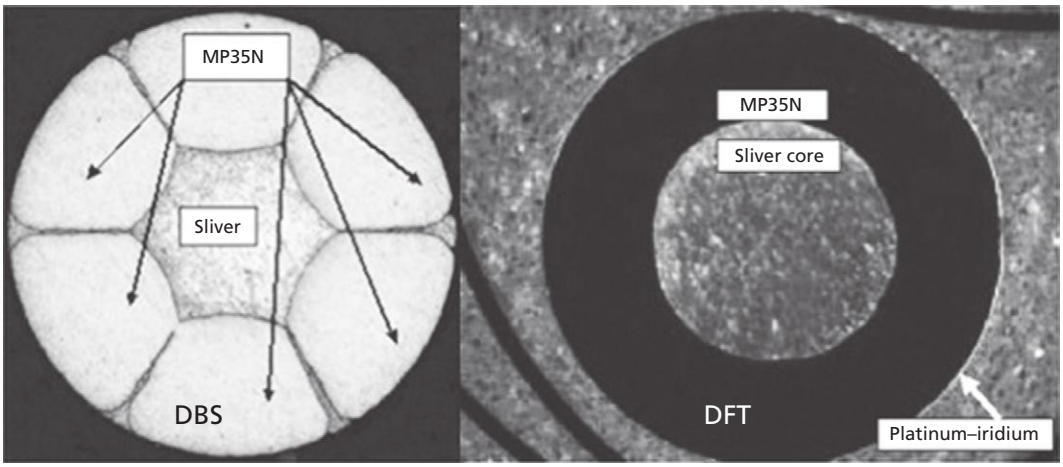


Figure 2.16 Cross-sections of the two types of conducting filaments (wires) used in pacemaker and ICD leads: Drawn brazed strand (DBS, left) and drawn filled tube (DFT, right).

Conductors

The primary conductors used in most pacing and ICD leads are MP35N and silver. MP35N is a superalloy that is double melted to remove impurities. It is composed of cobalt, nickel, chromium, and molybdenum. It is characterized by biocompatibility, high tensile strength, and resistance to corrosion. Because of its relatively high electrical resistivity (1033 $\mu\Omega$), MP35N is combined with efficient conductors such as silver. Single conducting filaments (wires) are made in two designs: a drawn brazed strand (DBS) and a drawn filled tube (DFT). Figure 2.16 shows cross-section examples of each. The DBS design consists of the MP35N® alloy stranded around a core of softer, highly conductive silver. The resulting wire combines increased fatigue life, high conductivity, and solderability with the ability to withstand greater mechanical stresses. The DFT design is coated with platinum or platinum–iridium. Extreme compressive forces are applied in order to form a sound mechanical bond between surfaces. This feature allows the DFT wire to exist as a round single wire or be shaped into a ribbon (squared edges). The tensile strength and electrical resistivity of this wire depend on the amount of silver in the core, which can be manufactured to the needs of the lead engineers. Both DFT wires and DBS wires can be formed into coils or twisted into cables. The conductors in pacing leads are generally in the form of a DFT wire.

Single wires are combined together into strands and then wound into cables for use as cable conductors (Figure 2.17). The number of wires used in a cable is related to its intended use, with larger cables used for high voltage applications and smaller cables for pacing applications. Cables can also be coated with ETFE fluoropolymers before being coiled into co-axial or co-radial lead designs (see "Lead designs"). This coating protects the silicone or polyurethane insulation. Cable conductors offer greater strength, fracture resistance, and redundancy than coiled conductors. Cable conductors are also non-compressible. The number of filaments and their arrangement within a given cable is variable from manufacturer to manufacturer, even for similar applications. Two examples are shown in Figure 2.18. Compared individually, a 7 × 7 (49 wire) cable has relatively greater flexibility but relatively lower torquability than a 1 × 19 (19 wire) design. Neither design has been shown to be clinically superior.

Despite the sophisticated manufacturing process, MP35N® can contain foreign inclusions of nitride, oxide, or carbide bodies that can negatively influence the metal fatigue life and potentially contribute to lead fracture. Titanium, which can be found in minute quantities in MP35N®, can form titanium

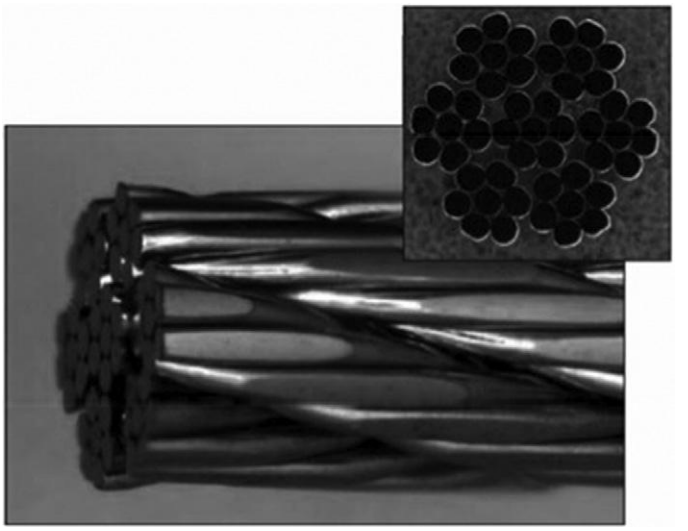


Figure 2.17 Multiple wires (filaments) wound into a strand (cable) (see text for details).

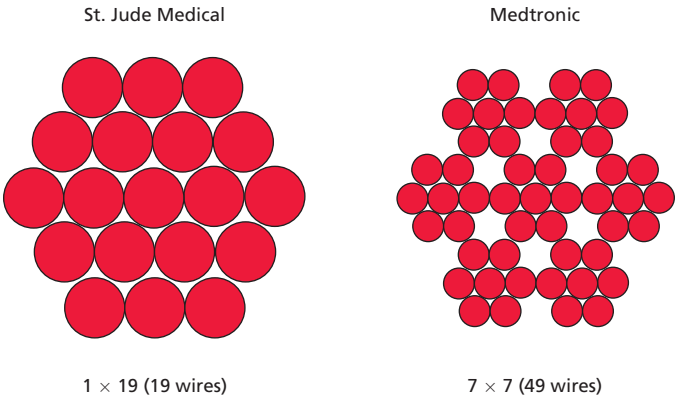


Figure 2.18 Cross-sectional representation of two high-voltage conductor designs used in ICD leads (see text for details).

carbide or titanium nitride inclusions that can contribute to fatigue cracking. Leads containing a modified, low titanium MP35N® alloy (from Medtronic) are now in use, but their impact on the clinical rates of lead failure due to fatigue and cracking needs to be assessed. Fractures due to fatigue cracking appear uncommon and usually occur at points of high mechanical stress, such as at the anchoring sleeve or costoclavicular ligament.[32]

The structure of the pace/sense coil conductor of the cathode is highly variable between manufacturers. Figure 2.19 shows the structure of the coil and the characteristics engineers consider. These characteristics are important because they affect the flexibility of the coil as well as its resistance to fracture. Wire diameter, number of filars (wires), and pitch all vary between manufactures and between lead families of a given manufacturer. Multifilar coils offer lower electrical resistance (optimal), but may have lower fatigue life when compared to bifilar designs. There is no consensus as to the optimal combination of these factors.

Insulation

The materials used in pacemaker leads for insulation play a critical role in their longevity and reliability, as well as in handling and implant characteristics. The ideal insulation material should be biologically inert, and exhibit no surface erosions, no molecular chain disruptions, no uptake of low-molecular-weight biological materials, and no

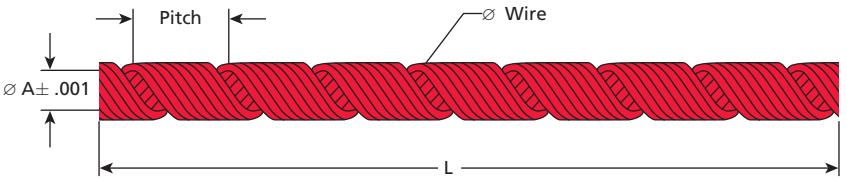


Figure 2.19 Schematic of the coil conductor for the cathode. Each filar has a diameter. Coil filarity is the number of separate wires within the coil. Pitch is a function of the filar diameter × the number of filar in the set + the space between filar sets. (Source: St. Jude Medical, Inc. Reproduced with permission of St. Jude Medical, Inc.)

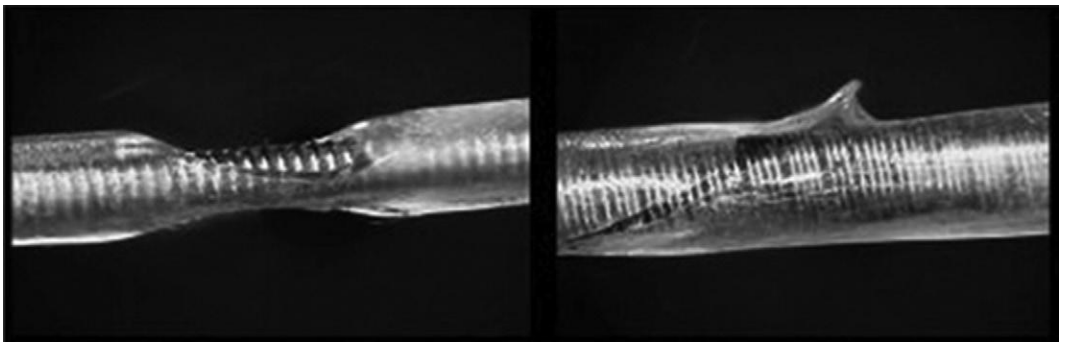


Figure 2.20 Example of lead abrasion (left) and cold flow and abrasion (right). (Source: St. Jude Medical, Inc. Reproduced with permission of St. Jude Medical, Inc.)

tendency to calcifications, while retaining stable mechanical properties. There is no single ideal insulation and some leads are constructed using multiple materials. Pacemaker leads are generally made of one insulation type. ICD leads are more complex, utilizing combinations of insulation material. Here we will discuss the different options for insulative coating of leads.

Fluoropolymers are fluorocarbon-based polymers that are characterized by high resistance to solvents, acids, and bases. Therefore, they have maximum biocompatibility and tensile strength, but their stiffness limits their use to thin coating (<0.076 mm) applications. Conductors are coated with a fluoropolymer layer to prevent adverse interactions with silicone tubing. Examples of fluoropolymers are PTFE (polytetrafluoroethylene, i.e. Teflon®, DuPont) and ETFE (ethylene tetrafluoroethylene).

Silicone rubber is a polymer that has a "backbone" of silicon–oxygen linkages; the same bond found in quartz and glass. It is both biostable and biocompatible. It also has high resistance to extreme temperatures and therefore is less susceptible to damage from electrocautery. Its main disadvantage is its low tensile strength, making it prone to tearing and abrasion wear. Abrasion wear comes from lead-to-can and lead-to-lead interaction within the pocket. This chronic interaction can result in cold flow (also known as creep), defined as increasing deformation under constant or cyclic compression (Figure 2.20). Silicone also has a high co-efficient of friction, making it difficult to pass alongside other leads. When silicone is used as primary insulation, relatively thick layers are used and covered with a lubricious coating or polyurethane in order to improve handling characteristics.

Of the insulation materials in use today, polyurethanes have the lowest biostability, relatively speaking. Polyurethanes are characterized by high tear strength, high elasticity, and a low co-efficient of friction. These qualities allow for smaller lead diameters. The observed interactions of polyurethane chemistry and body chemistry can lead to significant degradation of lead function, resulting from calcification (uncommon), environmental stress cracking (ESC), and chain scission. ESC

occurs, in part, as a result of polyurethane oxidation caused by macrophages that induce hydrogen peroxide formation on the polymer structure. Hydrogen peroxide is also produced by inflammatory cells as they make contact with the conductor. This results in oxidation-induced molecular chain breaks in the polyurethane and metal ion oxidation (MIO). Thermal instability and mechanical stresses also play a role in ESC. Polyurethane is not stable at high temperatures and is prone to melting when electrocautery is applied. The two most common polyurethanes that have been used are Pellethane 80A and Pellethane 55D (Upjohn Co., Torrance, CA, USA). Pellethane 80A has been associated with increased long-term failure rates. Pellethane 55D is more biostable and is now the dominant polyurethane in use today. Table 2.2 summarizes the advantages and disadvantages of silicone- and polyurethane-based leads.

Elast-Eon (AorTech Biomaterials, Clayton, Victoria, Australia) is a co-polymer composed of silicone rubber, polyurethane, and polyhexamethylene oxide (PHMO). The polyurethane is composed of methylene di-isocyanate (MDI) and butanediol (BD0). Elast-Eon has been specifically designed to be used in biomedical applications because it retains the strengths of its primary components (characterized by tear and abrasion resistance, lubricity, flexibility, and biostability). This material is used in the St. Jude Medical Optim® pacing leads (models 1888T and 2088T) and ICD leads (Riata-Optim® and Durata®). Although there are *in-vitro* and *in-vivo* animal studies regarding the performance of this co-polymer insulation, there are no long-term clinical data.[33] Registry data compiled from multiple studies reported that in 1092 patient who received an Optim® lead, there were no insulation damage-related adverse effects at a median follow-up of 7 months.[34] At least one study, however, has demonstrated that the co-polymer used in these leads is not protective against thermal injury from electrocautery.[35]

Table 2.2 Advantages and disadvantages of types of lead insulation

	Advantages	*Disadvantages*
Silicone rubber	30-year proven history	Tears easily
	Repairable	Cuts easily
	Low process sensitivity	Low abrasion resistance
	Easy fabrication/ molding	High friction in blood
	Very flexible	Requires larger diameter
		More thrombogenic and fibrotic
		Subject to cold flow failure
		Absorbs lipids (calcification)
Polyurethane	10-year proven history (P55D)	Relatively stiff
	High tear strength	Not repairable
	High cut resistance	Manufacturing process sensitive
	Low friction in blood	Metal ion oxidation
	High abrasion resistance	Environmental stress cracking
	Thinner diameters	History of clinical failures (P80A)
	Relatively non-thrombogenic	

Electrodes

The pacing electrode is the final interface between the lead and myocardium. Its design and composition greatly influence the overall electrical performance of the pacing system. In a bipolar pacing lead (see "Lead design"), the tip electrode is the cathode and the ring electrode is the anode (Figure 2.12). The stimulation threshold is a function of the radius of the electrode. A smaller radius is associated with a higher current density, lower pacing threshold, and higher resistance at the electrode–myocardium interface. In contrast, smaller radius electrodes result in high sensing impedance and electrode polarization impairing myocardial EGM sensing. The development of complex surface geometries has allowed reduction in electrode size while maintaining electrode surface area. The complex, textured surface of current pacing leads also minimizes the

polarization effect and improves both sensing and stimulation efficiency. The ability to differentiate a true evoked myocardial EGM from polarization-induced afterpotentials has dramatically improved with the development of these low-polarization electrodes. Low-polarization electrodes have also allowed for the development of autocapture algorithms (see "Automated capture").

The materials currently used for electrodes of permanent pacing leads include platinum–iridium, Elgiloy (cobalt–chromium–nickel), platinum coated with platinized titanium, vitreous or pyrolytic carbon coating a titanium or graphite core, platinum, iridium oxide, or titanium–nitride. Titanium–nitride has the lowest polarization effect. In addition to the shape of the electrode, fractalization of the surface structure of these electrodes has resulted in negligible polarization effect.[36] Other metals that have been used in the past include zinc, silver, copper, and nickel. These metals have been associated with direct tissue toxicity or corrosion. The polarity of the electrode may also influence chemical stability. Elgiloy is stable when used as a cathode but not when used as the anode, where it is susceptible to significant corrosion.

The use of corticosteroid-eluting electrodes has been a major advance in pacing lead technology. Dexamethasone sodium phosphate and/or dexamethasone acetate is impregnated on a silicone core or collar that surrounds the tip electrode. Corticosteriods have dramatically reduced the risk of exit block for pacing leads, ICD leads, and epimyocardial leads. Steroids do not affect acute implant thresholds, but do prevent the subacute post-implant stimulation threshold peak. They also reduce the variation in chronic pacing thresholds. These electrophysiological effects are mediated through corticosteroid-induced attenuation of the inflammatory reactions, resulting in thinner fibrous capsules.

Connector pins

Connector pins are made of stainless steel or titanium. During the early decades of pacing lead development, there were a variety of connector pin designs with and without sealing rings. Figure 2.21 shows varieties of lead connectors. There are relatively few leads in clinical service today with the 6-mm or 5-mm pins. In cases where they are still in service, a pacemaker with a compatible header block or lead adapter may be needed at the time of generator replacement (Figure 2.22). Lead adapters should be avoided whenever possible due to increased pocket bulk and increased likelihood of loose connections.

The current standard is IS-1 (Industry Standard) for pacing leads (Figure 2.23). The lead diameter at the head block is 3.2 mm and sealing rings are integrated to the lead. With this industry standard, all current bipolar pacing leads are compatible with all current manufacturer header designs. It is important to visualize the connector pin extending beyond the distal set screw in the header block. If

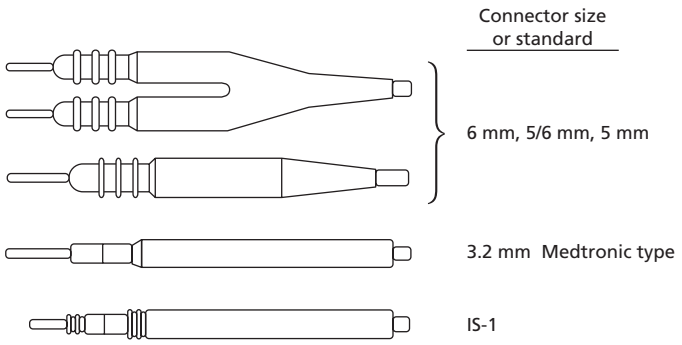


Figure 2.21 Four varieties of lead connectors. From top to bottom: a bifurcated bipolar design with two connector pins, each 5–6 mm in diameter, with sealing rings on the lead; a standard unipolar design of 5 or 6 mm in diameter with sealing rings on the lead; the Medtronic-type, low-profile connector has a 3.2-mm diameter and no sealing rings; and the IS-1 connector is the industry standard and also has sealing rings on the lead.



Figure 2.22 Adapter for leads terminated with 5/6-mm pins that need to be connected to a pacemaker with an IS-1 header block.

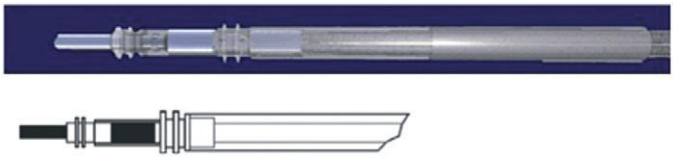


Figure 2.23 Photograph and schematic of an IS-1 pin terminated lead. Sealing rings are integrated into the lead.

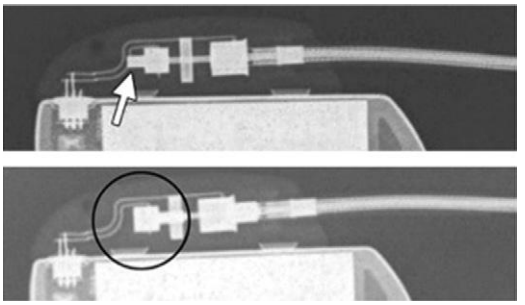


Figure 2.24 Radiograph demonstrating proper extension of the connector pin beyond the set-screw (top; arrow indicates fluoroscopic image of a pacemaker header with properly implanted lead pin) and inadequate extension beyond the set-screw (bottom; circle indicates improper lead pin position).

the connector pin is not properly seated in the header block, sensing artifact or failure to pace may result. Lead impedance measurements alone are not enough to detect this problem. Figure 2.24 shows a radiograph comparing a properly and improperly set lead pin.

Multipolar pacing leads such as those used in the CS will not be IS-1 compatible. They are connected to specialized header blocks using an IS-4 LLLL type pin similar to the pin assembly found on a DF-4 ICD lead.

Lead anchoring sleeve

The anchoring sleeve allows the lead to be secured to the fascia or muscle, and its proper use can help reduce the risk of lead damage. Currently, most sleeves are made of a biocompatible, peroxide catalyzed (MDX) silicon rubber and may contain a radiographically dense material to allow visualization under fluoroscopy. These sleeves have one, two, or three circumferential grooves to which non-absorbable sutures are secured. The number of grooves utilized is implanter dependent (at least two is common), but is less important than achieving adequate pressure to prevent slippage. In some cases, the interior surface of the tubular body includes inwardly extending projections with surfaces adapted to engage the lead body to prevent the sleeve from sliding along the lead body when this is held vertically. Sleeves should have enough rigidity to prevent tie-down damage, while at the same time preventing slippage. Inadequate tie-down force or an inadequate number of sutures is especially a problem with lead bodies coated with a lubricious material such as polyvinyl pyrrolidone (PVP). Balancing the risk of lead damage with lead dislodgement requires the implanter's familiarity with the specific lead and sleeve.

Lead advisories

As the indications for ICD systems expand, the impact of lead failures or recalls can be profound. Pacemaker or ICD lead failure, whether due to a design flaw or a singular failure in a given patient, can result in considerable morbidity in the form of symptomatic bradycardia, inappropriate shock, or pro-arrhythmia, as well as mortality due to failure to pace or deliver high-voltage therapy. It is important to have basic understanding of lead design and



Figure 2.25 Comparison of the current DF-1 connector (bottom) and the proposed DF-4 connector (top).

potential failure mechanisms in order to critically evaluate the literature and, more importantly, to manage the patient with lead failure. This section will discuss important aspect of lead design as it relates to lead failure and implications for contemporary patient management. Other clinical aspects of ICDs and ICD leads are discussed in later chapters of this book.

Currently, there are two ISO standards for the ICD yoke (connector pin assembly): IS-1/DF-1 yokes and DF-4 (or IS-4) pin assembly. Manufacturers have versions of each connection type for a given family of leads. Until recently, the IS-1/DF-1 yoke design was the industry standard. The pace/sense portion of the lead is terminated with an IS-1 pin and the high voltage coils are terminated with their respective DF-1 (ISO-11318) pins. Figure 2.25 shows a comparison of the designs. The DF-4 design eliminates the possibility of lead connection errors (i.e. interchanging the proximal and distal coils) due to a uniquely compatible port at the header. This design also has advantage with respect to pocket bulk as well as for lead-to-lead and lead-to-can interactions. A potential disadvantage is the possibility of multiple component fracture from one critically located stress point in the pocket. Furthermore, it is not possible to add a pace/sense lead or single element defibrillation coil due to the needs for a matched header. While the lead connector has been developed to allow connection of IS-1 and DF-1 pins, this is not an ideal solution and likely rarely will be used. Alternatively, the entire lead would need to be abandoned or extracted.

Early transvenous ICD leads were based on the *co-axial* design of pacemaker leads. In a co-axial lead design, each conductor is coiled around the central (cathode) coil conductor and separated by insulation tubing. Examples of these leads include the Medtronic Transvene® 6936, St. Jude/Ventritex TVL® RV 01, and the Guidant Endotak® 0073/75. The central coil allows stylet insertion and helix deployment. Due to the co-axial design and the need for multiple conductors, these leads had large diameters, ranging in size from 9.7 Fr to 12 Fr. This design is more prone to conductor fracture and insulation breach. Although no longer manufactured, many leads with the co-axial design are still in active use. For example, the Medtronic 6936 was released to the US market in 1993 and 23 700 leads were implanted. It is estimated that nearly 2000 leads are still in active use.

The co-axial design has been replaced by the multilumen design and is now the industry standard for ICD leads. Similar to the co-axial design, a central coil conductor is used as the cathode and allows for stylet insertion. Conductors for the anode and high voltage coil(s) are arranged as parallel cables and distributed around the central coil. The distribution of cables can be *symmetric*, as is the case for current St. Jude Medical leads, or *asymmetric*, as is the case for current Medtronic and Boston Scientific leads. Neither approach has been proven to be superior, but each has theoretical advantages and disadvantages (Figure 2.26). The symmetric lead design may be more prone to "stacking" of conductors when pressure is applied in any given vector across the lead diameter. Also, since cables are non-compressible, a symmetric design may be less flexible in any given direction than an asymmetric design. An asymmetric lead is likely to preferentially flex away from the conductors, in the direction of the relatively compressible coil. Therefore, the coil and conductor may experience a variable degree of bending and binding stress, depending on the direction in which the lead is flexed. Most leads are designed with one conductor for each element. The St. Jude Medical Riata® ST series and Durata® series of leads are designed with redundant conductors that are paired into a common oversized lumen. These redundant conductors terminate at a common junction at the coil, electrode, and yoke. There is no proven clinical advantage to this redundancy. The cables and coils are covered by fluoropolymers

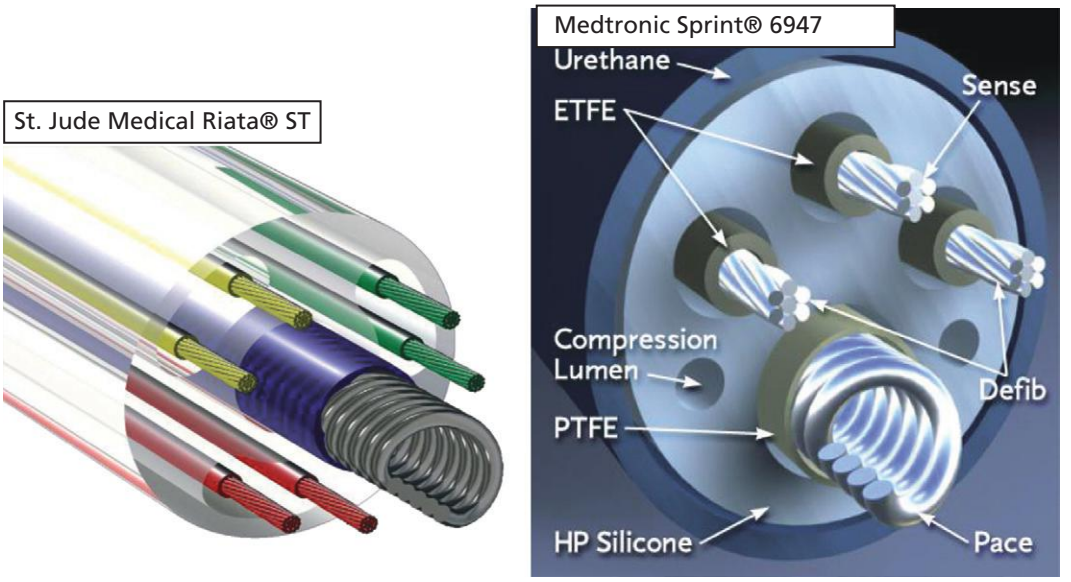


Figure 2.26 Two examples of multilumen lead design. The St. Jude Medical Riata® ST has a symmetric structure, while the Medtronic Sprint® 6947 has an asymmetric structure. The cabled conductors of the Riata® ST are paired and arranged in a common oversized lumen. ETFE, ethylene tetrafluoroethylene; HP, high performance; PTFE, polytetrafluoroethylene. (Source: St. Jude Medical, Inc. Reproduced with permission of St. Jude Medical, Inc.)

such as ETFE, which protect the cable and improve its dielectric strength.

Another design innovation is the use of compression lumens, which may protect against fracture by absorbing crush stress. As shown in Figure 2.26, some leads (Medtronic Sprint Quatro®) are designed with separate compression lumens. St. Jude Medical integrates a common lumen around each pair of conductors in its current ICD leads. This approach was also used in the Medtronic Sprint Fidelis® lead, which was withdrawn from the market. The Guidant (Boston Scientific) Endotak Reliance® series of leads have neither separate nor integrated crush lumens. There are no clinical data to suggest that the presence of compression lumens or their configuration prevents conductor fracture or effects lead reliability.

The need to place multiple leads into a single patient has highlighted the importance of lead diameter. Pacing leads range in size from 6 Fr to 9 Fr. Current ICD leads range from 6.3 Fr to 8.6 Fr. Multiple leads inserted through the subclavian and axillary veins may result in venous obstruction. In an effort to down size the lead diameter, engineers have had to weigh various design compromises against their potential impact on lead function and reliability. Smaller diameter leads have less insulation material. However, an asymmetric small diameter lead has more insulation than a symmetric small diameter lead. Small lead diameters result in greater pressure (pounds per square inch), potentially increasing the risk of myocardial perforation.

Lead failure can have more serious and immediate consequences than failure of the pulse generator. The manifestations of lead failure include high pacing or shock impedance, oversensing, undersensing, non-physiological VV intervals, failure to capture, and, less commonly, failure to defibrillate. The most common clinical presentation of lead failure is oversensing, resulting in delivery of multiple inappropriate shocks. The psychosocial consequences of inappropriate shocks are considerable. Inappropriate or failed shocks are the most serious expression of lead failure and can lead to morbidity and mortality. Pulse generator malfunction is usually not immediate and can be managed by replacement, but, in the case of lead failure, the

management issues are more complex. In most cases, a new high-voltage lead needs to be implanted and in some cases extraction of the existing lead is indicated. Implantation of an additional pace/sense (P/S) lead is common practice, but is associated with an increased risk of subsequent lead-related problems, such as with the retained high-voltage lead. The addition of a second high-voltage lead can cause lead-to-lead (distal coil-to-coil) interactions and can be particularly problematic if an integrated bipolar lead is used. Lead-to-lead interactions have also been implicated in lead fractures in areas that are otherwise mechanically stress free.

When considering lead materials and construction, multiple mechanisms of failure are conceivable. Lead failure can be caused by design flaws, implantation technique, and patient factors, in isolation or in combination. Patient-induced, repetitive or episodic mechanical trauma to the lead can result in insulation damage and conductor fracture. Twiddler's syndrome has been reported to cause both. Table 2.3 categorizes lead sites according to common lead failures. In the section below, particular failure mechanisms are discussed, with associated manufacturer recalls where applicable.

Table 2.3 Sites of lead failure

Insulation defects:
Internal
Outer
Conductor fractures
Conductor-to-coil connection defect
Conductor-to-electrode connection defect
Conductor-to-terminal ring connection defect
Fixation mechanism defect

Failure of the fixation mechanism has been described for both pacing and high-voltage leads. Individual cases of fixation problems have occurred, especially with repeated extensions and retractions. Among ICD leads, this failure mechanism resulting in a recall has not been a widespread problem.

The initial design of the conductor-to-terminal ring interface of the Endotak DSP Model 0125 lead (Guidant/CPI) had a flexion point that resulted in damage to the conductor and insulation. In one series, this design characteristic resulted in a 3.5% incidence of lead fracture over a 31-month follow-up period and manifested as non-physiological VV intervals.[37] The high fracture rate necessitated a redesign that allowed the connection point to be contained inside the header, thus protecting a vulnerable flexion point (Figure 2.27).

The Medtronic Transvene® (model 6936) is an example of an ICD lead with multiple failure mechanisms. This lead had a co-axial design that is no longer in use, but many are still in service today. Dorwarth *et al.* reported a 62% lead survival at 8 years with no relationship between lead survival and patient factors or implant technique. Interestingly, conductor fracture due to subclavian crush syndrome is a rare mechanism of failure for this lead.[37] Lead failure rates are not linear over time, with a near 90% survival at 4–5 years and a 60–80% survival at 8–9 years. There is a higher rate of lead failure following pulse generator replacement, suggesting that lead manipulation at the time of the procedure increases the risk of subsequent lead failure. In contrast to studies that showed

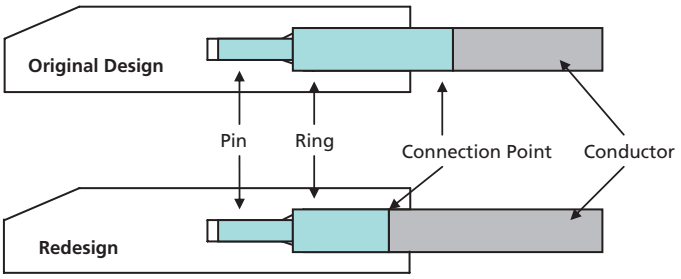


Figure 2.27 Schematic showing the IS-1 terminal inserting into the header of the original Endotak® DSP 0125 lead (Guidant/Cardiac Pacemakers, Inc.) (top) and the redesigned version (bottom).

insulation defects to be the most common mode of failure, one study reported from the Food and Drug Administration (FDA) database that fracture of the high-voltage coil accounted for the majority of failures (38%). This study also reported that the middle layer of polyurethane 80A was more likely to fail than the outer layer (28% and 13%), respectively.[38] Metal ion oxidation is thought to be responsible for the damage to the middle layer. A unique expression of failure of this lead is oversensing after an appropriate or inappropriate shock, resulting in additional inappropriate shocks. This may be specific to the failure of the middle insulation in a co-axial lead.[39] In order to test lead integrity at the time of generator replacement, a 1-V pacing pulse can be given between the ring and coil. A value of greater than 4.4 mA suggests that the middle insulation is intact. In this case, the manufacturer does not recommend replacement. However, given that the rate of lead failure seems to be higher after generator replacement, lead replacement should be considered.

Despite the complex mechanisms of failure, the clinical impact of the Transvene® 6936 is limited because of the relatively small number of leads implanted and still in use today. The Medtronic Sprint Fidelis® ICD lead, however, represents a larger clinical problem. The vast majority of implanted leads were the dual coil, active fixation model 6949 lead. According to the Medtronic Product Performance Reports (www.medtronic.com), of the estimated 186 691 implants in the US, 79 598 leads remain in active service today, with an overall product survival rate of 81% at 81 months.

The technique of resistance spot welding has been implicated as one of the failure mechanisms for the Medtronic Sprint Fidelis® lead. However, this assertion remains controversial. Welding of dissimilar metals (platinum and MP35N®) is a complex and controversial subject in materials science, and it is an over-simplification to state that two dissimilar metals cannot be welded. The manufacturer's returned product analysis (RPA) is the best means to understand the mechanism of lead failure. This analysis, to date, reveals that conductor fracture accounts for the vast majority of failures. Only a small percentage of fractures have occurred at the DF-1 connector segment or the proximal portion of the RV coil. Therefore, the inability to deliver high-voltage therapy is an uncommon expression of failure of this lead. Oversensing, loss of pacing, and inappropriate shocks are more likely presentations. The two sites of conductor fracture have been localized to the distal portion of the lead (conductor cable), near the anode (Figure 2.28), and at the proximal portion of the lead (conductor coil), near the anchoring sleeve. The "cast zone" is the area of the lead where the transition to the rigid sleeve head is made and the lead is sealed from body fluid leakage. This is an area of transitioning stiffness of the lead body as a whole and may contribute to the fracture mechanism. It is proximal to the weld site of the conductor and anode. Propagation of heat from the weld site to the fracture sites is an unlikely contributor to the fracture mechanism due to the distance. Of the proximal coil fractures, 60% have occurred immediately past the anchoring sleeve (potentially within the muscle) and 30% have occurred between the sleeve and yoke. While the locations of these fractures have been well defined, the relationship to design and construction is yet to be defined. Product performance reports suggest the rate of failure to be increasing with time. In an effort to identify impending lead fractures and reduce the risk of inappropriate shocks, Medtronic has made several recommendations. These include enabling lead impedance alerts and extending tachycardia detection intervals. The lead-integrity algorithm (LIA) is a downloadable RAMware that should be loaded to all Medtronic ICDs with a Fidelis lead. The LIA algorithm is effective in identifying impending fractures, but cannot capture all fractures before they present, especially if the change in impedance is less than the recommended alert level.

Another current lead recall involves the St. Jude Medical Riata™, Riata™-i, and Riata™ ST families of defibrillation leads. These leads were recalled in November 2011 due to externalization of the conductors. This manifestation of insulation abrasion is caused by a mechanism referred to as inside–out abrasion, where the ETFE-coated conductor cables abrade through the outside of the lead insulation body and become visible under fluoroscopy or X-ray (Figure 2.29). Externalization of the conductor is not synonymous with electrical malfunction.

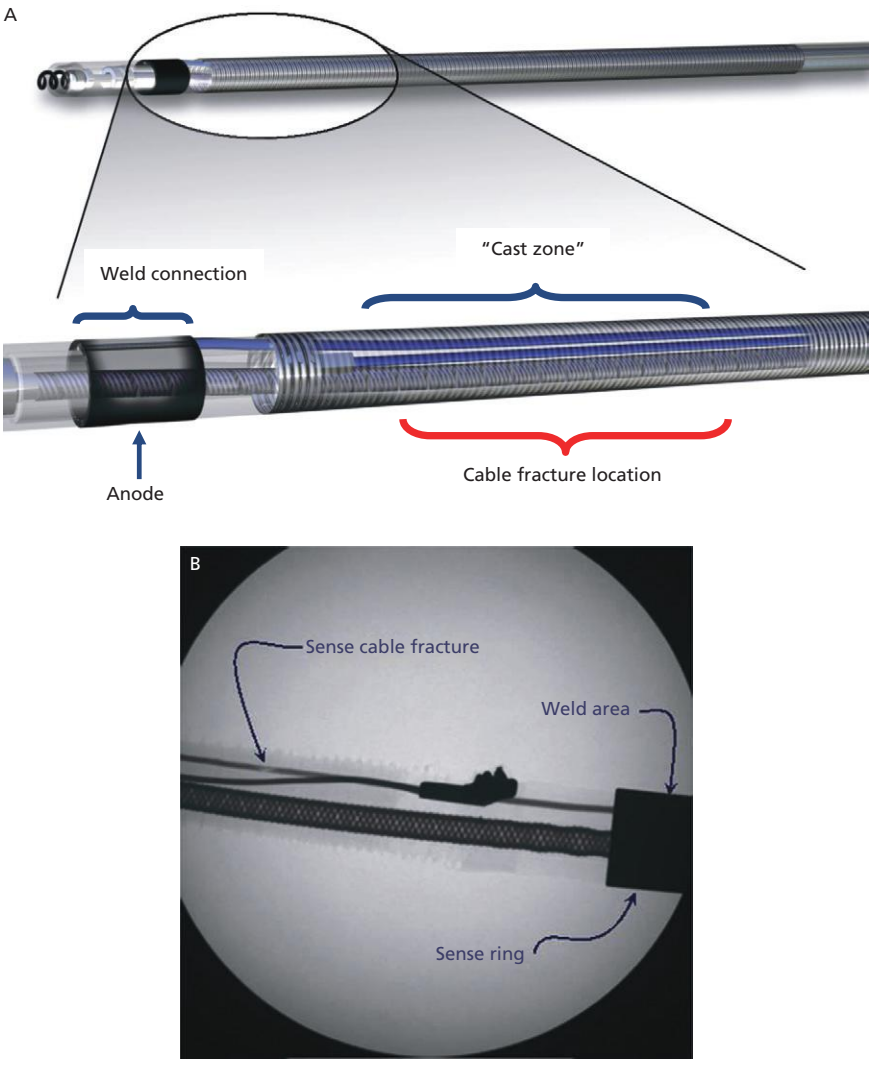


Figure 2.28 (A) Schematic of the "cast zone" (see text) and distal fracture site of the Sprint Fidelis® ICD lead. (B) Radiograph of a Sprint Fidelis® ICD lead demonstrating distal fracture site. The site of fracture is remote from the weld site of the conductor and anode ring. (Source: Medtronic, Inc. Reproduced with permission of Medtronic, Inc.)

St. Jude Medical's RPA suggests that 88% of confirmed externalizations are due to inside–out abrasion and 12% result from an external source of abrasion. Another failure mechanism is outside–in abrasion, mainly from interaction with other leads or the ICD can. As of this writing, the causes of inside–out abrasion remain speculative. One factor may be the mechanical pressure created by the cyclic interaction of the insulation and conductors.

The management of these patients remains a clinical challenge. The manufacturer recommends evidence of electrical malfunction as the trigger for intervention rather than routine radiographic imaging. Routine prophylactic explant or replacement of leads demonstrating externalized conductors in the absence of electrical abnormalities is not recommended. Finally, the recommended frequency of in-office follow-up has not been changed [3–6 months per Heart Rhythm Society

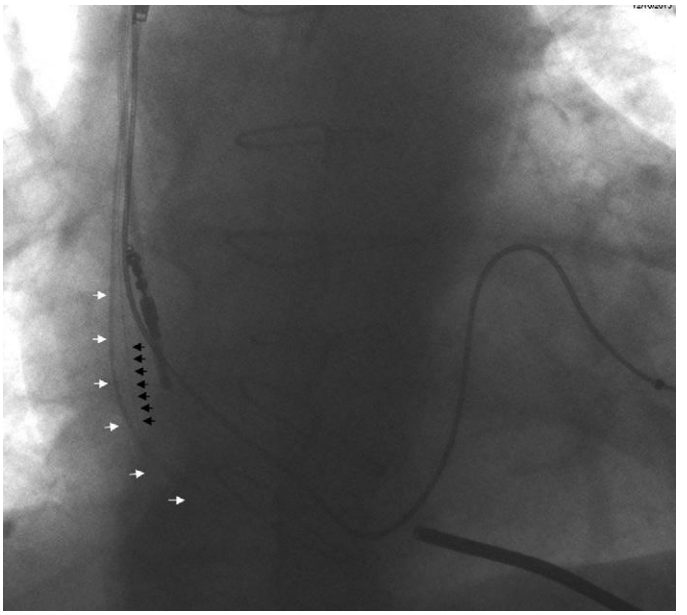


Figure 2.29 A radiograph of an externalized conductor (black arrows) from a St. Jude Medical Riata™ defibrillation lead. The white arrows mark the ICD lead body.

(HRS)/European Heart Rhythm Association (EHRA) consensus].

Monitoring, detecting, and reporting of lead malfunction and failure

A remarkable amount of research (bench and animal studies) and engineering skill go into the development of every pacing and defibrillation lead, even before pre-market testing. As evidenced by the history of lead recalls, these practices alone are inadequate predictors of lead performance and reliability. Sample sizes are too small, and *in-vivo* variables and implant technique are difficult to account for. Manufacturers use a set of standard tests when assessing lead performance on the bench. Each manufacturer also uses unique tests to meet its own internal standards. Leads design is an evolutionary process, but there are no accepted definitions of a "new" lead such as to warrant a new series of clinical data.

The true incidence of lead failure is difficult to ascertain because of under-reporting. Most failed leads are usually not explanted and not returned to the manufacturer for analysis. Leads may be damaged during removal, complicating the analysis of the failure mechanism. Current monitoring of lead performance relies primarily on industry-based post-market surveillance and voluntary reporting to the FDA. The MedWatch program (www.fda.gov/medwatch) allows physicians to report any concerns, including those related to medical devices. This information is entered into the Manufacturer and User Device Experience (MAUDE) database. However, in addition to under-reporting and reporting bias, the utility of the MAUDE database is limited by non-validated entries. HeartNet is a sub-network of the FDA's Medical Product Surveillance Network (MedSun) that focuses specifically on medical devices used in the electrophysiology laboratory. Entries are made into a publically searchable database by specialists from a very large number of pre-selected medical facilities. Post-market surveillance is also conducted by industry. This includes prospective registries, RPAs, and adverse event reports. RPAs have the potential to provide insight into the mechanism of lead failure, but are limited by the fact that many failed leads are abandoned and not extracted. Remote monitoring using proprietary Internet-based software and equipment specific to each manufacturer can provide enhanced surveillance and assist the management of individual patients. The HRS has recently published a set of guidelines addressing

the monitoring, detecting, and reporting of lead malfunction and failure.[40] In order for these various systems to be effective in identifying potential lead problems, the individual clinician needs to be proactive in reporting suspected malfunctions to the regulatory agencies and to the manufacturer. Once a problematic lead is identified, the RPA will likely remain the most effective means of diagnosing the mechanism of failure.

Pulse generators

The pulse generator is made of a header block and a device enclosure. These components are sealed together at production. The header block contains the set-screws for lead connection and, in some case, an embedded radiofrequency antenna. Within the enclosure can be found the power source and integrated circuit boards containing the timing circuit, sensing circuit, output circuit, memory, logic circuits, and physiological sensors. An inductive telemetry coil is also standard. Figure 2.30 shows a schematic of the circuits found within modern pacemakers. Some important aspects of each of these components will be discussed below.

Power source

The power source for most pacemakers today is a solid chemical battery. Although lithium–silver–chromate and lithium–thionyl chloride batteries have been used in the past, the most commonly used battery chemistry today remains lithium–iodine (LiI). Introduced in the early 1970s, this battery has been widely used as an industry standard for bradycardia devices because it has had an unsurpassed record of reliability. However, as pacemakers have become more complicated, their power needs have grown. As a result, the demands on the power source have increased exponentially. Lithium–carbon monofluoride (LiCFx), lithium–manganese dioxide ($LiMnO_2$), and hybrid batteries are increasingly being used in pacemakers.

Figure 2.31 shows a schematic of a sealed LiI battery. Lithium (Li) is located in the anode of the battery (electrically negative) and provides electrons to the external load. An oxide or halogen-rich compound (PI_2) is located in the cathode (electrically positive) and receives electrons. The anode and cathode of a battery should not be confused with the anode (positive) and cathode (negative) of a pacing electrode. The electrolyte separates the anodal and cathodal reactions and is capable of

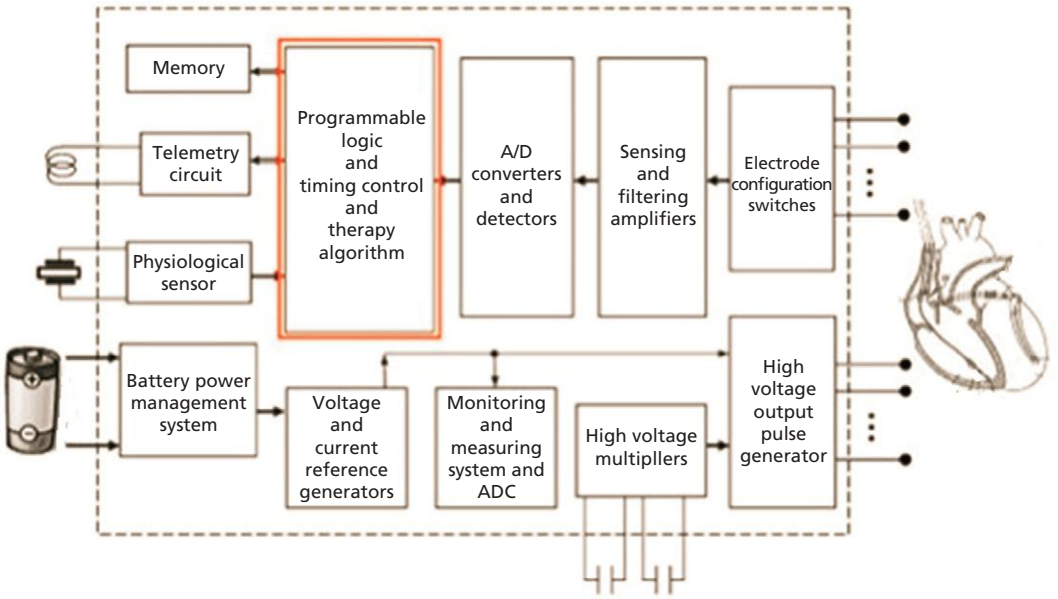


Figure 2.30 Schematic of the typical circuits found in modern pacemakers.

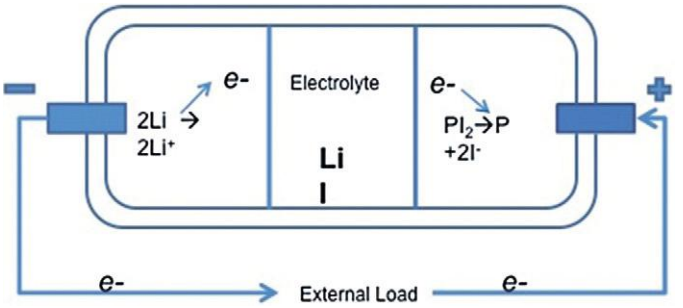


Figure 2.31 Schematic of a lithium–iodine battery (see text for details).

conducting ions but not electrons. A dissolved lithium salt (a complex of iodine and poly-2-vinyl pyridine) is the electrolyte used in LiI batteries. As the battery is drained, the mass of electrolyte increases, as does the internal battery impedance. The internal impedance of a cell determines its current carrying capability. A low internal resistance allows high currents. The LiI batteries used in today's pacemakers are capable of generating 2.8 V at the beginning of their service life.

Low-rate primary (non-rechargeable) cells typically are used in cardiac rhythm management (CRM) devices to treat bradycardia, where microampere-level currents are required to provide effective therapy (peak current drains $<100\,\mu A$). Most LiI batteries are low-rate cells. High-rate primary cells are typically used in CRM devices to treat tachycardia, as well as other implantable applications where ampere-level pulse currents are required to provide effective therapy. The lithium–silver–vanadium oxide batteries used in ICDs are examples of high-rate batteries and these can deliver ampere-level pulses. However, the growing complexity of pacemakers is leading to the need for more power delivery for a variety of uses, such as inductive and radiofrequency telemetry, EGM storage, rate modulation, and sensors. Engineers have developed medium-rate primary batteries to treat bradycardia as well as to meet these other demands. The lithium–carbon monofluoride Li/CFx battery is an example of a medium-rate primary cell capable of milliampere-level (up to 300 mA) pulse currents. Although Li/CFx cells have high current density and are capable of higher power delivery than LiI batteries, they exhibit an abrupt decline in voltage near the end of their life, making it difficult to design adequate replacement-time indicators. Nevertheless, this battery chemistry is increasingly being used in today's devices in combination with other battery chemistries to yield the desired properties. For example, silver–vanadium oxide (SVO) may be combined with CFx in the cathode to produce a hybrid cathode. This battery is capable of supporting high power needs and also has more predictable end-of-service properties. The composition (ratio) of the two chemistries can be varied to suit the needs of the device.

The importance of battery chemistry is not in the nuances of chemical reaction, but rather in the clinical implications. Battery chemistry determines initial voltage, voltage decay, and discharge rate characteristics. The rate of unwanted chemical reactions that cause internal current leakage between the positive and negative electrodes of the cell, like all chemical reactions, increases with temperature, thus increasing the battery decay. Though not clinically relevant after implant, this may be a factor that impacts storage conditions of devices on the shelf.

It is also important to consider the battery as part of the pacemaker or ICD system. The longevity of the battery is dependent on the usage conditions, but also the number and efficiency of the associated components of the integrated circuit boards. Clinically, once a system is implanted, it is important to maximize the longevity of the device by careful programming of outputs and selection of options. The use of capture management features, reducing the frequency of capacitor reformations (ICDs), and programming outputs to clinically safe margins is the first step. Second, disabling unused features, such as pre-detection EGM storage, can help preserve battery longevity. All

modern devices have an end-of-service indicator that alerts the clinician to impending battery depletion and allows adequate time for replacement of the device. These indicators include monitored battery voltage, battery impedance, and capacitor reformation times (ICDs only).

Microprocessors

Microprocessors have become the standard control circuits of implantable pacemakers and ICDs. Microprocessors have several advantages over older integrated circuits, including a far greater circuit density and greatly reduced current drain. Microprocessors also allow very sophisticated algorithms, requiring multiple calculations, to be incorporated into implantable devices, and have vastly increased data storage. The microprocessor can respond to changes in programming instructions that allow functions to be added or changed after implantation. The integrated circuit of pulse generators may contain both read-only memory (ROM) and random access memory (RAM).

ROM (typically 256 KB to 1 MB) is used to guide the sensing and output circuits. Critical pacemaker codes, such as those used for reset routines and program storage, are stored in ROM. Devices with 8- or 16-bit processors usually require several clock cycles to decode an instruction from memory. The processors operating with larger instruction words may load and execute an instruction in a single clock cycle, improving the efficiency of the repetitive tasks that are required for pacing and sensing.

In addition, RAM is used to store diagnostic information regarding pacing rate, intrinsic heart rates, and sensor output. The amount of RAM (1–16 MB) included in the pulse generator varies between models and manufacturers, but has rapidly increased in modern pulse generators, allowing for a far greater amount of diagnostic information to be stored. Such data include histograms of paced and intrinsic heart rate, sensor function, trends in heart rate and sensor function over time, storage of intracardiac EGMs from episodes of high atrial or ventricular rates, and mode-switching events. The rapidly expanding diagnostic capabilities of pacemakers has allowed for improved assessment of the physiological condition of the patient, including stored information about heart rate variability, respiration, intracardiac pressure, patient activity, lung water, and arrhythmia logs.

Almost all manufacturers offer fully RAM-based pulse generators. There are several important advantages to microprocessor-based pacemakers, including decreased production costs for an entire product line, increased flexibility to upgrade features in subsequent pacemaker models, and the capability for downloading new features into previously implanted pacemakers by telemetry. It is important to emphasize that the microprocessors used in permanent pacemakers must be custom designed to minimize current drain and operate with a LiI battery. Thus, a microprocessor that is used in a microcomputer and has access to a virtually unlimited power supply (AC current operating at 110 V) cannot be included in a permanent pacemaker.

Output circuit

The output circuit contains the output section and voltage multipliers. Pacing outputs of greater than the specified voltage of a cell are achieved by a variety of methods. One approach is to use capacitors located on the output circuits. These capacitors are charged by the battery in parallel, but then discharged in series. Multiple capacitors can be used to achieve the desired output voltages. The use of these voltage multipliers has a significant impact on battery longevity. For example, a programmed output of 5.6 V requires two capacitors, but results in a four-fold increase in current drain from the LiI battery. When a capacitor-based output circuit is used to deliver a specified voltage for a programmed pulse width, the actual wave form shows a drop from leading edge to trailing edge. The magnitude of the voltage drop is a function of the pacing impedance, but is not clinically important.

An alternative approach to capacitor-based voltage multipliers is to use the electromagnetic principle of inductance. An inductor, also known as a reactor, is simply a coil of wire that has specific electrical properties when subjected to a magnetic field. When an electrical current is passed through it, a magnetic field is created. This magnetic field helps to store the electrical current for a short time, even if the input is removed. When the magnetic field around the coil collapses,

the electrical current is discharged. This method allows for a more efficient current draw from the battery. However, the choice of method used is related to the overall design of the pacemaker and their relative efficiencies can only be viewed in this context.

Sensing circuit

The intracardiac EGM is conducted from the electrodes to the sensing circuit of the pulse generator, where it is amplified and filtered. The intracardiac EGM is filtered to remove unwanted frequencies, a process that markedly affects the amplitude of the processed signal. A bandpass filter attenuates components of the EGM on either side of the center frequency. The bandpass filters of different manufacturers vary significantly with regard to center frequency (from approximately 20 to 40 Hz), so intracardiac EGMs measured with a pacing system analyzer from one manufacturer may produce considerably different EGM amplitudes from those produced by the pulse generator sensing amplifier of another manufacturer. Following filtering of the intracardiac signal, the processed signal is compared with a reference voltage to determine if the signal exceeds a threshold detection level (programmed sensitivity). Signals with amplitudes greater than the sensitivity threshold level are sensed as intracardiac events, whereas signals of lower amplitude are discarded as noise. Signals that exceed the threshold level are sent to the timing circuit and logic circuits.

Most permanent pacemakers also contain noise reversion circuits that change the pulse generator to an asynchronous pacing mode when the sensing threshold level is exceeded at a rate faster than the noise reversion rate. The noise reversion mode prevents inhibition of pacing in the presence of electromagnetic interference. The electronic circuitry of the pulse generator must also be protected from damage caused by overwhelming electrical energy generated in the clinical environment. One technical example is the Zener diode that is designed to protect the integrated circuit from high external voltages such as may occur during defibrillation shocks or electrocautery. When the input voltage carried by the pacing leads exceeds the Zener voltage, the excess energy is shunted back to the myocardium through the leads. In addition to these features, which are designed to manage external electromagnetic interference, the sensing amplifier must prevent the detection of unwanted intracardiac signals, such as far-field R waves in the atrial EGM, afterpotentials, T waves, and retrogradely conducted P waves.

Timing circuit

The pacing cycle length, sensing refractory and alert periods, pulse duration and AV interval are precisely regulated by the timing circuit of the pulse generator. The timing circuit of a pulse generator is a crystal oscillator that generates a very accurate signal with a frequency in the kiloHertz range. The output of the crystal oscillator is sent to a digital timing and logic control circuit that operates internally generated clocks at divisions of the oscillator frequency. The output of the logic control circuit is a logic pulse that triggers the output pacing pulse, the blanking and refractory intervals, and the AV delay. The timing circuit also receives input from the sense amplifier to reset the escape intervals of an inhibited pacing system or trigger initiation of an AV delay for triggered pacing modes. The pulse generator also contains a rate-limiting circuit that prevents the pacing rate from exceeding an upper limit in the case of a random component failure. This runaway protection rate is typically in the range of 180–200 ppm.

Telemetry circuit

Programmable pulse generators have the capability of responding to radiofrequency signals emitted from the programmer as well as sending information in the reverse direction, from the pulse generator to the programmer. The pulse generator is capable of both transmitting information from a radiofrequency antenna and receiving information with a radiofrequency decoder. Telemetry information may be sent as radiofrequency signals or as a pulsed magnetic field. Information is sent from an external programmer to the pulse generator in coded programming sequences with a preset frequency spectrum. Most pulse generators require the radiofrequency signal to be pulsed with a specific frequency in a sequence that is typically 16 pulses in duration. Thus, the radiofrequency signal is quite precise, decreasing the likelihood of inappropriate alteration of the program by environmental

sources of radiofrequency energy or magnetic fields. This characteristic also prevents the programmers of one manufacturer from programming the pulse generator of another. The detected telemetry bursts from the programmer are sent as digital information from the radiofrequency demodulator to the telemetry control logic circuit of the pulse generator. This logic circuit also provides for properly timed pulses to be sent from the antenna of the pulse generator to the programmer. "Real-time telemetry" is the term used to describe the capability of a pulse generator to transmit information to the programmer regarding measurements of pulse amplitude and duration, lead impedance, battery impedance, and delivered current, charge, and energy.

Magnet mode

Pacemakers and some ICDs have a reed switch which normally is open until a magnet or magnetic field [e.g. a magnetic resonance imaging (MRI) scanner] comes into close contact with the device. The magnet will close the reed switch and the device will be switched to the "magnet mode." The magnet mode typically causes asynchronous pacing for a pacemaker (e.g. VOO, DOO, AOO) and deactivation of tachycardia therapy for most defibrillators, but bradycardia pacing and sensing functions are typically not affected. The magnet may be unable to close the reed switch if it is not powerful enough or the magnet function is programmed "off." In contemporary devices (some pacemakers and most ICDs), other technology, such as the Hall effect sensor, integrated solid-state detection, or GMR sensor, is used in place of the reed switch to optimize response to the magnetic field.

Magnetic resonance compatible pacemakers and leads

Conventional pacemakers and ICDs are regarded as a contraindication to MRI. Many concerns have been raised regarding the interaction of these devices with the magnetic field, including displacement of the lead or pulse generator, unintentional device reprogramming, inhibition of pacing, rapid or asynchronous pacing, and radiofrequency-induced heating of myocardial tissue near the lead tip, resulting in thermal injury. Therefore, even non-functional or abandoned endocardial or epicardial leads have been considered a contraindication to MRI. Electrical reset and reed switch inactivation have also been reported.[41] Interestingly, despite the variety of reported events, the overall incidence of adverse events remains relatively low.[42] However, these studies represent an inadequate number of patients to safely guide widespread clinical practice. Also, the study populations are not easy to compare because of the variety of devices (pacemaker versus ICD), number and type of leads, target of the MRI scan, and MRI strength and scanning protocol.

There have been attempts at creating a safety protocol for performing MRI scans in patients implanted with conventional devices, though these have not received widespread acceptance.[43] However, there is an estimated 50–75% probability that MRI will be indicated for a patient over the lifetime of a pacemaker.[44] These facts have provided the motivation to develop pacing systems with leads and pulse generators specifically engineered to be MRI compatible.

The FDA has recently approved the first MRI-conditional pacemaker in the US, the Medtronic Revo® pacing system. This system is now in its second generation (Advisa MRI™). Other manufacturers are also developing MRI-conditional devices, but still need to secure regulatory approval in the US to confirm their products' safety under multiple clinical and technical variables. These manufacturers already have MRI-conditional devices available in Europe. The safety of patients with these devices during an MR examination requires adherence to strict cardiological and radiological guidelines prior to, during, and after the scan is performed. Programming changes should be made prior to the scan according to the manufacturer's specifications. These changes may be as simple as the selection of an "MRI-mode" (i.e. MRI SureScan®, Medtronic), and then disabling this following the scan. Both cardiologists and radiologists need to be familiar with the recommendations for performing an MRI scan in patients with an MRI-conditional device. The term "conditional" reflects the necessary requirements for a safe scan. Table 2.4 summarizes these pre- and post-scan steps. Some steps and requirements may be manufacturer

Table 2.4 Confirmation of MRI safety with MRI-compatible devices

Cardiologist verified scan conditions	• Confirm implanted system is MRI-conditional • Implant >6 weeks • Stable pacing, sensing, and impedance parameters • No other devices, abandoned leads, adaptors or extenders • Programming changes recommended by manufacturer ("MRI mode")
Radiologist verified scan conditions	• 1.5-T closed bore MRI • Maximum gradient slew rate per axis ≤200 T/m/s • Whole body SAR <2 W/kg • Head SAR <3.2 W/kg • Monitoring of patient vital signs • Available external defibrillator

SAR, specific absorption rate.

specific. Finally, it should be emphasized that current MRI-conditional pacing systems have been tested at 1.5 T, and therefore implanted patients are likely to be excluded from the more powerful 3.0-T MRI scanners used in some studies.

Figure 2.32 shows the only currently available pacing lead specifically designed for safe use in MRI environments in the US (note also the radiographic marker associated with MRI-conditional devices). This lead is characterized by increased diameter and stiffness compared to other conventional pacing leads. The modifications to the lead are designed to reduce the potential for radiofrequency-induced electrode heating. The materials used in the 5086 MRI® lead are the same as those used in the 5076® lead with the exception of a special coating on the electrodes in the former. Structurally, the inner conductor of the 5086® lead is a two-filar design rather than a four-filar design. The overall lead diameter is slightly increased over

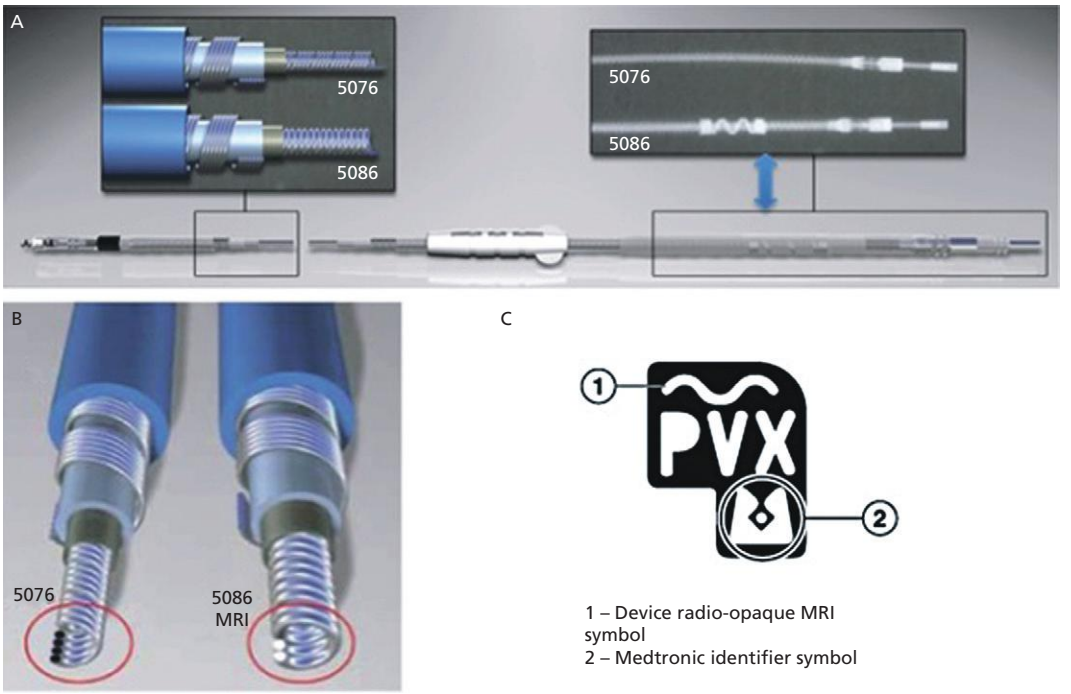


Figure 2.32 Select features of an MRI-conditional pacemaker system. (A) Fluoroscopic marker found on the proximal portion (arrow) of the lead identifying it as MRI-conditional. (B) The two-filar inner conductor of the 5086® lead and the four-filar inner conductor of the 5076® lead. (C) The fluoroscopic marker found on the header block of the MRI-conditional pacemaker (Medtronic Revo™ and Advisa™, Medtronic, Inc.). (Source: Medtronic, Inc. Reproduced with permission of Medtronic, Inc.)

the 5076® lead (Figure 2.32). Despite these differences, published studies of the direct comparison of conventional leads and MRI-conditional leads show no difference in the incidence of complications.[45–47]

The pulse generator for an MRI-conditional pacemaker has also undergone significant modification. These changes include revision of the internal circuitry to reduce the potential for cardiac stimulation, reductions in the amount of ferromagnetic material, protection of the internal power supply, and replacement of the reed switch with a Hall sensor to improve predictability in the static magnetic fields.[48]

Rate-adaptive pacing and other sensors

While the principal role of pacemakers is to prevent symptomatic or potentially life-threatening bradyarrhythmias, a more nuanced role is in the maintenance of adequate heart rate in response to specific physiological stressors. Under normal physiological situations, patients do not maintain a fixed heart rate. Rather, heart rate may vary depending on the clinical situation—whether the patient is at rest, exercising, or under conditions of emotional or physical stress, such as a febrile illness that may require a higher heart rate to maintain adequate cardiac output. In the absence of a sufficient heart rate response to physiological stress, patients may develop symptoms ranging from shortness of breath to frank syncope.

One common condition under which inadequate heart rate responses to physiological stress may be seen is sinus node dysfunction, which may be due to older age, medication use, prior sinus node ablation, prior heart transplant, or other cause. In addition, in patients with atrial fibrillation with either a slow ventricular response or prior AV node ablation, pacemakers may be required to augment the ventricular rate to similarly maintain adequate cardiac output.

Means of using a pacemaker to allow for adaptation of the pacing rate to the physiological need may range from the decision to implant a dual as compared to a single chamber pacemaker so that the ventricular rate can be maintained at the atrial rate, to more advanced use of sensors and programmable algorithms that offer a mechanism by which conditions of increased physiological stress are identified and alter the pacing rate. In the case of the former, some patients may have adequate sinus response to physiological stress, but the ventricular response may not similarly augment, as in the case of AV node dysfunction. In such cases, the pacemaker, in the absence of a means of sensing the atrial rhythm, may not augment the ventricular rate and thus will not maintain AV synchrony. Special types of single chamber leads that sense in both the atrium and ventricles but only pace the ventricle are available, and may be of utility in patients with normal sinus node function but impaired AV node function. However, most commonly, patients receive a true dual chamber system, in which dedicated, separate atrial and ventricular leads are used.

Regardless of the decision to use a single versus dual chamber system, however, there are many patients in whom the heart is unable to intrinsically respond to metabolic demands. In such cases, several different types of sensing technologies and programming algorithms have been developed that work to identify when there is a condition of increased metabolic demand requiring a change in the pacing rate. We will focus on the different types of sensors available, considerations related to their programming, and special conditions of sensor-based pacing adaptations that extend beyond changing the heart rate alone.

Types of sensors

There are several different types of sensors that may be employed in pacemakers. Most commonly, sensors work to augment heart rate in response to physical activity, whether by detecting patient movement or changes in respiratory rate. Using technology that detects changes in vibration, acceleration, or minute ventilation, pacemakers may be pre-programmed to induce concomitant changes in the paced rate if the physiological heart rate does not meet those parameters. Other sensors may use sensitivity to temperature, QT interval, or local myocardial contractility to respond to conditions under which increases in heart rate are desired, but for which sensors that detect only changes in physical activity would be inadequate.

Generally, sensors may be described as open or closed loop. Open loop sensors, which characterize practically all existing sensor technology, use external input to optimize the sensor response. In contrast, a closed loop sensor does not require external input but rather relies on intrinsic feedback to the sensor, allowing for self-regulation. Thus, unlike an open loop sensor, a closed loop sensor allows for the sensor to effectively mirror the sinus node in that it can respond to all forms of physiological stress, allow for positive or negative feedback (i.e. further changes in the physiological parameter allow for further modulation of the pacing rate), and this is all accomplished without the clinician needing to program specific variables into an algorithm (e.g. the slope of heart rate change, etc.).

When employed in pacemakers, sensors are integrated in a variety of algorithms that may or may not be programmable to control the degree to which the pacing rate is increased. A variety of parameters may be adjusted, including the sensor threshold, the slope defining the rapidity with which the heart rate is increased or decreased, and the maximum heart rate allowed by the device.

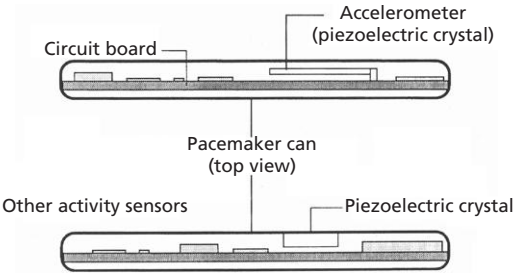


Figure 2.33 Schematic of two motion-sensing, rate-adaptive pacing systems. Top: An accelerometer is mounted on the circuit board of the pulse generator. Similar to a pedometer, the accelerometer arm moves with anteroposterior movement of the chest, which deforms a piezoresistive material and alerts the pacemaker that physical activity is occurring. Bottom: A piezoelectric crystal is bonded to the inside of the pulse generator case. The crystal detects vibrations, which include those generated during physical activity, as well as those resulting from pressure on the pacemaker case or vibrations from the environment, such as those from a motor vehicle.

Piezoelectric crystals (vibration sensors)

Piezoelectric crystals can detect mechanical vibration and pressure (Figure 2.33). They are bonded to the inside of the pulse generator can and their flexion and deformation result in the production of a small electrical current. This occurs when vibrations are transmitted throughout the human body, such as during stair climbing or walking, and typically in the range of 1–8 Hz. Greater frequency and amplitude of vibrations results in a greater degree of crystal flexion, and thereby a larger current. The electrical output from the crystal sensor is processed and used by the device to modulate the pacing rate proportionally.

However, vibration or distortion of any sort will deform the piezoelectric crystal, so direct pressure on the generator will activate this sensor, even if the device is otherwise motionless. Consequently, certain activities, such as lying in the prone position or riding in a vibrating motor vehicle, can result in sensor activation at a time when increased heart rate is not needed. Conversely, the piezoelectric crystal sensor does not respond well to certain types of activity, such as swimming or isometric exercise, where the vibrations the sensor detects are less prominent. The benefit is that such vibration sensors respond promptly to the onset of activity and thus are capable of modulating heart rate early in exercise.

Accelerometers

Another type of motion sensor is an accelerometer, which consists of an arm mounted on a circuit board that flexes in response to movement of the generator in the anteroposterior direction. Movement and flexion of the arm of the accelerometer results in deformation of an attached piezoelectric or piezoresistive material. The arm does not respond to pressure on the device *per se* as it is mechanically insulated from the can, but rather to changes in velocity. These changes in velocity are detected by the device and, based on a variety of programmable and non-programmable setpoints, will result in a change in heart rate.

Various studies have demonstrated that accelerometers are quite consistent in response between patients and under different physiological conditions, regardless of the degree and type of activity. When compared with vibration sensors, they are also more able to offer rate modulation

proportional to exercise workload. Other advantages include the ability to respond rapidly to the onset of activity, as well as to better filter out environmental noise when compared with vibration sensors.

However, accelerometers have several limitations. For example, prolonged activity may be associated with a constant velocity and, thus, no further acceleration will be seen even though the metabolic demand will continue to increase concomitantly with the duration of exercise. In turn, rates of acceleration may not directly correlate with the physiological need, as when comparing moving uphill versus downhill. Finally, non-movement based exertion, such as emotional stress or febrile illness, will not be detected by an accelerometer, limiting its ability to offer rate adaptation under all conditions.

Minute-ventilation sensors

Under conditions of isometric exercise or in which a constant velocity is maintained over a prolonged period of time, vibration or acceleration sensors may inadequately identify the level of metabolic demand. In turn, in some patients, such as those with heart failure or the elderly, the degree of metabolic demand may far outstrip the degree of physical motion (i.e. small degrees of physical activity may result in large increases in metabolic demand). Thus, sensors that depend on evaluating changes in minute ventilation have been developed. Minute-ventilation sensors rely on the changes in transthoracic impedance that occur during inspiration and expiration as a surrogate for the change in minute ventilation (equal to respiratory rate × tidal volume; Figure 2.34). Minute ventilation, in turn, correlates with oxygen consumption (VO_2), as both respiratory rate and tidal volume increase in proportion to VO_2.[49] Thus, minute-ventilation sensors may detect situations of increased metabolic demand in the absence of physical activity.

When the lungs are inflated during inspiration, there is more insulating air between the tip of the pacing lead and the pulse generator, increasing impedance in the circuit. In turn, when the lungs are deflated during expiration, the transthoracic impedance decreases. Low-energy, sub-threshold 320-mA pulses are delivered at a high frequency (20 Hz, or every 50 ms) through the lead in a unipolar configuration, allowing for frequent impedance measurements given that both the amplitude of the stimulus and the voltage may be measured (this requires at least one bipolar pacing lead in which the ring electrode may be used for pulse delivery, while the tip electrode may be used to measure the voltage). This continuous measurement of impedance allows the sensor to detect fluctuations in transthoracic impedance on the basis of the frequency of changes in impedance (which correlates with the respiratory rate), as well as changes in impedance amplitude (which correlates with the tidal volume). Using these parameters, minute ventilation can be calculated. Because transthoracic impedance fluctuates during the

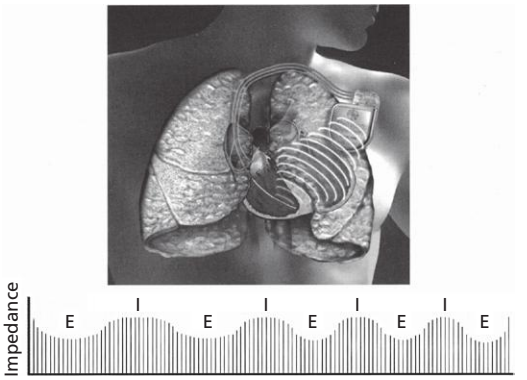


Figure 2.34 Schematic of how a minute-ventilation sensor works. Top: Rapid, low-energy pulses are delivered between the intracardiac pacing lead and the pacemaker can in the pectoral region, spanning lung tissue. The transthoracic impedance will vary, depending on how much air (insulator) is in the lungs. Bottom: Hypothetical graph of impedance measurements during slow, then faster respirations. When the lungs are more deflated during expiration (E), transthoracic impedance falls due to relatively less air and relatively more tissue fluid being present within the minute-ventilation circuit. When the lungs are more inflated during inspiration (I), transthoracic impedance rises. By tracking the rate of rise and fall in transthoracic impedance over a time frame of seconds, the minute-ventilation sensor can determine the respiratory rate, and this information can be used for rate-adaptive pacing. Over a time frame of days to weeks, more gradual trends in transthoracic impedance may reflect changes in lung water due to congestive heart failure, and some devices use this information to track heart failure status. (Source: Top image—Medtronic, Inc. Reproduced with permission of Medtronic, Inc.)

cardiac cycle, and with thoracic and arm movements, a low-pass filter is used to eliminate impedance fluctuations with frequencies that exceed the typical range of respiratory rates.

At the onset of activity, minute ventilation tends to increase more slowly than heart rate in the setting of an intact sinus node, whereas during sustained exercise at high workloads, minute ventilation increases out of proportion to heart rate and oxygen consumption, particularly if the anaerobic threshold is crossed. Because of this changing relationship between minute ventilation, oxygen consumption, and heart rate throughout exercise, the minute-ventilation sensor will typically use a steeper slope at the onset of exercise and a flatter slope at high levels of exercise when calculating the target pacing rate. In this fashion, a slight increase in respiration will translate into a greater degree of heart rate increase early on during exercise, but more dramatic increases in minute ventilation at peak exercise will result in a lesser degree of heart rate increase.

Limitations to earlier generations of minute-ventilation sensors include slow initial rate response. Namely, earlier generators did not induce the same degree of heart rate increase as early in exercise as other sensors, such as the vibration sensors or accelerometers. In addition, minute-ventilation sensors may be inappropriately activated with coughing, abnormal breathing patterns, or even upper extremity movement, which can result in changes in transthoracic impedance. They may also interfere with the respiratory rate monitors that are typically used in the hospital setting.

Blended minute-ventilation and activity sensors

Most pulse generators with minute-ventilation sensors also have an activity sensor, and measured data from both sensors can be combined to form a "blended sensor" that may provide an even better rate-adaptive response to exercise than either sensor alone.[50,51] Information from the activity sensor is typically weighed more heavily at the onset of exercise, when physical motion is more prominent than increased respiration, and the minute-ventilation sensor is more prominent after more sustained activity and in recovery, when metabolic needs remain elevated after physical motion has slowed or stopped. With this sensor combination, the rapid increase in pacing rate with the onset of activity and the more gradual decline of heart rate in recovery can closely approximate the physiological heart rate response pattern of the intact sinus node. Several studies have demonstrated the utility of such blended sensors.[50,51]

Peak endocardial acceleration sensor

Peak endocardial acceleration sensors use a specially designed lead with a microaccelerometer located in the lead tip.[52] This accelerometer measures mechanical vibrations generated by the heart during isovolumetric contraction. This signal directly correlates with contractility and variations in the peak-to-peak value are compared against a reference value. The purpose of this is to identify early changes in contractility that correlate with input from autonomic nervous system feedback to the heart. Even in the absence of appropriate sinus or AV nodal function, the autonomic nervous system will still have a direct impact on myocardial contractility that can be used as a surrogate marker for demonstrating need for change in heart rate. Thus, increased contractility indicates a need for increased heart rate and cardiac output. There is evidence to suggest potential benefit in patients with vasodepressor syncope in whom pacing rate can be adjusted prior to a fall in heart rate or blood pressure. It has also proven useful for rate-adaptive pacing. In addition, this sensor may be used for hemodynamic monitoring with biventricular devices.[53] Specifically, AV and VV delays may be adjusted in responses to changes in myocardial contractility.[53]

Right ventricular impedance sensor

Right ventricular impedance sensors use intracardiac impedance as a real-time marker of physiological need to adapt the rate in a closed loop system. One such sensor that is clinically available in Biotronik devices is termed Closed Loop Stimulation (CLS). This system works by analyzing contractility based on impedance changes on a beat-to-beat basis to determine the pacing rate required to match hemodynamic needs. This system works on the same principle as the respiratory sensors, but instead of looking for ventilation-related impedance changes, the

algorithm is optimized to measure impedance changes in response to cardiac contraction. The system works by triggering rate increases in response to pre-specified impedance triggers. In diastole, when the RV is filled, there will be a smaller fraction of myocardium interfacing with the lead tip, and the impedance will be lower. In systole, the impedance will be higher. If contractility increases, such as during physical exertion or high emotional stress, the RV will be less filled and thus the impedance will be higher. This, in turn, is used to trigger the device to pace faster. Trials have suggested the superiority of this algorithm when compared with standard accelerometer-based sensors, and utility in conditions such as neurocardiogenic syncope.[54] As this sensor also responds to contractility changes from other, non-exertional, neurocardiogenic triggers, it may provide heart rate support during emotional or mental stress.

QT interval sensors

Alternative sensors that do not require a specialized pacing lead include those that measure the QT interval (Vitatron®). The QT interval will shorten in response to increased heart rate and sympathetic tone. For a device to measure the QT interval, a pacing stimulus must be delivered to generate a QRS–T complex, and then the evoked electrical response that follows must be filtered in a way to permit detection of the lower amplitude, lower slew rate repolarization (T wave) signal. The QT interval can be markedly influenced by medications, electrolyte disturbances or ischemia, which may confound its use as a rate-adaptive parameter at times. The QT sensor can also be blended with an accelerometer for more optimal performance.

Dynamic AV and VV interval programming

In patients with biventricular devices, optimization of the AV and left ventricular–right ventricular (VV) timings may offer hemodynamic benefit.[55] Specifically, optimizing AV time so there is sufficient time for the left atrium to contract prior to LV contraction, or optimizing VV time to sufficiently optimize the relative time at which RV contraction occurs compared to LV contraction, may impact hemodynamics. However, intra-atrial, intraventricular, and AV conduction times may vary with activity level. Thus, intervals programmed at rest may not be ideal during exercise or other situations characterized by increased metabolic demand. For example, shortening of the AV interval with exercise may require more dynamic changes in the programmed AV delay. The CLEAR study, as discussed with the peak endocardial acceleration sensor, suggested that adaptive VV timing may offer significant clinical benefit in terms of functional capacity.[53] However, further studies are needed to validate the role of rate-adaptive AV and VV timing, and determine what sensors/parameters would prove most useful for such algorithms. Currently, the routine use of AV and VV optimization is controversial and mostly reserved for patients with sub-optimal initial response to biventricular pacing.

Programming of pacemaker sensor algorithms

There is variability in the relationship between sensor input and appropriate heart rate in different individuals, with factors such as age, body size, weight, degree of fitness and functional status, device location and orientation, and types of exertion playing a role. It is for this reason that rate-adaptive sensors have several programmable and non-programmable parameters and algorithms that are used to tailor heart rate response to the individual. One issue is the widely variable terminology and algorithms available between device companies. Though the principles behind individual sensors are common, the features that are programmable and the way they are featured in the algorithms may vary.

Across platforms, pacemakers, regardless of manufacturer, will have the option to program specific values, including a base rate, a maximum sensor rate, an activity threshold (which determines how much sensor input is needed before rate modulation occurs), a reaction time (i.e. how soon to start increasing the heart rate in response to sensor activation), a slope (i.e. the rapidity with which the pacing rate should be increased), and a recovery time (i.e. the rapidity with which the pacing rate should return to baseline) (Figure 2.35). Most devices also offer a lifestyle input that helps determine an optimal heart rate profile,

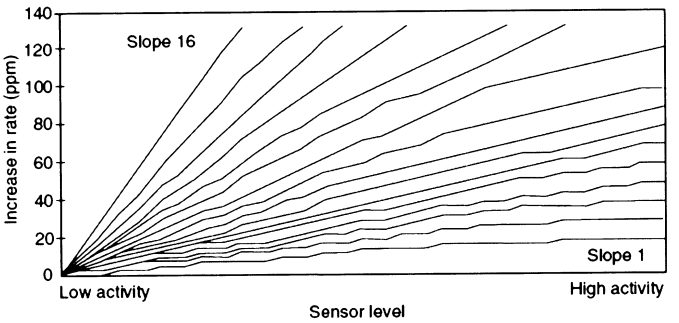


Figure 2.35 Behavior of different "slope" settings in a St. Jude Medical rate-adaptive pacemaker. A lower slope setting will augment the pacing rate less than a higher slope setting for a given amount of sensor input. (Source: St. Jude Medical, Inc. Reproduced with permission of St. Jude Medical, Inc.)

which is characterized by the degree to which the patient typically exerts him/herself.

Many devices will self-adjust several programmable sensor parameters after taking into account the activity profile and rate histograms. These adjustments are used to mimic a physiological heart rate response in patients with abnormal chronotropic response. However, the rate to which the heart rate is increased for any given sensor input is intimately tied to the maximum sensor rate (e.g. programming a higher maximum sensor rate may result in a wider fluctuation in the adjusted pacing rate due to a certain level of activity, all other programming being left the same).

Achievement of the optimal group of parameters for an individual may require frequent programming adjustments. Ideally, the patient should engage in routine physical activities and identify those that result in the most physical strain. Correlating the inability to engage in these activities with inadequate pacing rate may sometimes be difficult. Performing exercise stress tests may offer one option by which performance of the sensor may be assessed in the office. However, it needs to be determined whether activity-related symptoms are primarily due to lack of chronotropic response as opposed to other factors (such as deconditioning, respiratory issues, or lack of myocardial contractility in the setting of heart failure).

Finally, it is important to consider the wide variety of sensors. Device companies offering more than one sensor in the same system may afford the ability to turn one off or to use both. How different combinations of programming and sensors work in a given patient may vary depending on the clinical situation. Furthermore, due to the different nomenclature that may be used and differences in the numeric designations for specific sensor settings, it is important to understand the meaning of each setting before performing a programming change. For example, a higher numeric value for a specific parameter may increase or decrease the degree of rate-adaptive pacing depending on the device and which parameter is being adjusted. Thus, having an intimate understanding of all the programmable features is critical to achieving effective rate-adaptive pacing.

Choosing the right sensor

There are several considerations when choosing the appropriate sensor. A sensor should allow for proportional heart rate responses to changes in metabolic demands, variability in the rapidity with which the rate response is achieved depending on the physiological needs, and the ability to respond not just to physical changes but also to other situations that may require changes in pacing rate, such as emotional stress. Ideally, such sensors will also be specific enough not to be influenced by other non-physiological signals (i.e. noise) and be implementable irrespective of the type of lead used (i.e. they should be able to be used with any standard pacing lead).

Technical considerations in the choice and use of sensors are also required. Many of the aforedescribed sensors have moving parts (e.g.

accelerometers) and thus must be durable for the lifetime of the generator. Furthermore, the use of sensors may necessarily incur some drain on the battery, and consideration needs to be given to the effect on device longevity. Finally, consideration needs to be given to the programmability of specific sensor algorithms based on the type(s) of sensor used and the needs of the patient. It is possible that certain algorithms and sensors may be of greater use in some patients than others, and clinical trials comparing the efficacy of the different algorithms are lacking.

Conclusion

Pacemakers have evolved significantly to the point where they offer a wide array of options to patients, including rate-adaptive pacing, longer battery life, and improved lead configurations to potentially make pacing more effective. The basic concepts of pacing are critical to understanding the more advanced features of modern pacemakers. Additionally, an understanding of the potential benefits and downsides of the diverse array of algorithms available in modern pacemakers is necessary to assist the clinician in device selection and programming.

References

1 Hodgkin AL, Huxley AF. A quantitative description of membrane current and its application to conduction and excitation in nerve. *J Physiol* 1952; 117: 500–544.

2 DiFrancesco D, Ferroni A, Mazzanti M, Tromba C. Properties of the hyperpolarizing-activated current (If) in cells isolated from the rabbit sino-atrial node. *J Physiol* 1986; 377: 61–88.

3 Spach MS, Dolber PC, Heidlage JF, Kootsey JM, Johnson EA. Propagating depolarization in anisotropic human and canine cardiac muscle: Apparent directional differences in membrane capacitance. A simplified model for selective directional effects of modifying the sodium conductance on Vmax, tau foot, and the propagation safety factor. *Circ Res* 1987; 60: 206–219.

4 Furman S, Hurzeler P, DeCaprio V. The ventricular endocardial electrogram and pacemaker sensing. *J Thorac Cardiovasc Surg* 1977; 73: 258–266.

5 DeCaprio V, Hurzeler P, Furman S. A comparison of unipolar and bipolar electrograms for cardiac pacemaker sensing. *Circulation* 1977; 56: 750–755.

6 Secemsky SI, Hauser RG, Denes P, Edwards LM. Unipolar sensing abnormalities: Incidence and clinical significance of skeletal muscle interference and undersensing in 228 patients. *Pacing Clin Electrophysiol* 1982; 5: 10–19.

7 Amundson DC, McArthur W, Mosharrafa M. The porous endocardial electrode. *Pacing Clin Electrophysiol* 1979; 2: 40–50.

8 Winfree AT. The electrical thresholds of ventricular myocardium. *J Cardiovasc Electrophysiol* 1990; 1: 393–410.

9 Irnich W. The fundamental law of electrostimulation and its application to defibrillation. *Pacing Clin Electrophysiol* 1990; 13: 1433–1447.

10 Coates S, Thwaites B. The strength–duration curve and its importance in pacing efficiency: A study of 325 pacing leads in 229 patients. *Pacing Clin Electrophysiol* 2000; 23: 1273–1277.

11 Castellanos A, Jr, Lemberg L, Johnson D, Berkovits BV. The Wedensky effect in the human heart. *Br Heart J* 1966; 28: 276–283.

12 Buxton AE, Marchlinski FE, Miller JM, Morrison DF, Frame LH, Josephson ME. The human atrial strength–interval relation. Influence of cycle length and procainamide. *Circulation* 1989; 79: 271–280.

13 Mehra R, Furman S. Comparison of cathodal, anodal, and bipolar strength–interval curves with temporary and permanent pacing electrodes. *Br Heart J* 1979; 41: 468–476.

14 Swerdlow CD, Friedman PA. Advanced ICD troubleshooting: Part II. *Pacing Clin Electrophysiol* 2006; 29: 70–96.

15 Dendy KF, Powell BD, Cha YM, *et al*. Anodal stimulation: An underrecognized cause of nonresponders to cardiac resynchronization therapy. *Indian Pacing Electrophysiol J* 2011; 11: 64–72.

16 Saxonhouse SJ, Conti JB, Curtis AB. Current of injury predicts adequate active lead fixation in permanent pacemaker/defibrillation leads. *J Am Coll Cardiol* 2005; 45: 412–417.

17 Platia EV, Brinker JA. Time course of transvenous pacemaker stimulation impedance, capture threshold, and electrogram amplitude. *Pacing Clin Electrophysiol* 1986; 9: 620–625.

18 Beyersdorf F, Schneider M, Kreuzer J, Falk S, Zegelman M, Satter P. Studies of the tissue reaction induced by transvenous pacemaker electrodes. I. Microscopic examination of the extent of connective tissue around the electrode tip in the human right ventricle. *Pacing Clin Electrophysiol* 1988; 11: 1753–1759.

19 Mond H, Stokes K, Helland J, *et al*. The porous titanium steroid eluting electrode: A double blind study assessing the stimulation threshold effects of steroid. *Pacing Clin Electrophysiol* 1988; 11: 214–219.

20 Boriani G, Rusconi L, Biffi M, *et al*. Role of ventricular autocapture function in increasing longevity of DDDR pacemakers: A prospective study. *Europace* 2006; 8: 216–220.

21 Lau C, Cameron DA, Nishimura SC, *et al*. A cardiac evoked response algorithm providing threshold tracking: A North American multicenter study. Clinical investigators of the microny-regency clinical evaluation study. *Pacing Clin Electrophysiol* 2000; 23: 953–959.

22 Biffi M, Bertini M, Saporito D, *et al*. Actual pacemaker longevity: The benefit of stimulation by automatic capture verification. *Pacing Clin Electrophysiol* 2010; 33: 873–881.

23 Dohrmann ML, Goldschlager NF. Myocardial stimulation threshold in patients with cardiac pacemakers: Effect of physiologic variables, pharmacologic agents, and lead electrodes. *Cardiol Clin* 1985; 3: 527–537.

24 Ohlow MA, Lauer B, Brunelli M, Daralammouri Y, Geller C. The use of a quadripolar left ventricular lead increases successful implantation rates in patients with phrenic nerve stimulation and/or high pacing thresholds undergoing cardiac resynchronisation therapy with conventional bipolar leads. *Indian Pacing Electrophysiol J* 2013; 13: 58–65.

25 Asirvatham SJ, Bruce CJ, Danielsen A, *et al*. Intramyocardial pacing and sensing for the enhancement of cardiac stimulation and sensing specificity. *Pacing Clin Electrophysiol* 2007; 30: 748–754.

26 Moriña-Vázquez P, Roa-Garrido J, Fernández-Gómez JM, Venegas-Gamero J, Pichardo RB, Carranza MH. Direct left ventricular endocardial pacing: An alternative when traditional resynchronization via coronary sinus is not feasible or effective. *Pacing Clin Electrophysiol* 2013; 36: 699–706.

27 Elencwajg B, Lopez Cabanillas N, *et al*. The Jurdham procedure: Endocardial left ventricular lead insertion via a femoral transseptal sheath for cardiac resynchronization therapy pectoral device implantation. *Heart Rhythm* 2012; 9: 1798–1804.

28 Hidden-Lucet F, Halimi F, Gallais Y, Petitot JC, Fontaine G, Frank R. Low chronic pacing thresholds of steroid-eluting active-fixation ventricular pacemaker leads: A useful alternative to passive-fixation leads. *Pacing Clin Electrophysiol* 2000; 23: 1798–1800.

29 Vlay SC. Complications of active-fixation electrodes. *Pacing Clin Electrophysiol* 2002; 25: 1153–1154.

30 Shali S, Wushou A, Liu E, *et al*. Time course of current of injury is related to acute stability of active-fixation pacing leads in rabbits. *PLoS One* 2013; 8: e57727.

31 Kalahasty G, Ellenbogen KA. The active fixation coronary sinus lead: More peril than promise? *Pacing Clin Electrophysiol* 2012; 35: 639–640.

32 Kazama S, Nishiyama K, Machii M, *et al*. Long-term follow up of ventricular endocardial pacing leads. Complications, electrical performance, and longevity of 561 right ventricular leads. *Jpn Heart J*. 1993; 34: 193–200.

33 Mathur AB, Collier TO, Kao WJ, *et al*. In vivo biocompatibility and biostability of modified polyurethanes. *J Biomed Mat Res* 1997; 36: 246–257.

34 Epstein AE, Baker JH, 2nd, Beau SL, Deering TF, Greenberg SM, Goldman DS. Performance of the St. Jude Medical Riata leads. *Heart Rhythm* 2009; 6: 204–209.

35 Lim KK, Reddy S, Desai S, *et al*. Effects of electrocautery on transvenous lead insulation materials. *J Cardiovasc Electrophysiol* 2009; 20: 429–435.

36 Bolz A, Hubmann M, Hardt R, Riedmuller J, Schaldach M. Low polarization pacing lead for detecting the ventricular-evoked response. *Med Prog Technol* 1993; 19: 129–137.

37 Dorwarth U, Frey B, Dugas M, *et al*. Transvenous defibrillation leads: High incidence of failure during long-term follow-up. *J Cardiovasc Electrophysiol* 2003; 14: 38–43.

38 Hauser RG, Cannom D, Hayes DL, *et al*. Long-term structural failure of coaxial polyurethane implantable cardioverter defibrillator leads. *Pacing Clin Electrophysiol* 2002; 25: 879–882.

39 Ellenbogen KA, Wood MA, Shepard RK, *et al*. Detection and management of an implantable cardioverter defibrillator lead failure: Incidence and clinical implications. *J Am Coll Cardiol* 2003; 41: 73–80.

40 Maisel WH, Hauser RG, Hammill SC, *et al*. Recommendations from the Heart Rhythm Society task force on lead performance policies and guidelines: Developed in collaboration with the American College of Cardiology (ACC) and the American Heart Association (AHA). *Heart Rhythm* 2009; 6: 869–885.

41 Sommer T, Naehle CP, Yang A, *et al*. Strategy for safe performance of extrathoracic magnetic resonance imaging at 1.5 Tesla in the presence of cardiac pacemakers in non-pacemaker-dependent patients: A prospective study with 115 examinations. *Circulation* 2006; 114: 1285–1292.

42 Gimbel JR. The safety of mri scanning of pacemakers and ICDs: What are the critical elements of safe scanning? Ask me again at 10 000. *Europace* 2010; 12: 915–917.

43 Nazarian S, Halperin HR. How to perform magnetic resonance imaging on patients with implantable cardiac arrhythmia devices. *Heart Rhythm* 2009; 6: 138–143.

44 Kalin R, Stanton MS. Current clinical issues for mri scanning of pacemaker and defibrillator patients. *Pacing Clin Electrophysiol* 2005; 28: 326–328.

45 Forleo GB, Santini L, Della Rocca DG, *et al*. Safety and efficacy of a new magnetic resonance imaging-compatible pacing system: Early results of a prospective comparison with conventional dual-chamber implant outcomes. *Heart Rhythm* 2010; 7: 750–754.

46 Wollmann CG, Thudt K, Vock P, Globits S, Mayr H. Clinical routine implantation of a dual chamber pacemaker system designed for safe use with MRI: A single center, retrospective study on lead performance of Medtronic lead 5086MRI in comparison to Medtronic leads 4592–53 and 4092–58. *Herzschrittmacherther Elektrophysiol* 2011; 22: 233–236, 239–242.

47 Wilkoff BL, Bello D, Taborsky M, *et al*. Magnetic resonance imaging in patients with a pacemaker system designed for the magnetic resonance environment. *Heart Rhythm* 2011; 8: 65–73.

48 Jung W, Zvereva V, Hajredini B, Jackle S. Safe magnetic resonance image scanning of the pacemaker patient: Current technologies and future directions. *Europace* 2012; 14: 631–637.

49 Kay GN, Bubien RS, Epstein AE, Plumb VJ. Rate-modulated cardiac pacing based on transthoracic impedance measurements of minute ventilation: Correlation with exercise gas exchange. *J Am Coll Cardiol* 1989; 14: 1283–1289.

50 Coman J, Freedman R, Koplan BA, *et al*. A blended sensor restores chronotropic response more favorably than an accelerometer alone in pacemaker patients: The life study results. *Pacing Clin Electrophysiol* 2008; 31: 1433–1442.

51 Shukla HH, Flaker GC, Hellkamp AS, *et al*. Clinical and quality of life comparison of accelerometer, piezoelectric crystal, and blended sensors in DDDR-paced patients with sinus node dysfunction in the mode selection trial (MOST). *Pacing Clin Electrophysiol* 2005; 28: 762–770.

52 Greco EM, Ferrario M, Romano S. Clinical evaluation of peak endocardial acceleration as a sensor for rate responsive pacing. *Pacing Clin Electrophysiol* 2003; 26: 812–818.

53 Ritter P, Delnoy PP, Padeletti L, *et al*. A randomized pilot study of optimization of cardiac resynchronization therapy in sinus rhythm patients using a peak endocardial acceleration sensor vs. Standard methods. *Europace* 2012; 14: 1324–1333.

54 Lindovska M, Kamenik L, Pollock B, *et al*. Clinical observations with closed loop stimulation pacemakers in a large patient cohort: The Cylos Routine Documentation Registry (Record). *Europace* 2012; 14: 1587–1595.

55 Shanmugam N, Prada-Delgado O, Campos AG, *et al*. Rate-adaptive AV delay and exercise performance following cardiac resynchronization therapy. *Heart Rhythm* 2012; 9: 1815–1821.

3

CHAPTER 3

Hemodynamics of cardiac pacing and pacing mode selection

Bruce S. Stambler[1] *and Niraj Varma*[2]

[1] Case Western Reserve University, Cleveland, OH, USA
[2] Cleveland Clinic, Cleveland, OH, USA

Introduction

Cardiac pacing in an individual patient can have either beneficial or detrimental effects on hemodynamic function and clinical outcomes. Appropriate selection of a cardiac rhythm management device for a given patient and optimal management of a patient with a permanent pacing device require proper understanding of the major factors that influence hemodynamic function. While early generations of cardiac pacemakers were sufficient technologically to prevent symptomatic bradycardia, the goal of cardiac pacing over the last few decades has been the attainment of "physiological" pacing. Many variables in pacing systems can affect cardiac hemodynamic function. The ideal pacemaker should maintain and optimize heart rate, atrioventricular (AV) synchrony, and ventricular activation to enable cardiac output to meet the metabolic needs of the patient, whether at rest or during exercise. The concept and definition of physiological pacing have evolved over time in concert with our understanding of pacing-related cardiovascular hemodynamics, as well as with technological sophistication.

In the current era, the goals of physiological pacing include maintaining heart rate, optimizing AV synchrony, minimizing right ventricular (RV) pacing to avoid ventricular desynchronization, using alternative RV pacing sites for improved hemodynamic performance, and selecting appropriate patients for cardiac resynchronization therapy (CRT). Optimization of hemodynamic function in the pacemaker patient is determined to a large extent by a complex interaction between device-related variables (e.g. pacing mode, pacing lead position, pacing rate, rate responsiveness, AV relationships, atrial and ventricular activation sequences, frequency of RV pacing, etc.) and the underlying patient substrate (e.g. atrial rhythm, chronotropic competence, AV and ventricular conduction, ventricular function, history of heart failure and/or myocardial infarction, etc.).[1]

Correction of bradycardia

When a patient with AV block or sinus node disease experiences sudden bradycardia, the blood pressure and cardiac output fall, leading to reduced cerebral perfusion. The primary therapeutic goal of cardiac pacing is to correct symptomatic bradycardia in such conditions. It is the only effective treatment that can prevent death or syncope caused by ventricular asystole. Simply increasing the heart rate will result in improvement of the hemodynamic abnormalities, including normalization of systolic blood pressure.

Cardiac Pacing and ICDs, Sixth Edition. Edited by Kenneth A. Ellenbogen and Karoly Kaszala.
© 2014 John Wiley & Sons, Ltd. Published 2014 by John Wiley & Sons, Ltd.

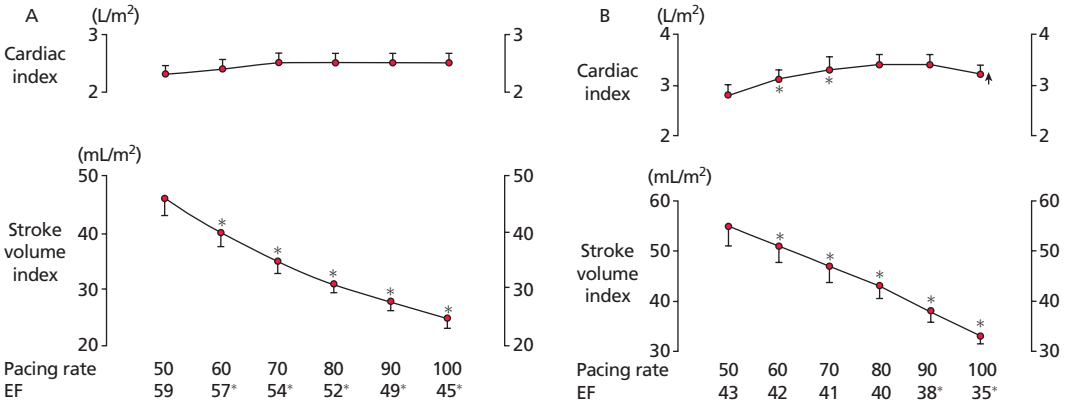


Figure 3.1 Effects of ventricular pacing rate on cardiac index, stroke volume index, and left ventricular ejection fraction (EF) in patients with a normal heart size and ejection fraction (A) and in patients with cardiomegaly and depressed ejection fraction (B). In patients with normal hearts, cardiac index did not change significantly as ventricular pacing rate was increased from 50 to 100 bpm. In contrast, in patients with cardiomyopathy, mean cardiac index was highest at ventricular pacing rates of 70 to 90 bpm. In both groups, increases in pacing rates resulted in significant linear decreases in stroke volume index. In patients with normal hearts, ejection fraction decreased at pacing rates from 60 to 100 bpm compared to 50 bpm. In patients with cardiomyopathy, ejection fraction was significantly reduced only at pacing rates of 90 to 100 bpm. *Significantly different ($p < 0.05$) from values at lower pacing rates. (Source: Narahara KA, Blettel ML 1983.[3] Reproduced with permission of Wolters Kluwer Health.)

Early work on the ideal pacing rate indicated that a rate between 70 and 90 bpm results in maximal increase in cardiac output during ventricular pacing at rest (Figure 3.1).[2,3] Further augmentation of heart rate via ventricular pacing resulted in either no additional increase or a decrease in cardiac output accompanied by an increase in peripheral vascular resistance and decrease in left ventricular ejection fraction (LVEF). Historically, when earliest generation single chamber ventricular pacemakers were manufactured with only one rate, 70 bpm was the rate usually chosen. However, it should be kept in mind that in an individual patient it is likely that different resting ventricular rates (either higher or lower) may be required to optimize hemodynamics at rest. In patients with systolic and/or diastolic dysfunction or hypertensive hypertrophic heart disease, higher heart rates may limit maximal cardiac output by shortening diastolic filling time, reducing left ventricular (LV) compliance, and increasing systemic vascular resistance (Figure 3.1). Increasing heart rate also augments cardiac oxygen consumption and if this occurs without an enhancement of cardiac output, then a lower pumping efficiency will occur at the higher rate.

Chronotropic incompetence and rate modulation

In addition to maintaining resting heart rate in the physiological range, pacemaker therapy can allow the heart rate to rise during exercise. A variety of terms have been used to describe the capacity of a pacing system to respond to physiological need by increasing or decreasing pacing rate. The earliest term used to describe this physiological property of pacing systems was rate responsive. Significant objection to this term (for grammatical reasons) has led to the more acceptable use of the terms rate adaptive and rate modulating. However, all these terms are used interchangeably.

When the chronotropic function of the sinus node is impaired, the capability of a pacing system to provide rate adaptation depends on the presence of physiological sensors that monitor the need for heart rate modulation. Rate-adaptive pacing is available in almost all modern pulse generators. Rate-adaptive pacing sensors detect physical or physiological indices to mimic the rate response of the normal sinus node. A variety of sensors have been developed to modulate pacing rate according to metabolic demands and to correct chronotropic

incompetence.[4] Activity, accelerometer, minute-ventilation, and QT-interval sensors are commercially available. There is no single sensor that ideally mimics normal cardiac physiology and perfectly modulates heart rate according to metabolic demands. A detailed review of the technology of physiological sensors is given in Chapter 2.

Exercise physiology

The importance of rate modulation in pacing systems is related directly and specifically to the importance of matching cardiac output with physiological need. The predominant need for rate modulation derives from physical activity or exertion. A rise in heart rate with greater workload improves exercise capacity. However, there are other physiological situations in which, normally, there are modulations of heart rate(e.g. during fever and emotional stress). These situations, however, have received less attention, especially in the context of pacing systems.

During exercise—or "work"—the body tissues increase their demand for oxygen.[5] In addition, there is increased need for removal of metabolic by-products, such as CO_2, from tissues. The body has a number of physiological mechanisms in place to provide for increased metabolic demands during exercise. Redistribution of blood flow to working tissues, increased ability of working tissues to extract oxygen from blood, and, most important, increased cardiac output are these mechanisms. Here, we focus on the last of these, the body's ability to increase cardiac output with exercise, as this is what rate modulation provides.

The importance of cardiac output during work must be appreciated. A direct, relatively linear relationship exists between the amount of work accomplished and oxygen consumption. Maximal work capacity, therefore, is specifically related to maximum oxygen consumption. Further, consistent with the Fick principle:

$$\text{Cardiac output} = O_2 \text{ consumption} / \text{AV } O_2 \text{ difference}$$

where AV means arterial–venous. Also:

$$\text{Cardiac output} = \text{Stroke volume} \times \text{Heart rate}$$

By substitution in these equations:

$$O_2 \text{ consumption} = \text{Stroke volume} \times \text{Heart rate} \times \text{AV } O_2 \text{ difference}$$

Because oxygen consumption is directly linearly proportional to work (Figure 3.2):

$$\text{Work} = \text{Stroke volume} \times \text{Heart rate} \times \text{AV } O_2 \text{ difference}$$

Increasing any of these variables will support an increased ability to do work, but the increase in heart rate is the most important determinant. Maximum work, in normal individuals, is accomplished by an increase in stroke volume to approximately 150% of the resting value, an increase in heart rate to approximately 300% of the

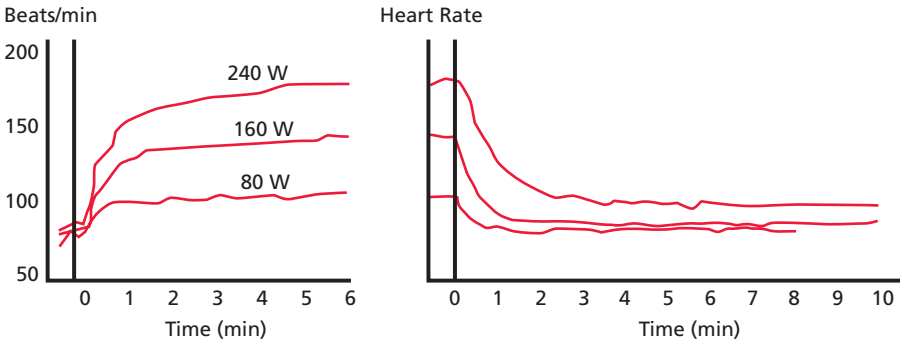


Figure 3.2 Heart rate response at onset and termination of exercise in eight healthy young men at different workloads. At onset of exercise, the majority of the total increment in heart rate occurs in the first minute of effort. (Source: Linnarsson D 1974.[6] Reproduced with permission of John Wiley & Sons Ltd.)

resting value, and an increase in AV O_2 difference to approximately 250% of the resting value. These changes allow an increase in work to over 10 times resting levels. In normal individuals, peak cardiac output can be increased to 300% of resting values simply by an increase in heart rate. During peak exercise, the stroke volume is increased to approximately 150% of the resting value. This increase in stroke volume is not linear and is achieved at approximately the halfway point between the rest and maximal exercise levels. The increased stroke volume is accomplished by an increase in venous return, ventricular filling, and contractility. It is ideal to optimize stroke volume, because this is a more energy efficient way of accomplishing cardiac output (milliliters of cardiac output/milliliters of O_2 consumption) than by an increase in heart rate.

The normal heart rate response to exercise follows a triphasic response (Figure 3.2).[6] Heart rate increases most rapidly within the first 10–15 s of maximum effort exercise and reaches 70% of total heart rate increase in this phase. A slower exponential rise in rate follows during the next 60–90 s. Finally, a slow linear increase or plateau phase results from sustained activity. Heart rate deceleration with cessation of exercise is generally slower than acceleration and follows a biphasic or triphasic response.

Chronotropic incompetence

The inability to increase and maintain heart rate appropriately with exercise is called chronotropic incompetence.[7] A number of criteria have been proposed to diagnose chronotropic incompetence, including the inability to increase heart rate with exercise to at least 70–85% of the maximum predicted heart rate (maximum predicted heart rate = 220 − age in years). This is a useful criterion for diagnosing chronotropic incompetence, but it cannot be used in individuals with limitations on their exercise function unrelated to cardiopulmonary status. Thus, the diagnosis of chronotropic incompetence is difficult if the patient cannot undergo formal exercise testing or perform a simple hall walk test. Further, there are patients with delayed chronotropic responses who could benefit from rate-adaptive pacing systems but might be missed by this criterion. More complicated formulas have been developed to allow determination of the presence of chronotropic incompetence by exercise testing with assessments made by stage. The Wilkoff chronotropic assessment exercise protocol (CAEP) is performed via treadmill testing and is often used for chronotropic competency evaluation.[8] It uses gradual increases in both elevation and speed, and can be used for the evaluation of devices with a variety of sensor types.

Chronotropic incompetence is common among pacemaker patients. However, the frequency of chronotropic incompetence in part depends on the definition used and method of assessment. Among a cohort of pacemaker patients [42% AV block, 56% sinus node disease, and 59% atrial fibrillation (AF)], 51% were diagnosed as having chronotropic incompetence based on the Wilkoff chronotropic index.[9] Among patients in whom sinoatrial disease is the primary indication for pacing, not all will manifest chronotropic incompetence during formal exercise testing. Some individuals with sinus node dysfunction may demonstrate normal chronotropic response to exercise, whereas others may have little or no ability to increase heart rate during exercise. Thus, the need for rate-adaptive pacing is unpredictable in sinoatrial disease. The overall pattern of chronotropic response in an individual is variable and may evolve over time. Some patients are able to achieve the appropriate heart rate for the level of exercise, but do so more slowly than is normal. Patients with any form of chronotropic incompetence are candidates for pacing systems with rate-modulation capabilities. It is also noted that making predictions regarding the future need for rate-adaptive pacing is unreliable at the time of implantation. This is usually not a clinical issue, because rate-adaptive pacing is available in almost all modern pacemaker generators and can be programmed "on" if needed after implantation.

Chronotropic incompetence may be provoked by disease, most commonly ischemic heart disease, valvular heart disease, and heart failure, or induced by drugs. In a study of pacemaker patients, significant predictors of chronotropic incompetence included the existence of coronary artery disease, presence of an acquired valvular heart disease, former cardiac surgery, and therapy with digitalis, β-blockers, or amiodarone.[9] Chronotropic incompetence has important prognostic implications in patients with coronary artery disease. It predicts

all-cause mortality independent of angiographic severity of coronary artery disease.[10] The prevalence of chronotropic impairment in heart failure patients also is variably reported (25–70%), possibly due to a lack of a standardized definition and/or differing assessment methodologies.[11] Chronotropic impairment impacts the physical function and quality of life of heart failure patients.

Advantages and clinical benefits of rate modulation

As is obvious from the foregoing discussion of exercise physiology, the ability of patients to increase heart rate with exercise is the primary means of meeting metabolic demands. Thus, exertional intolerance is inevitable if heart rate cannot be increased appropriately. The ability to increase rate is the most important determinant of cardiac output and exercise capacity, especially at higher levels of exertion. A positive linear correlation between improvement of exercise capacity and heart rate is observed. An inappropriate chronotropic response to exercise can decrease peak exercise oxygen uptake by as much as 15–20%.

Quantification of the improvement in work capacity in pacemaker populations comparing non–rate-modulated with rate-modulated modes has shown the advantages of the rate-modulated systems. Rate-modulated pacing systems have been shown not only to improve the heart rate response with exercise, but also to increase work capacity. For every 40% increase in paced rate during rate-modulated pacing compared with non–rate-modulated pacing, there is a 10% increase in work capacity. Compared with VVI pacing, VVIR mode improves exercise duration and cardiac index in patients undergoing paired stress testing. These improvements are independent of patient age and ejection fraction. Even greater improvements in exercise hemodynamics are documented with DDDR pacing compared with either VVIR or DDD modes. Compared with VVIR, DDDR pacing has demonstrated improved exercise capacity, cardiac output, and cardiac metabolic indices, suggesting more efficient cardiac work. In patients with sick sinus syndrome, DDDR pacing provides greater maximal heart rates, longer exercise times, higher maximal oxygen uptake, and higher oxygen uptake at anaerobic threshold than DDD pacing (Figure 3.3). These benefits are attributed largely to the increased heart rate in the rate-adaptive mode.

Despite recognized theoretical benefits of rate modulation on exercise performance, it is realized that many pacemaker recipients are elderly and function at submaximal levels of exertion during virtually all their daily activities. Rarely does the typical pacemaker patient require improvement in

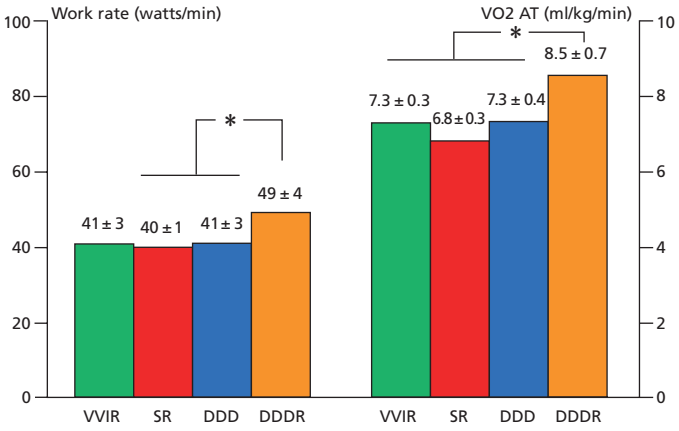


Figure 3.3 Work rate versus oxygen uptake at anaerobic threshold in nine patients with sinus node dysfunction. Each patient underwent testing in sinus rhythm (SR), VVIR, DDD, and DDDR pacing modes using a respiratory sensor pacemaker. Oxygen uptake was greater in DDDR mode compared with all others at anaerobic threshold, AT, anaerobic threshold. (Source: Lemke B *et al.* Aerobic capacity in rate modulated pacing. PACE 1992; 15: 1914–8. Reproduced with permission of John Wiley & Sons Ltd.)

maximal work capacity and few are expected to stress to their maximal heart rate, except for the young or extremely vigorous. References are available that provide normal ranges of heart rates in response to moderate exercise according to age, sex, and body surface area, which have relevance to rate-adaptive pacemaker programming. However, such rates are often inappropriate in some patients, such as those with coronary artery disease, valvular disease, or diastolic dysfunction. Optimization of heart rate by providing rate modulation at sub-maximal levels of exertion during activities of daily living most often is the therapeutic aim. This may require individualized pacemaker programming to suit the unique needs of each patient.

From an evidence-based perspective, it is notable that despite the physiological basis for rate-adaptive pacing and acute improvements in exercise hemodynamics with the use of this technology, it has not been clearly and consistently established that rate-adaptive pacing provides clinically relevant improvements in symptoms, quality of life or other relevant cardiovascular outcomes. In a small trial of patients with the tachy–brady syndrome, symptomatic improvement was demonstrated in patients programmed to the DDDR compared with the DDD mode.[12] The improvement in symptoms in the DDDR group was mostly due to reduced palpitations related to fewer mode switching episodes. The Advanced Elements of Pacing Trial (ADEPT) studied 872 patients with at least mild chronotropic incompetence and found no significant improvements in quality of life in patients assigned to rate-modulated compared with fixed-rate pacemakers (DDDR vs. DDD).[13,14] Furthermore, there were no differences in the composite end-point of death, non-fatal myocardial infarction, stroke, hospitalization for heart failure, or AF between the two groups. Interestingly, the DDDR group was significantly more likely to experience hospitalization for heart failure compared with the DDD group (7.3% vs. 3.5%). Thus, it should be concluded that the addition of rate modulation in conventional dual chamber devices, in spite of attempting to replicate the normal response to exercise, does not have a positive impact on quality of life or cardiovascular outcomes. It may be speculated that the increased frequency of RV pacing at higher heart rates during rate-modulated pacing, with the resultant forced ventricular dyssynchrony, may increase the risk of heart failure and negate the potential benefits of restoring chronotropic competence. The clinical utility and importance of rate modulation during biventricular pacing has not been well studied.

Although there are a variety of sensors that can be used for rate modulation in currently available pacemakers, there is little evidence to support a major clinical difference in outcomes between sensors and their combinations. Interestingly, when three of the most commonly utilized rate-adaptive sensors (accelerometer, piezoelectric, and blended sensors; see Chapter 2) were compared in DDDR-paced patients with sinus node dysfunction in the Mode Selection Trial (MOST), quality of life analyses demonstrated that patients with blended sensors had significantly worse physical function than did patients with the other two sensor systems.[15] There were no significant differences, after adjustment for baseline differences, among the three sensors in clinical end-points after long-term follow-up, including no significant differences in the risk of death, heart failure hospitalization, AF, and the combined end-point of mortality and stroke.

Atrioventricular synchrony

The introduction of dual chamber (AV sequential) pacing in 1962 was designed to avoid AV desynchronization imposed during ventricular-only pacing and improve hemodynamics.[16] Enthusiasm for AV sequential (DDD) pacing and the importance of maintaining AV synchrony was so high in the 1980s that at that time many in the field believed that these pacemakers could permit the restoration of normal cardiac physiology.[17] Furthermore, at one time, dual chamber [right atrial (RA) and RV] cardiac pacing was proposed as a possible therapy for heart failure. However, subsequent studies and randomized clinical trials of pacemaker therapy have provided important new insights into the hemodynamics of AV synchrony and pacing mode selection. The widespread recognition of the potential deleterious effects of frequent RV pacing along with the introduction of LV-based pacing and CRT have further complicated consideration of the hemodynamics of AV synchrony, optimal

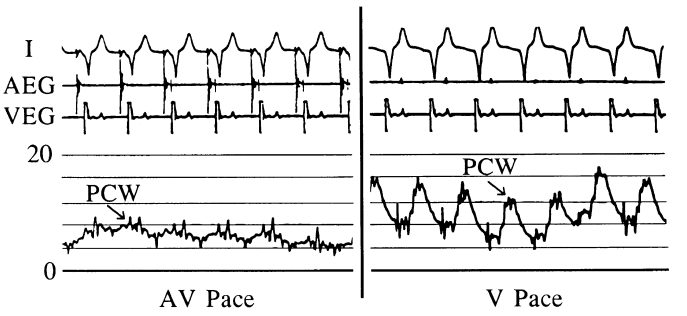


Figure 3.4 Pulmonary capillary wedge (PCW) pressure recordings from a single patient during (left) atrioventricular (AV) pacing (AV Pace) and (right) ventricular pacing (V Pace) at 80 ppm with AV interval = 150 ms. Scale in mmHg. I, ECG lead I; AEG, atrial electrogram; VEG, ventricular electrogram.

pacemaker mode selection, and dual chamber pacemaker programming.

The hemodynamic benefits of AV synchrony accrue from its ability to (1) maximize ventricular preload and therefore contractility; (2) close AV valves before ventricular systole, limiting AV valvular regurgitation; (3) maintain low mean atrial pressures, thus facilitating venous return; and (4) regulate autonomic and neurohumoral reflexes involving atrial pressure and volume.

Advantages

The loss of AV synchrony during ventricular pacing in the presence of sinus rhythm is associated most consistently with increases in atrial pressures, alterations in pulmonary and systemic venous flow patterns, and AV valvular regurgitation.[18] Effects of AV desynchronization on systemic blood pressure and cardiac output are more variable between patients. Autonomic activation of the vagal inhibitory reflexes associated with atrial distension can result in an inappropriate decrease in peripheral vascular resistance. Rarely, VVI pacing with loss of appropriate AV synchrony can produce dramatic responses and disabling symptomatology with severe symptomatic hypotension, decreased cardiac output, and syncope.

Atrial pressures

An increase in atrial pressures during ventricular pacing is probably the major mechanism by which symptoms are produced when AV synchrony is not maintained. Increases in atrial pressure during ventricular pacing (VVI) are related primarily to atrial contraction against closed AV valves during ventricular systole. During AV synchrony, atrial contraction augments ventricular end-diastolic filling pressure while maintaining a low mean atrial pressure throughout diastole. In the absence of AV synchrony, a higher mean atrial pressure is required to achieve the same degree of ventricular filling. By this mechanism, AV synchrony is associated with lower venous and left atrial (LA) pressures (Figure 3.4).

In Figure 3.4, the left panel shows recordings of the pulmonary capillary wedge pressure in one patient during AV-synchronous pacing [80 pulses per minute (ppm), AV interval 150 ms]. The right panel shows the pulmonary capillary wedge pressure during ventricular pacing (80 ppm) with intact ventriculoatrial (VA) conduction. A relatively normal pulmonary capillary wedge pressure tracing is produced during AV pacing with mean pressures between 4 and 8 mmHg and without significant phasic aberration. In contrast, during ventricular pacing, the mean pressures are elevated to between 8 and 12 mmHg with large A waves (or VA waves) that, at times, exceed 16 mmHg. This elevation in atrial pressures, and specifically the production of giant or "cannon" A waves, occurs because of LA contraction against a closed mitral valve; the increased pressure wave is present not only in the LA, but also in the pulmonary veins and pulmonary capillary wedge

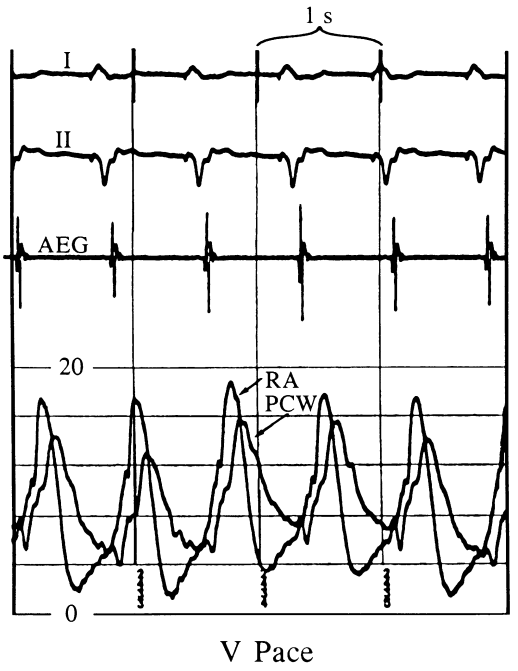


Figure 3.5 Right atrial (RA) and pulmonary capillary wedge (PCW) pressure recordings during ventricular pacing (V Pace) at 80 ppm with 1:1 ventriculoatrial conduction. Scale in mmHg. I, II standard ECG leads; AEG, atrial electrogram.

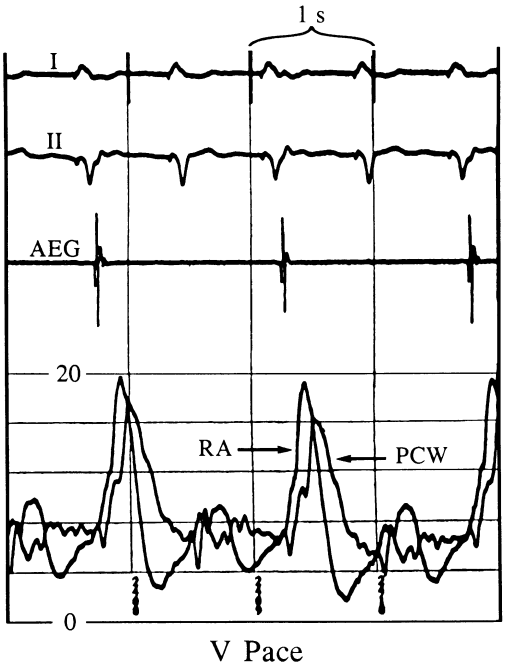


Figure 3.6 Right atrial (RA) and pulmonary capillary wedge (PCW) pressure recordings during ventricular pacing (V Pace) at 80 ppm with 2:1 ventriculoatrial conduction. Scale in mmHg. I and II, standard ECG leads; AEG, atrial electrogram.

position. The same phenomenon occurs on the right side of the heart.

Figures 3.5 and 3.6 display simultaneous RA and pulmonary capillary wedge recordings during ventricular pacing (80 ppm) in which VA conduction is intact. In Figure 3.5, 1:1 VA conduction is present, while in Figure 3.6, there is 2:1 VA conduction. Intact VA conduction produces consistent elevations in pressure in the LA and RA due to contraction of the atria against closed AV valves. Even when VA conduction is not intact, because of unequal atrial and ventricular rates, there will be frequent periods when atrial contraction occurs during ventricular systole, during which the AV valves are closed; hence, the problems of elevated pressures in the atria and pulmonary veins occur. Some patients are actually more symptomatic when VA conduction is not intact, due to intermittency of these elevated pressures, thus preventing patients from establishing tolerance to this phenomenon.

The relationship of the phasic changes in the pulmonary capillary wedge (and LA) pressures to LV pressures can be seen in Figures 3.7, 3.8, and 3.9. Figure 3.7 is a display of normal LV and pulmonary capillary wedge pressure recordings during AV pacing (80 ppm, AV interval of 150 ms). The appropriately timed A wave can be seen in both the LV and pulmonary capillary wedge pressure recordings. In contrast, as Figure 3.8 shows, during ventricular pacing (80 ppm) with a consistent 1:1 VA relationship, the loss of the A wave contribution to the upstroke of the LV pressure recording and the giant A wave, late in ventricular systole, can be seen consistently in the pulmonary capillary wedge pressure recording. Figure 3.9 displays this relationship when the atrial contraction is random in relation to ventricular contraction.

Pulmonary venous flow patterns

Doppler echocardiography can provide noninvasive insight into physiological, pacemaker-

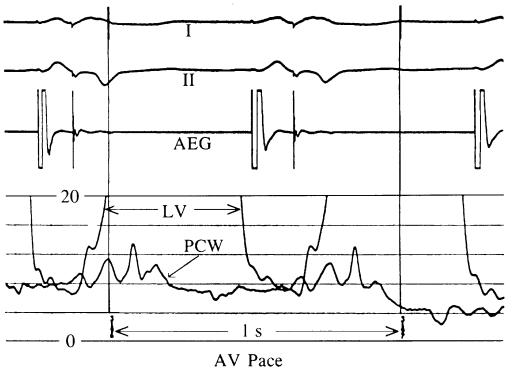


Figure 3.7 Left ventricular (LV) and pulmonary capillary wedge (PCW) pressure recordings during atrioventricular (AV) pacing at 80 ppm with AV interval = 150 ms. Scale in mmHg. I and II, standard ECG leads; AEG, atrial electrogram.

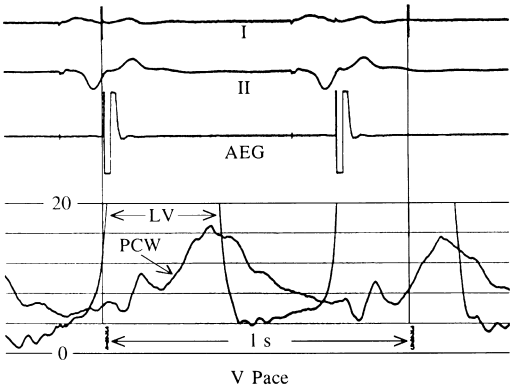


Figure 3.8 Left ventricular (LV) and pulmonary capillary wedge (PCW) pressure recordings during ventricular pacing at 80 ppm with a 1:1 ventriculoatrial (VA) relationship (VA interval = 150 ms). Scale in mmHg. I and II, standard ECG leads; AEG, atrial electrogram.

related changes in paced patients, including alterations in pulmonary vein flow and LA mechanical function (Figures 3.10 and 3.11). VA (retrograde) conduction produces a contraction of the atria against closed AV valves, which induces a reversal of blood flow from the LA toward the pulmonary veins. This can be recognized by retrograde flow into the pulmonary vein (z wave) on the pulsed-Doppler echocardiographic recording (Figure 3.10). Even when retrograde conduction during ventricular pacing is absent, atrial contraction may still occur shortly after ventricular activation by chance, resulting in intermittent regurgitation into the pulmonary veins (Figure 3.11). Inappropriately timed atrial reverse flow at the time of ventricular systole markedly decreases the systolic flow velocities of pulmonary veins and reverses flow into the pulmonary veins. A study using transesophageal Doppler echocardiography has demonstrated that atrial reverse flow into the pulmonary veins is a consistent finding in patients during VVI pacing when VA conduction is present. Furthermore, during ventricular pacing (VVI) with VA conduction, patients with clinical signs and symptoms of pacemaker syndrome (i.e. hypotension with dizziness, dyspnea, fatigue) have significantly higher atrial reverse flow velocities into their pulmonary veins than patients without pacemaker syndrome (Figures 3.12 and 3.13).

Atrioventricular valvular regurgitation

Effective and properly timed atrial and ventricular contraction is functionally important for complete mitral valve leaflet closure.[19] Thus, it is not

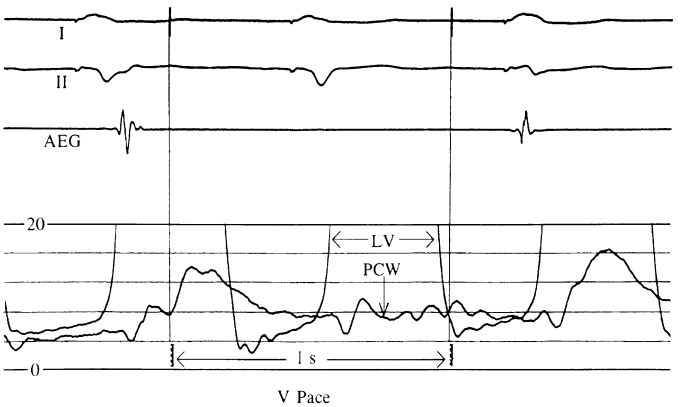


Figure 3.9 Left ventricular (LV) and pulmonary capillary wedge (PCW) pressure recordings during ventricular pacing at 80 ppm with ventriculoatrial dissociation. Scale in mmHg. I and II, standard ECG leads; AEG, atrial electrogram.

surprising that RV pacing (VVI) is associated with substantial worsening or production of significant mitral and/or tricuspid regurgitation in some patients due to the loss of AV synchrony or an inappropriately timed AV interval.[20] In an experimental model in sheep, ventricular pacing was associated with delayed mitral valve leaflet closure and increased mitral valve regurgitant volume compared with baseline in sinus rhythm. In contrast, during AV pacing, mitral regurgitant volume and leaflet and annular dynamics were unchanged from baseline.

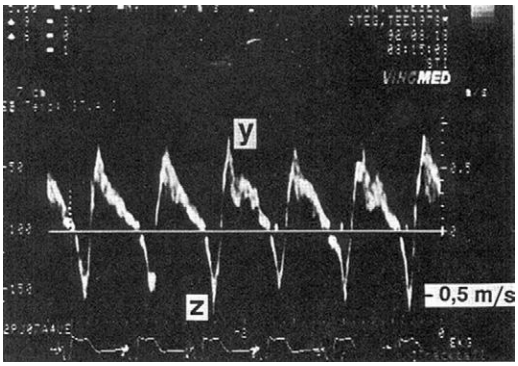


Figure 3.10 Ventricular pacing with 1:1 retrograde conduction. In this transesophageal pulsed-Doppler echocardiographic recording, positive values depict antegrade flow in a pulmonary vein, whereas negative values depict retrograde flow. After each ventricular stimulus (see ECG at the bottom of the tracing), a retrograde P wave appears, resulting in regurgitation into the pulmonary vein (z wave). (Source: Stierle U *et al.* Adverse pacemaker hemodynamics evaluated by pulmonary venous flow monitoring. *Pacing Clin Electrophysiol* 1995; 18: 2028–34. Reproduced with permission of John Wiley & Sons Ltd.)

A number of case reports have described dramatic reductions in the severity of mitral regurgitation (MR) in patients with severe MR during ventricular pacing after upgrading to a dual chamber device (Figure 3.14). In one study, the majority of patients (67%) with signs and symptoms of pacemaker syndrome during ventricular pacing (VVI) with retrograde conduction had significant MR (≥moderate) documented. Strikingly, MR disappeared in these patients after reprogramming to DDD mode. Other investigators likewise have demonstrated that the extent of valve regurgitation may be an important factor in the genesis of subclinical pacemaker syndrome. Thus, RV pacing can cause AV valve regurgitation in some patients that may resolve with the resumption of AV synchrony using AAI pacing or AV pacing programming to DDD mode.

When atrial contraction is not followed by an adequately synchronized ventricular contraction, the AV pressure gradient reverses during atrial relaxation and diastolic ventricular pressures exceed

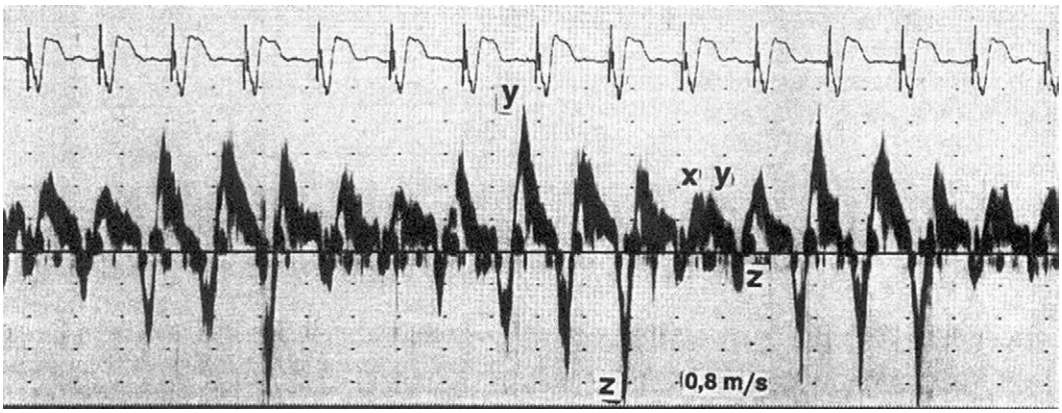


Figure 3.11 Ventricular pacing without retrograde conduction. Transesophageal pulsed-Doppler echocardiographic recording as in Figure 3.10. With a VVI pacing rate (75 bpm) different from the sinus rate, P waves appear shortly after the ventricular stimulus in three of the five cycles, resulting in regurgitation into the pulmonary vein (z wave as in Figure 3.10). (Source: Stierle U *et al.* Adverse pacemaker hemodynamics evaluated by pulmonary venous flow monitoring. *Pacing Clin Electrophysiol* 1995; 18: 2028–34. Reproduced with permission of John Wiley & Sons Ltd.)

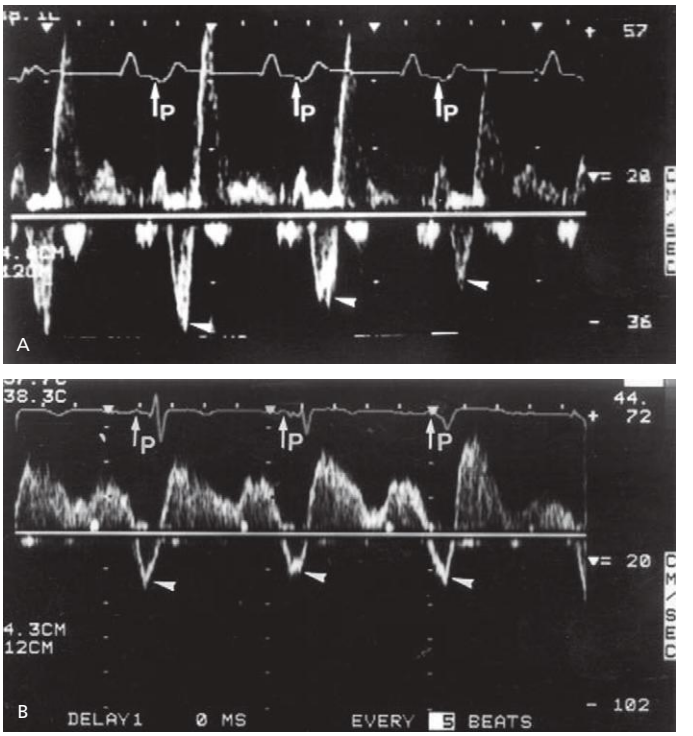


Figure 3.12 Representative Doppler tracings of left pulmonary vein flow in a patient with clinical pacemaker syndrome before (A) and after (B) reprogramming to DDD mode. (A) Atrial reverse flow (arrowheads) of the pulmonary vein regularly occurs after the electrocardiographically retrograde P wave (P). (B) Atrial reverse flow (arrowheads) of the pulmonary vein is noted after the electrocardiographically antegrade P wave (P). Systolic flow velocities of the pulmonary vein are increased compared with those in A. (Source: Lee TM *et al.* Role of transesophageal echocardiography in the evaluation of patients with clinical pacemaker syndrome. *Am Heart J* 1998; 135: 634–40. Reproduced with permission of Elsevier.)

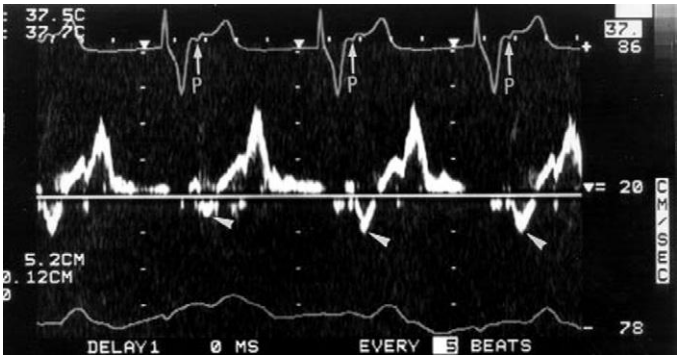


Figure 3.13 Representative Doppler tracings of left pulmonary vein flow together with respiration in an asymptomatic patient during VVI pacing. Atrial reverse flow (arrowheads) of the pulmonary vein is noted after the electrocardiographically retrograde P wave (P), similar to Figure 3.12A. The magnitude of atrial reverse flow is significantly lower than that in Figure 3.12A. (Source: Lee TM *et al.* Role of transesophageal echocardiography in the evaluation of patients with clinical pacemaker syndrome. *Am Heart J* 1998; 135: 634–40. Reproduced with permission of Elsevier.)

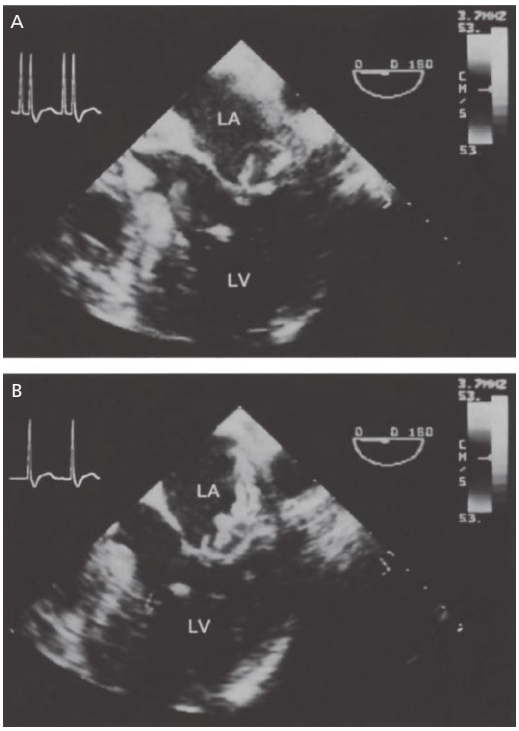


Figure 3.14 (A) Transesophageal Doppler flow image showing mitral regurgitant jet. There was mild mitral regurgitation during atrioventricular sequential pacing. (B) Transesophageal Doppler flow image showing a mitral regurgitation jet during ventricular pacing (10 s after image shown in A). With ventricular pacing, mitral regurgitation is severe. LA, left atrium; LV, left ventricle. (Source: Berglund H, Nishioka T, Hackner E *et al.* Ventricular pacing: a cause of reversible severe mitral regurgitation. *Am Heart J* 1996; 131: 1035–7. Reproduced with permission of Elsevier.)

those in the atria (VA pressure gradient).[21] This results in diastolic AV valve regurgitation because the mitral and tricuspid valves are incompletely closed. The presence of diastolic MR highlights the importance of adequately timed AV synchrony for optimal diastolic filling of the ventricle. Diastolic mitral and tricuspid regurgitation is a common finding when AV synchrony is lost, such as during ventricular-only pacing (e.g. VVI) or in the presence of AV conduction abnormalities (Figure 3.15). Significant elevation of LV end-diastolic filling pressures will contribute to worsening of diastolic MR during AV dyssynchrony.

In most pacemaker patients, however, worsening of AV regurgitation appears to play a lesser role in elevating atrial pressure than does the contraction of the atria against closed AV valves during ventricular pacing. Furthermore, in the absence of ventricular dysfunction or structural heart disease, diastolic MR during AV desynchronization is usually a benign phenomenon without significant therapeutic clinical implications. Using transesophageal Doppler echocardiography, significant MR was found during VVI pacing with VA conduction in only 8% of a group of patients without clinical pacemaker syndrome.

Blood pressure

For grouped patient data, AV synchrony generally provides similar or slightly greater systolic and mean blood pressures than ventricular pacing. A typical example of the blood pressure comparison among atrial, AV, and ventricular pacing is shown in Figure 3.16. In this case, essentially no differences exist between the blood pressures when comparing atrial with AV pacing. The blood pressure during ventricular pacing is slightly lower than during either atrial or AV pacing.

Although not the typical response, some individuals do have dramatic and symptomatic decreases in systemic blood pressure when ventricular pacing is instituted (Figure 3.17). Several mechanisms may be responsible for this phenomenon. Loss of LV preload volume from mistimed atrial contraction (loss of atrial "kick") and activation of inhibitory cardiac reflexes (due also to inappropriately timed atrial contraction) have been the mechanisms most commonly implicated. This marked hypotension can produce dramatic symptoms, including syncope. In a clinical setting, if this problem is suspected but hypotension with symptoms cannot be reproduced in a supine position, an upright or semi-upright posture may unmask the problem, especially if it is related to a LV preload deficiency caused by loss of atrial contribution to ventricular filling. An important consideration in the hemodynamic response to ventricular pacing is VA conduction. VA conduction, the ability to conduct electrical impulses retrograde from the ventricles through the AV junction to the atria, can lead to atrial contraction during ventricular systole or, in cases of long VA conduction, early diastole. This can cause loss of the atrial contribution to ventricular filling as well as other hemodynamic

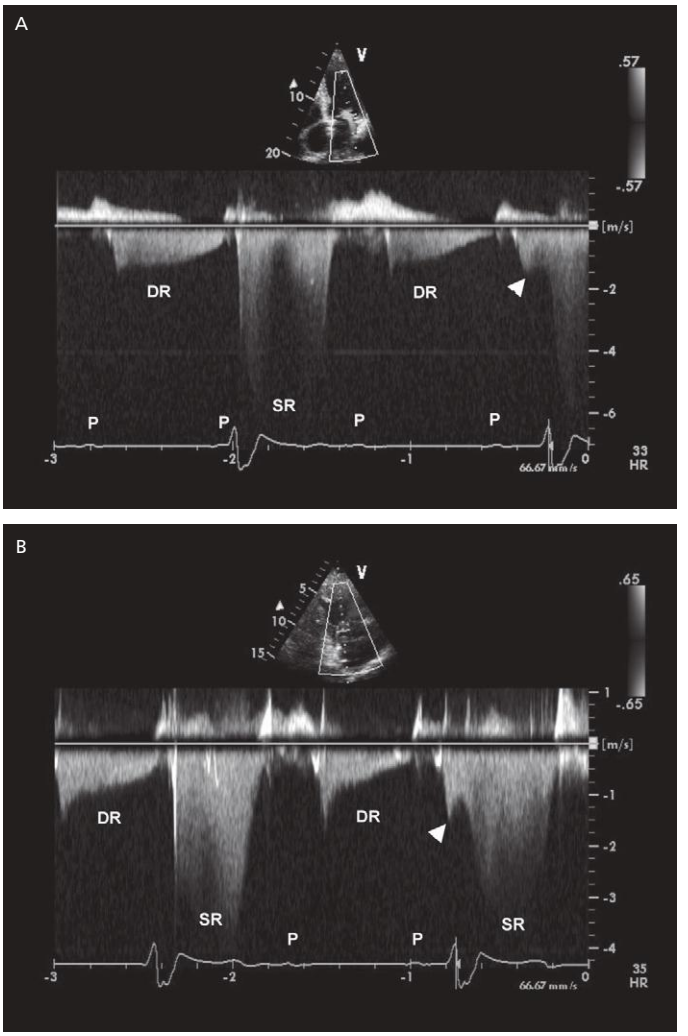


Figure 3.15 Mitral valve (A) and tricuspid valve (B) continuous-wave Doppler recordings from an apical transducer position obtained in an 80-year-old male with complete atrioventricular (AV) block. There is a ventricular escape rhythm at 33–35 bpm (QRS complexes). Note the diastolic AV valve regurgitation that occurs when the P wave is not followed by an appropriately timed ventricular contraction. Also note that diastolic AV regurgitation is reduced (arrowhead) when the ventricular contraction (QRS complex at the right side of each image) happens by chance to fall at an appropriate interval after the P wave (simulating a more synchronized AV relationship). DR, diastolic regurgitation; P, P wave; SR, systolic regurgitation.

problems. VA conduction has been found in as many as 90% of patients with sick sinus syndrome and in 15–35% of individuals with a variety of degrees of AV block. During ventricular pacing, even when VA conduction is not intact, if the ventricular pacing rate is unequal to the atrial rate, there will be periods of time when atrial contraction occurs during ventricular systole with the resulting disadvantageous hemodynamics.

Cardiac output

Properly timed atrial contraction provides a significant increase in ventricular end-diastolic volume and is responsible for the so-called atrial kick (Figure 3.18). Studies have shown a wide range in the actual importance of the atrial contribution to ventricular filling depending on the patient population and study conditions. By increasing the end-diastolic volumes (right and left ventricles),

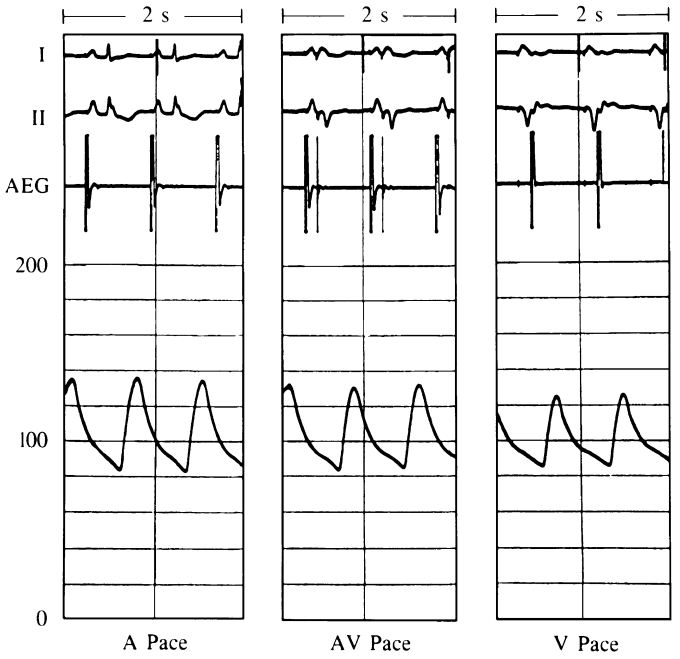


Figure 3.16 Femoral artery pressure recordings from one patient. Left to right: during atrial pacing (A Pace); during atrioventricular (AV) sequential pacing (AV Pace); and during ventricular pacing (V Pace). All tracings are at 80 ppm with an AV interval of 150 ms during AV pacing. Scale in mmHg. I, II, and III, standard ECG leads; AEG, atrial electrogram.

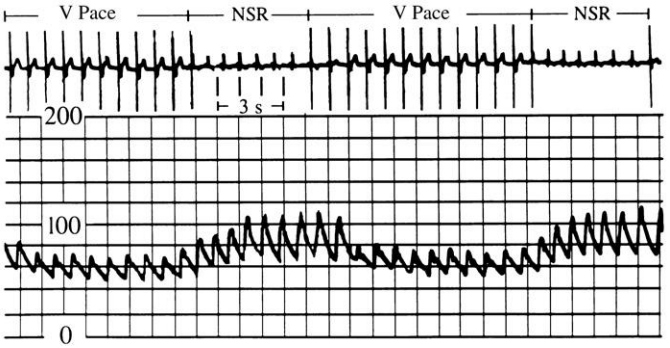


Figure 3.17 Radial artery pressure recording from a patient during right ventricular pacing (V Pace) at 80 ppm and normal sinus rhythm (NSR) (scale in mmHg). This patient's blood pressure, measured by radial artery line, drops from approximately 110/70 mmHg during sinus rhythm to approximately 75/55 mmHg during ventricular pacing.

the cardiac output is, in turn, increased. The average increase in cardiac output in a pacing population, if AV synchrony is maintained, is between 15% and 25% in comparison with non–AV-synchronized ventricular pacing. In a recent study in pediatric patients with congenital complete AV block and normal ventricular function, cardiac output was measured using a noninvasive method involving inert gas rebreathing and was shown to be 18% higher in synchronous AV pacing with optimized AV intervals than during VVIR pacing.[22]

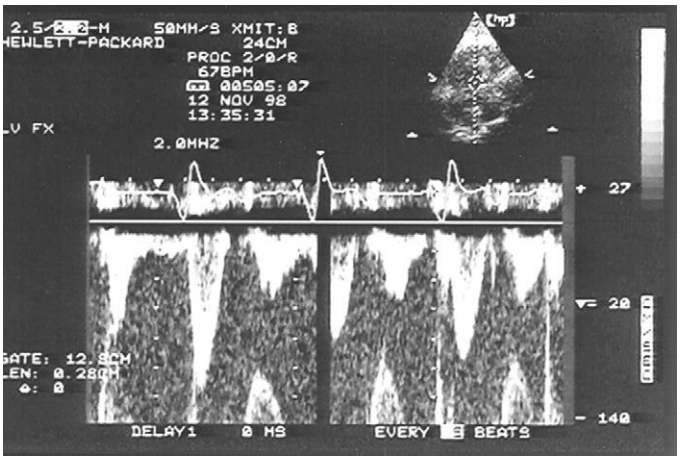


Figure 3.18 Doppler echocardiographic evaluation of the velocity time integral in the left ventricular outflow tract obtained from a patient with a VVI pacemaker originally implanted for complete heart block. The sinus mechanism was intact and the patient had palpitations and symptoms consistent with a low cardiac output. There is marked beat-to-beat fluctuation in the stroke volume in accord with waxing and waning co-incidental atrioventricular (AV) synchrony, clearly demonstrating a benefit of restoring AV synchrony and providing justification for replacement of an otherwise normally functioning VVI pacemaker with a more appropriate dual chamber system. (Source: Courtesy of Paul A. Levine, MD.)

The hemodynamic benefits of AV-synchronized versus ventricular pacing also have been demonstrated for patients after myocardial infarction and cardiac surgery. Patients with reduced cardiac output—especially if such reduced function is due to relative volume depletion or only mild-to-moderately depressed LV function—frequently benefit significantly from maintenance of AV synchrony. In a group of patients with severe LV systolic dysfunction (mean LV ejection fraction, 0.21 ± 0.07) and New York Heart Association (NYHA) class II–IV heart failure, there were significant reductions in cardiac index (~12%) with single chamber VVI pacing compared with pacing modes that maintained AV synchrony (AAI or DDD with ventricular pacing from the RV apex or outflow tract)[23] (Figure 3.19).

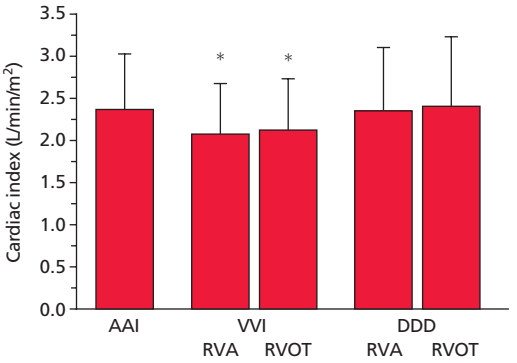


Figure 3.19 Effect of pacing site and mode on cardiac index. Measurements during pacing at a fixed rate were compared in each patient. Pacing was performed in AAI, VVI, and DDD modes from the right ventricular apex (RVA) or outflow tract (RVOT). Means ± SD are shown. *$P < 0.05$ vs. AAI. (Source: Gold MR *et al.* 2000.[90] Reproduced with permission of Elsevier.)

There is a general perception that patients with abnormal cardiac function benefit most from maintenance of AV synchrony. This may be true, but the reasons are frequently not due to better cardiac output. In fact, if cardiac output were the only hemodynamic consideration, it is patients with very poor ventricular function (markedly increased end-diastolic volume and depressed ejection fraction) that benefit least from AV synchrony. This can be best understood by using the concept of ventricular function curves that compare stroke volume or cardiac output with LV end-diastolic volume or preload.

Figure 3.20 shows hypothetical ventricular function curves for a patient with normal ventricular

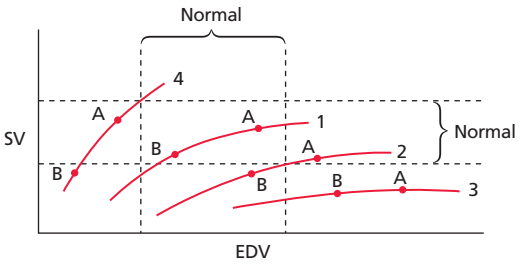


Figure 3.20 Hypothetical ventricular function curves comparing (1) stroke volume (SV) and left ventricular end-diastolic volume (EDV) in patients with normal ventricular function; (2) moderately depressed ventricular function; (3) severely depressed ventricular function; and (4) hyperdynamic ventricular function. Point A = with normal atrioventricular (AV) sequence. Point B = without normal AV sequence.

function (curve 1), one with moderate LV dysfunction (curve 2), one with very poor LV function and a markedly dilated ventricle (curve 3), and one with hypertrophic cardiomyopathy (curve 4). These curves describe the performance of the LV in generating stroke volume (or cardiac output) in relation to the end-diastolic volume (or preload). In patients with normal LV function (curve 1), as end-diastolic volume increases, stroke volume (and cardiac output) increases until the flat or descending portion of the curve is reached. In patients with depressed LV function (curves 2 and 3), there is a lesser increase in stroke volume that depends on end-diastolic volume to the point that, in patients with poor LV function (curve 3), there is negligible improvement in stroke volume with further increases in end-diastolic volume. On the other hand, patients with hypertrophic or hypertensive cardiomyopathy tend to have small ventricles that are normal (i.e. normal systolic function) or hyperdynamic in function (curve 4). Small increases in end-diastolic volume can significantly increase stroke volume in this situation. As has been discussed, AV synchrony provides the atrial kick that increases end-diastolic volume. Point A on these curves represents the hypothetical stroke volume and end-diastolic volume during AV pacing. Point B represents stroke volume and end-diastolic volume during ventricular pacing (with associated loss of atrial kick). In the normal situation (curve 1), although end-diastolic volume is greater and hence stroke volume is greater during AV-synchronized pacing, the loss of AV synchrony during ventricular pacing does not drop the end-diastolic volume and the stroke volume significantly. This, however, might not be the case if the filling volume were otherwise reduced by volume depletion due to blood loss, diuresis, and so on. In these situations, even with normal LV function, the higher end-diastolic volumes and stroke volumes provided by properly timed atrial contraction might be important. With depressed LV function of a moderate degree (curve 2), although maintenance of AV synchrony provides for a greater end-diastolic volume, the stroke volume advantage is diminished. It is possible that, due to overall reduction in stroke volume (and cardiac output), even this modest increment in stroke volume would be of important benefit. In patients with more severely depressed LV function and extremely flat LV function curves (curve 3), end-diastolic volume can be augmented with maintenance of AV synchrony, but there is little advantage in stroke volume.

With regard to patients with hypertrophic cardiomyopathy or highly non-compliant ventricles (curve 4), maintenance of AV synchrony may be very important in enhancing stroke volume and cardiac output because of the relatively small end-diastolic volumes. This is because small increments in end-diastolic volume may substantially increase the stroke volume due to the steep slope of the curve. This relatively steep-sloped ventricular function curve is also characteristic of patients with ventricular diastolic dysfunction, a group for whom maintenance of AV synchrony also is very important. Figure 3.21 displays this concept in a group of patients studied using quantitative nuclear techniques.[24] Although only data from the supine position at 80 ppm are shown (AV interval 150 ms during AV-synchronized pacing), the same situation hemodynamically was found to be present at a faster pacing rate (100 ppm) and in an upright posture.

The conceptual approach of ventricular function curves is useful for practical understanding of the benefits of AV synchrony. However, movement along single ventricular function curves probably is overly simplistic. A number of variables that can affect hemodynamic function, such as afterload, can be modulated by other factors that might cause

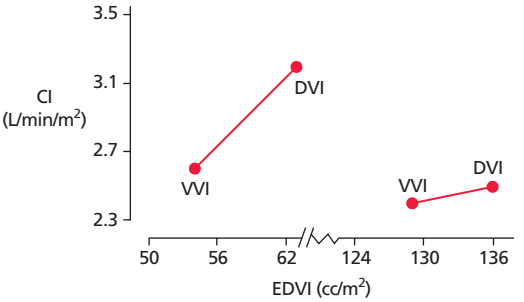


Figure 3.21 Ventricular function curves comparing cardiac index (CI) and left ventricular end-diastolic volume index (EDVI) from (left) a group of nine patients with relatively normal ventricular function and (right) a group of four patients with markedly depressed ventricular function. The patients were studied in the supine position at a pacing rate of 80 ppm and atrioventricular (AV) interval during DVI pacing of 150 ms. Points are group mean. DVI, AV sequential pacing (AV synchrony); VVI, ventricular pacing (no AV synchrony).

shifting from one curve to another, as well as movement along a given curve. In this regard, systemic vascular resistance may be significantly higher during ventricular pacing. The increase in systemic vascular resistance is related mechanistically to an increase in neural reflexes. These autonomic responses to ventricular pacing include increased peripheral sympathetic nerve tone and circulating catecholamine levels supportive of blood pressure when cardiac output is diminished.

A hemodynamic variable that is usually not significantly affected in most individuals during AV versus ventricular pacing is ejection fraction. Although the components of ejection fraction—both end-diastolic volume and stroke volume—are significantly lower during ventricular pacing, ejection fraction is unaffected because both the numerator (stroke volume) and the denominator (end-diastolic volume) of the ejection fraction vary in the same proportion. Ejection fraction is a crude measurement of contractile performance, so it is not surprising that the presence or absence of AV synchrony, which primarily affects preload and cardiac output, has no effect on ejection fraction.

Autonomic neural and neurohormone level alterations

Single chamber RV pacing is associated with higher levels of sympathetic nerve activity, cardiac norepinephrine spill over, and plasma epinephrine and norepinephrine levels than AV synchronous pacing.[25] Catecholamine levels increase most during VVI pacing with retrograde conduction. The enhanced sympathetic outflow appears to be mediated by the arterial and cardiopulmonary baroreflexes.

Plasma levels of natriuretic peptides, including atrial and brain natriuretic peptides (ANP and BNP, respectively), appear to reflect the presence of appropriate AV synchrony and the hemodynamic changes produced by different cardiac pacing modes. A number of studies have demonstrated that RV pacing without AV synchrony (VVI) is associated with higher levels of plasma ANP and BNP, when compared with pacing modes with AV synchrony (AAI or DDD).[26] Increased natriuretic peptide levels develop within several minutes after AV synchrony is lost, both at rest and during exercise. These hormonal alterations persist over the long term, but return toward normal after AV synchrony is restored. The release of these hormones occurs in response to worsened cardiac hemodynamics, reflecting atrial distension, higher atrial pressures, and increased LV filling pressures with AV desynchronization. Low levels of natriuretic peptides might be used as a cardiac biomarker reflective of the presence of a physiological pacing mode.

Mortality and cardiovascular outcomes

At least five prospective randomized trials have compared AV synchronous pacing modes (AAI or DDD with or without rate response) with the ventricular-only pacing mode (VVI) on mortality and important cardiovascular outcomes in patients with bradycardia indications for permanent pacemaker implantation[27–31] (Table 3.1). A meta-analysis has summarized the results of these five trials in over 7000 patients.[32] The major conclusions of this systematic review of these important clinical trials in the field of cardiac pacing were that (1) atrial-based pacing does not reduce all-cause mortality, cardiovascular death, or heart failure; (2) atrial-based pacing does reduce the incidence of AF [hazard ratio (HR) 0.80; 95% confidence interval (CI) 0.72–0.89; $P = 0.00003$); (3) atrial-based pacing is associated with a reduction of borderline significance in stroke (HR 0.81; 95% CI 0.67–0.99;

Table 3.1 Randomized controlled trials of pacemaker mode selection

Trial	*Date*	*No. of patients*	*Average F/U (years)*	*Indication*	*Pacing modes*	*Mean age (years)*	*Primary end-point*	*Summary of results; P value (hazard ratio; 95% CI)*	*Mortality (%/year)*	*AF (%/year)*	*Thromboembolism (%/year)*
Danish[27]	1994	225	5.5	Sinus node dysfunction	AAI vs. VVI	76	Mortality, AF, thromboembolism	Mortality: 0.045 (0.66; 0.44–0.99) AF: 0.012 (0.54; 0.33–0.89) Thromboembolism: 0.023 (0.47; 0.24–0.92)	5.8 vs. 6.8	4.1 vs. 7.1	1.7 vs. 5.4
PASE[28]	1998	407	1.5	All pacemaker patients ≥65 years old	DDDR vs. VVIR	76	Quality of life	No overall group differences between pacing modes	10.7 vs. 11.3	11.3 vs. 12.7	1.3 vs. 2.3
CTOPP[29]	2000	2568	6.0	All pacemaker patients	DDD/ DDDR or AAI/AAIR vs. VVI/ VVIR	73	Cardiovascular death or stroke	0.26 (0.91; 0.78–1.05); (AF less frequent in atrial-based group)	6.3 vs. 6.6	5.3 vs. 6.6	1.0 vs. 1.1
MOST[30]	2002	2010	4.5	Sinus node dysfunction	DDDR vs. VVIR	74	Death or non-fatal stroke	0.40 (0.97; 0.80–1.18); (AF and heart failure reduced in DDDR)	7.0 vs. 7.3	7.9 vs. 10.0	1.4 vs. 1.8
UKPACE[31]	2005	2021	4.6	AV block ≥70 years old	DDD vs. VVI/VVIR	80	Death	0.56 (0.96; 0.83–1.11)	7.4 vs. 7.2	2.8 vs. 3.0	1.7 vs. 2.1

AAI, atrial pacing; AAIR, atrial pacing with rate adaptation; AF, atrial fibrillation; AV, atrioventricular; Date, date of study publication; DDD, dual chamber pacing; DDDR, dual chamber pacing with rate adaptation; F/U, follow-up; VVI, ventricular pacing; VVIR, ventricular pacing with rate adaptation.

Sources: The annual incidences of death, atrial fibrillation, and thromboembolism were obtained from the primary publications along with reference 22 and Nielsen JC. Pacing mode selection in patients with sick sinus syndrome. *Dan Med Bull* 2007; 54: 1–17.

$P = 0.035$); and (4) no patient subgroups derived a special benefit from atrial-based pacing. Aside from these conclusions, there is evidence derived from the clinical trials that dual chamber devices modestly improve quality of life and are less likely to be associated with pacemaker syndrome.[33] Thus, most clinicians believe that the clinical evidence is sufficient to justify routine use of pacing modes that provide AV synchrony. Consistent with this clinical practice, the 2012 HRS/ACCF Expert Consensus Statement on Pacemaker Device and Mode Selection give AV synchronous pacing modes a class I recommendation in patients with sinus node dysfunction (DDD or AAI) or AV conduction block (DDD).[34]

Effects of optimal atrioventricular interval timing

The mere presence of a consistent AV relationship may not ensure the best possible hemodynamics or clinical outcomes in a patient with a cardiac pacemaker. The potential contribution of a correctly timed AV delay to cardiac output varies from 13% to 40%.[35] Some have suggested that when the AV delay is selected empirically, it is programmed incorrectly in approximately two-thirds of patients.[36] Some AV timing relationships clearly are detrimental such as during 1:1 VA conduction or with inappropriately short or long AV delays. An excessively short AV delay may limit active filling of the ventricle and promote systolic AV valvular regurgitation as ventricular contraction begins while the AV valves are open. An excessively long AV delay may result in loss of the booster pump function of the atria related to two factors: (1) inadequate diastolic filling of the ventricle because atrial contraction does not occur near the onset of LV systolic contraction but rather is superimposed on early passive filling; and (2) diastolic AV valvular regurgitation due to reopening of the valve before ventricular systole.

An optimally timed AV interval maximizes LV filling and stroke volume by the Frank–Starling mechanism. Atrial contraction should occur optimally just before the isovolumic contraction phase. This was well demonstrated in an acute experimental model in canines with complete AV block in which net LV chamber filling was measured with a mitral annular flow probe while the AV timing delay was varied.[37] Increasing AV delay from 0 (simultaneous AV contraction) to a more physiological range (e.g. around 80–120 ms) enhanced net chamber filling. In the physiological range of AV intervals, atrial systole is completed and the mitral valve closes as LV pressure begins to rise. At long AV delays (e.g. >275 ms), net filling declines, and at very long delays (e.g. 320 ms), net filling actually falls below that observed at no AV delay. At long AV delays, atrial systole is superimposed with early rapid filling, mitral valve closure is dependent on LV pressure rise, which generates presystolic regurgitation, and net LV filling declines.

In patients at rest with normal ventricular function, the optimal range for the AV interval when the RA and ventricle are paced is on average between 150 and 200 ms (Figure 3.22). This interval however may vary considerably from patient to patient and from time to time in a specific patient (i.e. as short as 100 ms and up to 250 ms). For the reasons noted below, the optimal AV interval when the atrium is sensed will be 20–50 ms shorter than when the RA is paced.

Interindividual variation in the optimal AV interval depends on the degree of interatrial and interventricular conduction delays that occur in response to DDD pacing. In conventional right heart pacing systems, the activation sequence of the left-sided chambers may be quite different from the pacemaker programmed values in situations where marked interatrial and interventricular conduction delays develop in response to pacing or are present intrinsically. Optimal LV contraction should start immediately at the end of LA transport. However, delays introduced by sensing and pacing of right heart chambers may cause misalignment between electrical and mechanical events, especially of the left heart chambers. Optimal AV pacing may need to account for and correct for these delays introduced by pacing with an appropriately timed, AV pacing interval. Such a "physiological" AV interval compensates for pacing- and sensing-induced delays, and assures that LA transport is completed just before LV contraction starts.

For example, RA pacing (especially from the RA appendage or lateral RA wall) prolongs the duration of the P wave and consequently the time from the P wave onset to the end of LA transport, or the

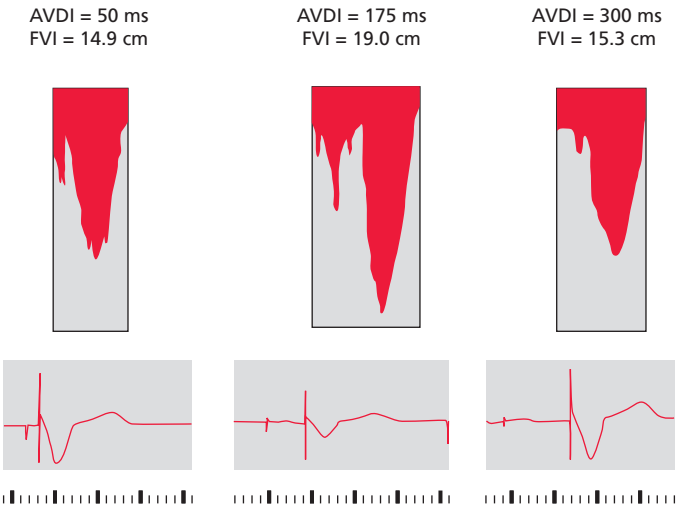


Figure 3.22 Doppler aortic flow velocity integrals (FVI) recorded at varying atrioventricular (AV) pacing intervals. Note the maximal aortic flow velocity at an AV interval (AVI) of 175 ms. (Source: Janosik DL, Pearson AC, Buckingham TA *et al.* The hemodynamic benefit of differential atrioventricular delay intervals for sensed and paced atrial events during physiologic pacing. *J Am Coll Cardiol* 1989; 14: 499–507. Reproduced with permission of Elsevier.)

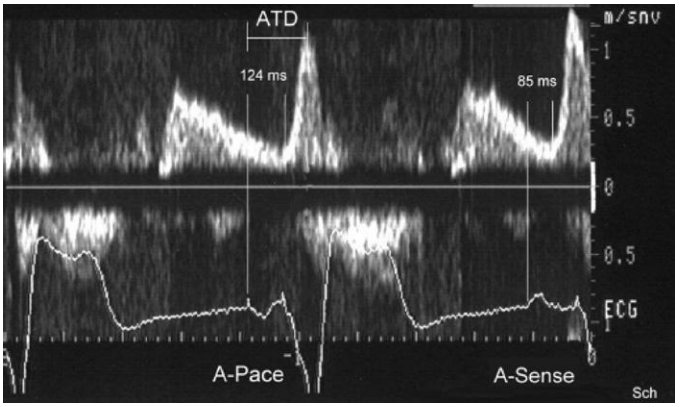


Figure 3.23 Atrial transport delay (ATD) is prolonged during atrial pacing compared with atrial sensing. Atrial-paced and -sensed ATD are shown. ATD is the time from the onset of P to the peak of the mitral Doppler A wave, a surrogate of the end of active atrial transport. On the first beat (atrial-paced beat) the time from the pacing pulse to the peak of the mitral Doppler A wave is the paced ATD. On the second beat (atrial-sensed beat) the time from the onset of the P wave to the peak of the A wave is the sensed ATD. (Source: Chirife R *et al.* 2008.[46] Reproduced with permission of John Wiley & Sons Ltd.)

atrial transport delay (ATD) (Figure 3.23). Likewise, RV pacing, especially when performed from the RV apex, alters the onset of LV systole and prolongs the interventricular delay (Figure 3.24). In addition to artificial pacing and sensing delays, in patients with underlying, high-grade, interatrial conduction delay in the presence of atrial disease, long AV intervals (250–350 ms) sometimes may be required to provide effective LA systole. Programming a short or "physiological" AV delay in such patients may result in a LA that is activated late, producing LA contraction against a closed mitral valve. In patients with interatrial delay or block, consideration may also be given to pacing from

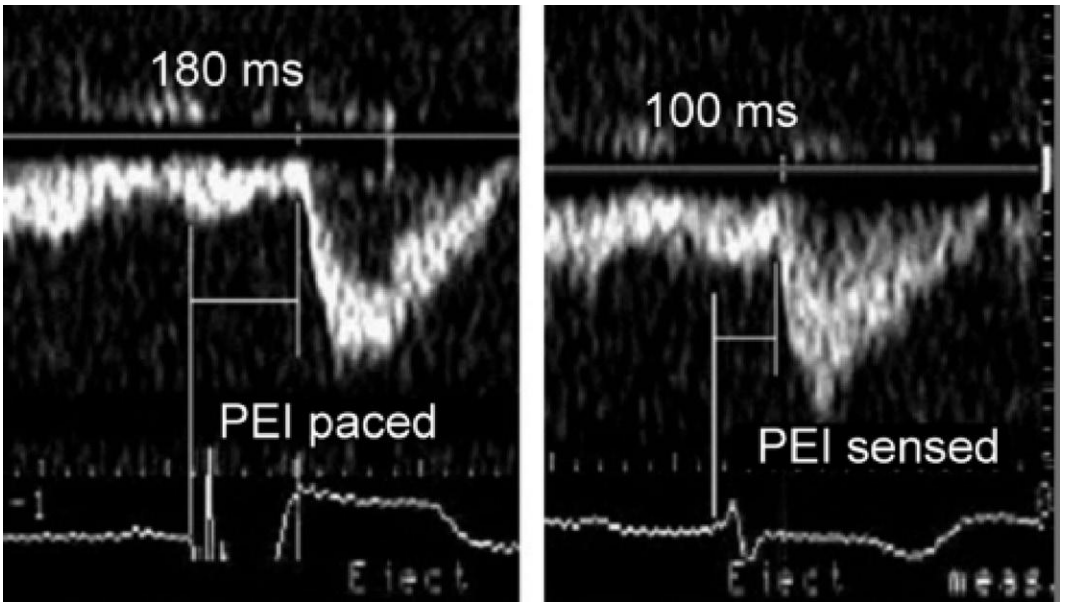


Figure 3.24 Right ventricular (RV) pacing delays left ventricular activation compared with sensed ventricular beats. The RV pacing-induced interventricular delay (IVD) can be assessed as shown here by calculating the difference between RV-paced and RV-sensed left pre-ejection intervals (PEIs). The extent of lengthening of PEI by RV pacing is proportional to IVD. In this example, IVD = 180 − 100 = 80 ms. (Source: Chirife R *et al.* 2008.[46] Reproduced with permission of John Wiley & Sons Ltd.)

the RA septum (Bachmann's bundle), coronary sinus, or biatrially to advance left electrical atrial activation.

Manipulation of the AV delay using dual chamber pacing devices as a primary therapeutic modality in patients with dilated cardiomyopathy was a focus in the field of cardiac pacing prior to the demonstration of the benefits of biventricular pacing in heart failure. Several small studies evaluated the impact of dual chamber pacing with optimal AV delay on hemodynamic and clinical parameters in patients with heart failure and significant MR.[38–40] However, conflicting results were published in this regard. In an early study, Brecker *et al.* studied the effects of dual chamber pacing in patients with dilated cardiomyopathy and prolonged AV delay.[41] Shortening the AV delay by institution of AV synchronous pacing with leads in the RA and RV apex reduced diastolic regurgitation and enhanced diastolic filling. In a randomized trial, 38 patients in sinus rhythm with heart failure were randomly assigned to optimal medical therapy or optimal medical therapy with dual chamber pacing.[40] AV delay was optimized according to echocardiographic parameters and generally ranged between 100 and 120 ms (in 14 of 19 patients). There was no difference between the two arms in most clinical end-points, although the degree of MR and systolic LV diameter were both reduced in patients assigned to dual chamber pacing. Several additional studies have reported that optimizing AV delay may produce hemodynamic improvement in patients with heart failure; however, the benefits were often quite modest and not consistently demonstrated.[42,43]

The approach of shortening the AV interval during RV pacing in patients with heart failure remains controversial and cannot be advocated. The major benefit of this approach may be confined to the subset of individuals with prolonged PR intervals and diastolic MR. Appropriate patients for dual chamber pacing with short AV intervals may be those with symptomatic heart failure in sinus rhythm with a long PR interval, prolonged functional diastolic MR ($\geq$450 ms in duration), and a short ventricular filling time ($<$200 ms at rest). Furthermore, in the setting of marked first-degree AV block (PR interval $>$300 ms), a

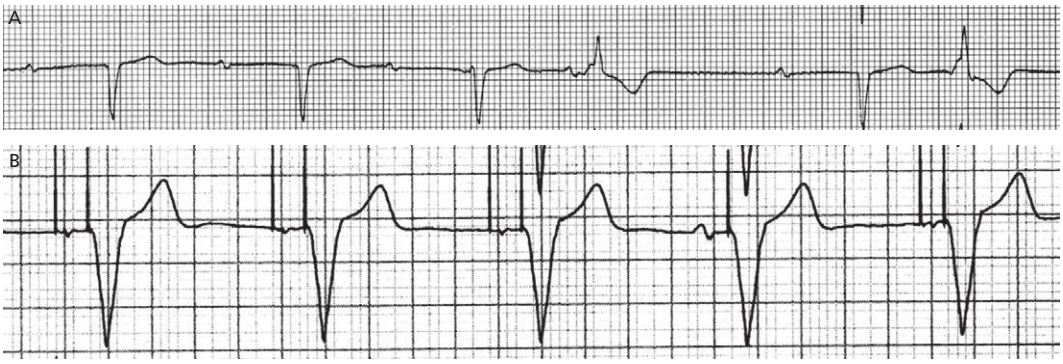


Figure 3.25 ECG tracings from a 74-year-old male with complaints of fatigue and exercise intolerance without syncope or dizziness. (A) Marked first-degree atrioventricular (AV) block is present (PR interval >500 ms) with a normal QRS duration and premature ventricular contractions (PVCs). The Holter monitor from this patient demonstrated first-degree, second-degree (type I), and 2:1 AV block with heart rates from 36 to 150 bpm. The longest pause was 2.7 s. There were also very frequent PVCs (>9000 in 24 h). (B) DDD rhythm with appropriate AV intervals (150/120 ms). Following dual chamber pacemaker implantation, the patient noted a marked improvement in his symptoms and functional capacity, with more energy and overall improved quality of life.

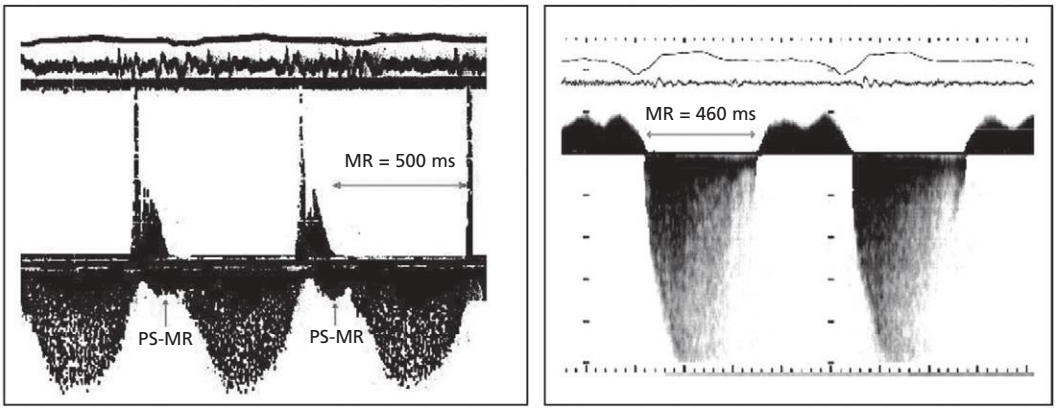


Figure 3.26 Continuous-wave Doppler recordings show mitral regurgitation (MR) in a patient with dilated cardiomyopathy and prolonged PR interval, before and after DDD pacing with AV delay optimization. Left: MR is of long duration (500 ms) during native conduction with a distinct pre-systolic component (PS-MR), impinging into and abbreviating the left ventricular (LV) filling time. Right: Shortening the AV delay to 100 ms with DDD pacing eliminates PS-MR, shortens the total MR duration, and increases the LV filling time. (Source: Salukhe TV, Henein MY, Sutton R 2003.[21] Reproduced with permission of Oxford University Press.)

pacemaker-like syndrome can occur in the absence of a pacemaker (sometimes referred to as "pseudopacemaker syndrome") (Figure 3.25).[44] In these cases, atrial systole effectively occurs during or immediately after ventricular systole, resulting in loss of effective AV synchrony. In patients with marked first-degree AV block, dual chamber (RA and RV) pacing at a short AV interval may improve hemodynamics by optimization of atrial and ventricular synchrony and elimination of diastolic MR.[21] Elimination or reduction of diastolic regurgitation can result in lengthening of the diastolic LV filling time and augmentation of stroke volume and cardiac output (Figure 3.26).

Determination of optimal atrioventricular interval

A variety of invasive and non-invasive techniques have been used to determine the optimal AV interval in pacemaker patients. Doppler echocardiography is often used in clinical trials and has become an accepted method that can be beneficial in determining the optimal AV delay for an individual patient. This approach can analyze diastolic transmitral Doppler flow velocity (e and a waves), stroke volume assessed by aortic velocity time integral (VTI), and AV valve regurgitation for optimization of AV intervals. The Ritter method of AV interval optimization, which uses the mitral valve inflow Doppler profile, is the most widely applied technique. This technique is based on the assumption that the AV delay that maximizes cardiac output is the one that provides the longest LV filling time without interruption of the A wave (atrial contraction wave) and allows ventricular systole to begin immediately subsequent to maximum diastolic ventricular filling, thus avoiding cannon A waves and diastolic MR (Figure 3.27). The goal of AV optimization is to align the end of LA transport with the onset of LV contraction. In the Ritter method, a short AV interval (AV_{short}) is programmed in which there is clear A wave truncation on the Doppler mitral inflow assessment. The interval from the QRS onset to the completion of the A wave (QA_{short}) is then measured. Next, a long AV delay (AV_{long}) without A wave truncation is programmed and the interval from the QRS onset to the completion of the A wave (QA_{long}) is again measured. The optimal AV delay is defined as: $AV_{opt} = AV_{long} - (QA_{short} - QA_{long})$. An alternative to the Ritter method that uses Doppler echocardiography is the iterative method, which is designed to maximize diastolic filling time by measuring the shortest AV interval that does not result in A wave attenuation.

Due to the cost, inconvenience, and time required to perform a Doppler echocardiography study, simpler alternatives that use surface electrocardiography (ECG) alone to optimize the AV interval in an individual patient have been proposed and investigated. While ECG-based approaches for AV optimization are of interest, they have not been widely adopted.

One of the surface ECG approaches defines the optimal AV delay based on an arbitrary delay of 100 ms from the end of the surface P wave to the peak/nadir of the paced ventricular complex (Figure 3.28).[45] The end of the surface P wave represents the end of LA activation, whereas the peak/nadir of the paced ventricular complex coincides with the onset of the isovolumetric contraction

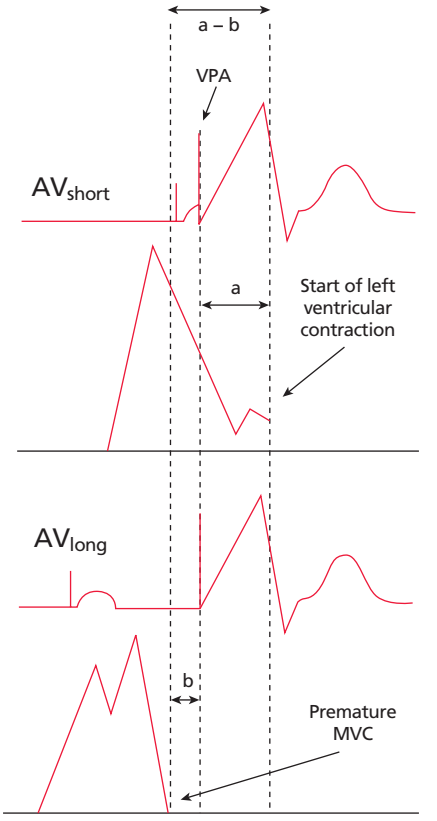


Figure 3.27 Doppler technique for optimizing the atrioventricular (AV) interval. The surface ECG and Doppler mitral inflow pattern are depicted schematically for a very short AV interval (e.g. 50 ms; top) and a very long AV interval (e.g. 250 ms; bottom). Interval a represents the longest time between the ventricular pacing artifact (VPA) and the mitral valve closure (MVC) for the short AV interval. Interval b represents the time between ventricular pacing and mitral valve closure during the long AV interval, and may be a negative value due to diastolic regurgitation. The optimal AV delay is calculated as the long AV delay minus the difference between intervals a and b. (Source: Adapted from Kinderman M *et al.* Optimizing the AV delay in DDD pacemaker patients with high degree AV block: mitral valve Doppler versus impedance cardiography. *PACE* 1997; 20: 2453–62. Reproduced with permission of John Wiley & Sons Ltd.)

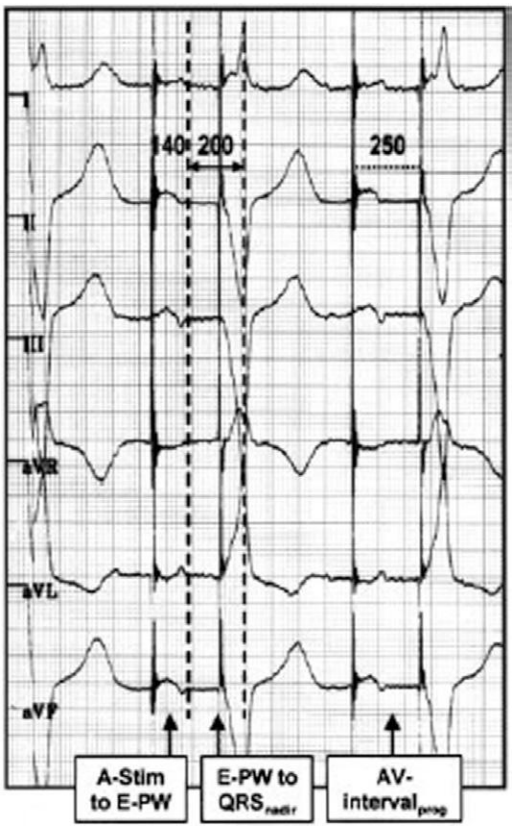


Figure 3.28 Determination of optimal paced atrioventricular (AV) delay (AVD_{opt}) by surface ECG. First, a long AV delay of 250 ms was programmed (AVD_{prog}, programmed interval from atrial to ventricular stimulus). The interval from the end of the P wave to the peak/nadir of the paced ventricular complex (T) was 200 ms. The interval from the atrial stimulus to the end of the P wave (the global atrial conduction time) was 140 ms. According to the algorithm, $AVD_{opt} = AVD_{prog} + 100 - T$, the optimized AV delay was 150 ms. A-Stim to E-PW, interval between the pacing stimulus and the end of P wave deflection; AV-$interval_{prog}$, long AV delay programmed for testing; E-PW to QRS_{nadir}, end of P wave (E-PW) to peak/nadir of paced QRS. (Source: Strohmer B *et al.* 2004.[45] Reproduced with permission of John Wiley & Sons Ltd.)

period. The AV delay is considered optimal when the end of LA contraction (A wave) coincides with complete mitral valve closure and the onset of the isovolumetric contraction period.

Another ECG-based AV optimization approach uses measurements of P wave and QRS durations to predict interatrial and interventricular electromechanical delays, and calculates the optimal AV interval based on validated regression equations that derive electromechanical timing delays obtained by Doppler echocardiography.[46] This approach is based on the premise that the optimal AV is defined by the LA transport delay (ATD)—the interventricular delay (IVD)—the P sense offset (in the case of atrial sensing). The ATD is predicted from measurement of sensed or paced P wave duration, interventricular delay from paced QRS duration, and P sense offset is 30 ms by default or the time from P onset to P detection using the surface ECG and pacemaker marker channels. Estimates of ATD and IVD obtained from Doppler echocardiography then can be calculated from validated regression equations using the ECG measurements of P wave and QRS durations or from tables provided by these investigators and plugged into the proposed optimal AV interval formula (Table 3.2). For example, if measured atrial-paced P wave duration is 140 ms, the investigators indicate that the expected ATD is 190 ms and if paced QRS duration is 180 ms, expected IVD is 62 ms. Thus, for RA pacing/RV pacing, optimal AV delay = 190 − 62 = 128 ms.

A highly simplified ECG approach for AV optimization that only uses the surface P wave (a measure of interatrial conduction time) also has been proposed.[47] In this small study, the P wave duration correlated to the optimal AV delay as calculated by the Ritter method by a factor of 1.26. Based on these data, the authors suggested that by adding one-fourth of the P wave duration to its baseline measurement, the optimal AV delay during AV pacing can be approximately determined.

Although leaving a device at the nominal AV interval settings may not ensure optimal cardiac hemodynamics, clinical outcomes data on the role of AV optimization have not been definitive. A strategy of AV optimization programming is yet to be implemented or accepted on a wide-scale basis. No consensus exists regarding which patients should undergo AV optimization or when this process should be performed. Much of the evidence regarding AV optimization for pacing derives from small, single-center, acute, nonrandomized trials, many of which lack a control group. Gold *et al.* performed a prospective, acute hemodynamic study of 28 patients comparing the

Table 3.2 Determination of optimal atrioventricular (AV) delays using the atrial transport delay (ATD) and interventricular delay (IVD) derived from the P wave and QRS duration ECG measurements. From this table, it is possible to estimate the duration of right atrial (RA)-paced ATD and right ventricular (RV)-paced IVD from the corresponding P or QRS duration column in the table. Once ATD and IVD are found, calculation of the optimal AV follows from ATD—IVD. For example, as shown in this table, if measured RA-paced P wave duration is 140 ms, expected ATD is 190 ms. If RV-paced QRS duration is 140 ms, expected IVD is 47 ms. Thus, during RA and RV pacing, optimal AV delay = 190 − 47 = 143 ms. In the case of atrial-sensed pacemaker timing cycles with RV pacing, optimal AV delay can be determined by subtracting the P-sensed offset (PSO; i.e. the time from surface P onset to P detection). The value of PSO can be either default (30 ms) or measured from the ECG and pacemaker marker channels. So, in this example, the optimal AV delay during RA sensing and RV pacing is 143 − 30 ms = 113 ms. (Source: Chirife R *et al.* 2008.[46] Reproduced with permission of John Wiley & Sons Ltd.)

P or QRS duration (ms)	*ATD (ms)*	*IVD (ms)*
80	132	23
90	142	27
100	152	31
110	161	35
120	171	39
130	181	43
140	190	47
150	200	51
160	210	55
170	219	59
180	229	62
190	238	66
200	248	70
210	258	74
220	267	78
230	277	82
240	287	86
250	296	90

optimal AV delay during CRT determined by invasively measured LV d*P*/d*t* to several non-invasive methods, including a fixed AV delay, the Ritter method, aortic outflow velocity–time integral (VTI), and intracardiac electrogram-based calculations.[48] The intracardiac electrogram-based method best predicted the optimal AV delay associated with the maximal acute hemodynamic response. By contrast, the Ritter method was least accurate. Likewise, in a prior study of 30 patients with cardiomyopathy, the Ritter method had the worst correlation compared to invasively measured LV d*P*/d*t* in predicting the optimal AV delay.[49] The best performing Doppler echocardiographic measurement was mitral inflow VTI, which seemed to provide the clearest discrimination to determine optimum AV delay. A larger retrospective report of 215 patients found that AV optimization utilizing the Ritter or iterative method improved LV hemodynamics in only a minority of patients undergoing CRT.[50] Despite these observations, the echocardiography for CRT guidelines published by the American Society of Echocardiography in 2008 recommended the use of the Ritter or iterative method for calculation of the optimal AV delay.[51]

Large-scale randomized controlled trials validating that AV interval optimization results in long-term improvement in clinical outcomes do not exist. Among patients receiving CRT, The SmartDelay Determined AV Optimization: A Comparison to Other AV Delay Methods Used in Cardiac Resynchronization Therapy (SMART-AV) delay trial prospectively randomized patients to a fixed empirical AV delay (120 ms), echocardiographically optimized AV delay, or AV delay optimized with SmartDelay™ (an empirically derived electrogram-based algorithm).[52] At the end of follow-up, the trial found no differences in LV end-systolic volume or any of the secondary endpoints: LV end-diastolic volume, ejection fraction, NYHA class, quality of life, and 6-min walk distance. This study indicates that routine use of echocardiographic optimization or algorithm-based AV interval optimization cannot be recommended as being clinically warranted in patients undergoing CRT. Most individuals will exhibit satisfactory hemodynamics using standard "out-of-the-box" settings and do not need to undergo echocardiographically-guided AV optimization. Interestingly, in the SMART-AV delay trial, women optimized via echocardiography or with SMART-AV delay responded more favorably than women randomized to the fixed AV interval.[52,53] Thus, AV optimization in selected patients who do not respond to CRT may be warranted. Also, it is

still reasonable to consider individualized AV optimization in patients who are hospitalized with acute heart failure or pacemaker syndrome.

Atrial-sensed versus atrial-paced atrioventricular intervals

Appropriate programming of the AV interval also may depend on whether the atrium is sensed or paced. Programming differential AV intervals for sensing and pacing may give rise to small but significant increases in cardiac output in patients with LV dysfunction, due to differences in atrial-paced versus -sensed conduction times.[54] If atrial activity is sensed, this marks the initiation of the pacemaker AV interval. Because some atrial activation already has occurred at the time that the sensing amplifier detects the presence of a P wave, the AV interval based on sensed atrial activity should be shorter (by about 30 ms on average) than when the atrium is paced to begin both the AV interval and atrial electrical activation (Figure 3.29). Generally, an atrial-sensed AV interval of 20–50 ms less than the atrial-paced AV interval is programmed, but the most appropriate difference is probably variable in different patients.

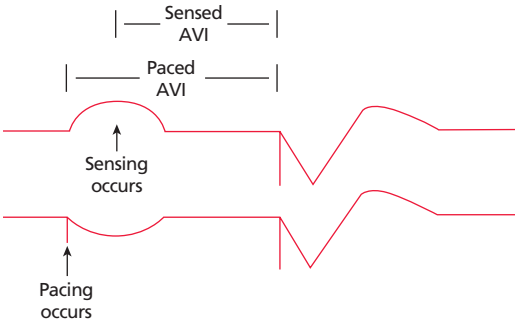


Figure 3.29 Hypothetical relationship of appropriate atrioventricular intervals (AVIs) during atrial sensing versus atrial pacing at initiation of the AVI.

Atrial versus atrioventricular pacing

Both atrial and AV pacing have the advantage of providing AV synchrony. Aside from differing AV intervals, the major difference between atrial and AV sequential pacing is the ectopic ventricular activation with RV pacing in the dual chamber mode versus intrinsic AV conduction during atrial-only pacing. In recent years, there has been recognition of the potential detrimental effects of RV pacing on hemodynamic function. Studies have shown acute improvements in cardiac output, ejection fraction, and pulmonary capillary wedge pressure with AAI compared with DDD pacing. RV pacing compared with intrinsic ventricular activation produces increases in LV filling pressures and end-systolic volume, as well as reductions in regional septal ejection fraction, ventricular d*P*/d*t*, stroke volume, and indices of diastolic function. Chronic RV pacing is associated with an increased risk of AF, heart failure, and mortality.[27,30,55,56] Thus, as a result of the concern over the long-term consequences of chronic RV pacing, there has been a shift away from imposed AV sequential pacing in the dual chamber mode to use of programmed AV intervals and pacemaker algorithms that allow for maintenance of AV synchrony and atrial emptying but minimize RV pacing.

In some patients, in order to minimize RV pacing in the dual chamber mode, it may be necessary to program the device to very long AV delays, sometimes near the available maximal programmable values. Furthermore, atrial-based pacing (AAI and AAIR) can further prolong AV conduction over that during sensed (intrinsic) atrial rhythm. Prolonged AV (and PQ) delays, even when followed by intrinsic ventricular conduction or fusion, may compromise atrial transport function, reduce ventricular preload, and promote diastolic MR and AF.[57] As noted earlier at long AV delays, net LV filling is reduced because atrial systole is superimposed on early rapid filling and mitral valve closure is dependent on the LV pressure rise, which generates presystolic regurgitation. Thus, a low percent of ventricular pacing may not be desirable when it is associated with very prolonged AV intervals (i.e. AV >275–300 ms or PQ >180–200 ms), especially at higher heart rates.

Rate-adaptive atrioventricular delay

In dual chamber devices programmed in the DDDR mode, rate-adaptive pacing might be sensor driven (atrial or AV sequential pacing) or result from ventricular tracking of the atrial rhythm. When rate adaptation is activated, a sensor-driven rate is recorded. If the sensor-driven rate exceeds

both the intrinsic atrial rate and the lower rate limit, rate-adaptive pacing occurs. A programmed maximum sensor rate determines the fastest rate at which pacing can occur.

Dual chamber devices allow rate-adaptive AV delays to be programmed that can shorten the AV delay up to the maximum tracking or sensor-driven rate. This feature is designed to simulate normal shortening of the PR interval during exercise and allows AV synchrony to be maintained at higher heart rates. At higher heart rates, optimal hemodynamics may require shorter AV delays than are best at lower rates. With exercise, there is a relatively linear decrease in the normal PR interval as exercise increases from the resting state to near maximal exertion. The total reduction in spontaneous PR interval in normal individuals is about 20–50 ms or approximately 4 ms for each 10-beat increment in heart rate. Rate-adaptive AV interval shortening is a programmable feature in DDD pacemakers, which is designed to mimic the normal physiological response of the PR interval to increasing heart rates. Cardiac output can be more effectively increased and pulmonary capillary wedge pressures (and presumably atrial pressures) can be effectively maintained at lower levels using rate-variable AV intervals rather than fixed AV intervals.

Maintaining optimal AV synchrony may be less important during exercise than at rest in providing ventricular filling. The importance of AV synchrony diminishes at higher heart rates as the early and late diastolic filling phases converge. However, the loss of AV synchrony can compromise stroke volume even during exercise. In Figures 3.30 and 3.31, the relative hemodynamic benefits of rate modulation and stroke volume, and rate modulation and AV synchrony, respectively, scaled from rest to maximum exertion can be seen for a general population. At rest, AV synchrony is of pre-eminent benefit, whereas this benefit diminishes as maximal exercise is approached, especially in relation to rate modulation. Rate modulation is of very little value at rest, but becomes quite important early in exercise and increases in relative benefit as maximal exercise is approached. Rate modulation and AV synchrony are complementary, not competitive, physiological concepts.

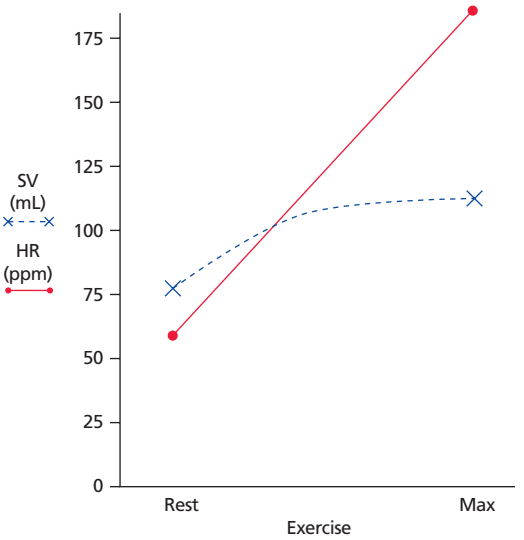


Figure 3.30 Normal stroke volume (SV) and heart rate (HR) response to exercise.

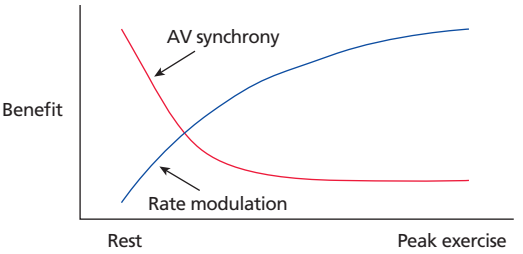


Figure 3.31 Hypothetical, general relationship between atrioventricular (AV) synchrony and rate modulation with respect to hemodynamic benefit, both at rest and during exercise.

Pacemaker syndrome

Pacemaker syndrome describes a condition comprising a variety of symptoms and signs produced by ventricular pacing that are relieved by restoration of AV synchrony.[58] Although it is most often the result of VVI pacing, pacemaker syndrome can result from any pacing mode that results in AV dyssynchrony, even AAI pacing with long PR intervals.[59]

Two difficulties in ascribing symptoms and signs specifically to pacemaker syndrome are commonly encountered. First, patients who have pacemakers implanted are frequently those with other cardio-

vascular problems that produce the symptoms and signs described. Second, many pacemaker patients unfortunately have the belief that having the pacemaker, *de facto*, forces them to accept a less than normal sense of well-being. An extreme symptom frequently associated with pacemaker syndrome is syncope. Syncope is very uncommon and is most likely related to profound hypotension—and, in some, a decrease in cardiac output—associated with loss of AV synchrony. Additional symptoms related to blood pressure and cardiac output include malaise, easy fatigability, a sense of weakness, lightheadedness, and dizziness. Symptoms related to higher atrial and venous pressures include dyspnea (frequently at rest), orthopnea, paroxysmal nocturnal dyspnea, a sensation of fullness and/or pulsations in the neck and chest, as well as palpitations, chest pain, nausea, and peripheral edema. Experience has shown that careful questioning is frequently necessary to elucidate these symptoms. It is not uncommon for patients who have had a pacemaker implanted for some time to deny symptoms, but, on specific questioning, to admit to having experienced symptoms that can be directly related to ventricular pacing with loss of AV synchrony. Careful examination is necessary to find physical signs related to ventricular pacing. Some of these signs include relative or absolute hypotension that can be continuous or fluctuating, neck vein distension with prominent "cannon" A waves, pulmonary rales, and rarely peripheral edema.

The incidence of pacemaker syndrome during ventricular pacing is quite variable in the literature, ranging from 2% to 83% depending in part on the definition used to diagnose this clinical entity.[27] Pacemaker syndrome was defined in the Mode Selection Trial (MOST) in patients with sick sinus syndrome as either new or worsened dyspnea, orthopnea, elevated jugular pressure, rales, and edema with VA conduction during ventricular pacing, or symptoms of dizziness, weakness, presyncope, or syncope, and a 20-mmHg reduction of systolic blood pressure when the patient was ventricularly paced compared with atrial pacing or sinus rhythm.[60] Based on this definition, pacemaker syndrome occurred in 18.3% of those in sinus rhythm treated with VVIR pacing ($n = 996$) in MOST. This incidence is similar to the 26% found in the Pacemaker Selection in the Elderly (PASE) trial.[61] The strongest predictor of pacemaker syndrome in MOST was a higher percent of ventricular-paced beats. Pacemaker syndrome caused a marked decrease in quality of life, which improved significantly after reprogramming to the DDDR pacing mode.

In a substudy of the PASE trial, development of pacemaker syndrome in patients programmed to VVIR pacing was diagnosed within the first week after implantation and was associated with elevated plasma ANP levels (>90 pg/mL). After cross-over from VVIR to DDDR pacing mode in these patients, there was prompt resolution of the symptoms that led to the diagnosis and a decline in plasma ANP levels (<90 pg/mL). Physiologically, increased release of ANP during VVI pacing may reduce arterial pressure because of its potent vasodilator effects and reflexly result in enhanced sympathetic nervous outflow. This may account for or worsen the signs and symptoms of pacemaker syndrome. ANP release may serve as a clinical marker of pacemaker syndrome in VVIR-paced patients and may be involved in its pathogenesis.

Pacemaker syndrome results from a complex interaction of hemodynamic, neurohumoral, and vascular changes induced by the loss of AV synchrony (Figure 3.32). It is speculated that patients who develop pacemaker syndrome during ventricular pacing may have a failure to increase systemic vascular resistance adequately despite elevated peripheral sympathetic nerve traffic and circulating catecholamines (Figure 3.33). Sympathetic neural activation is a normal physiological response during ventricular pacing.[25] In addition to reduced stroke volume and cardiac output resulting from loss of atrial kick during ventricular pacing, pacemaker syndrome may result in some patients from an inadequate sympathetic response to ventricular pacing, with a failure to compensate for upright posture with augmentation in sympathetic tone. In others, the elevated venous pressures resulting from atrial contraction against closed AV valves may activate inhibitory atrial and cardiopulmonary vagal afferent nerves that can counteract the protective vasoconstrictive reflex, resulting in peripheral vasodilation and hypotension.

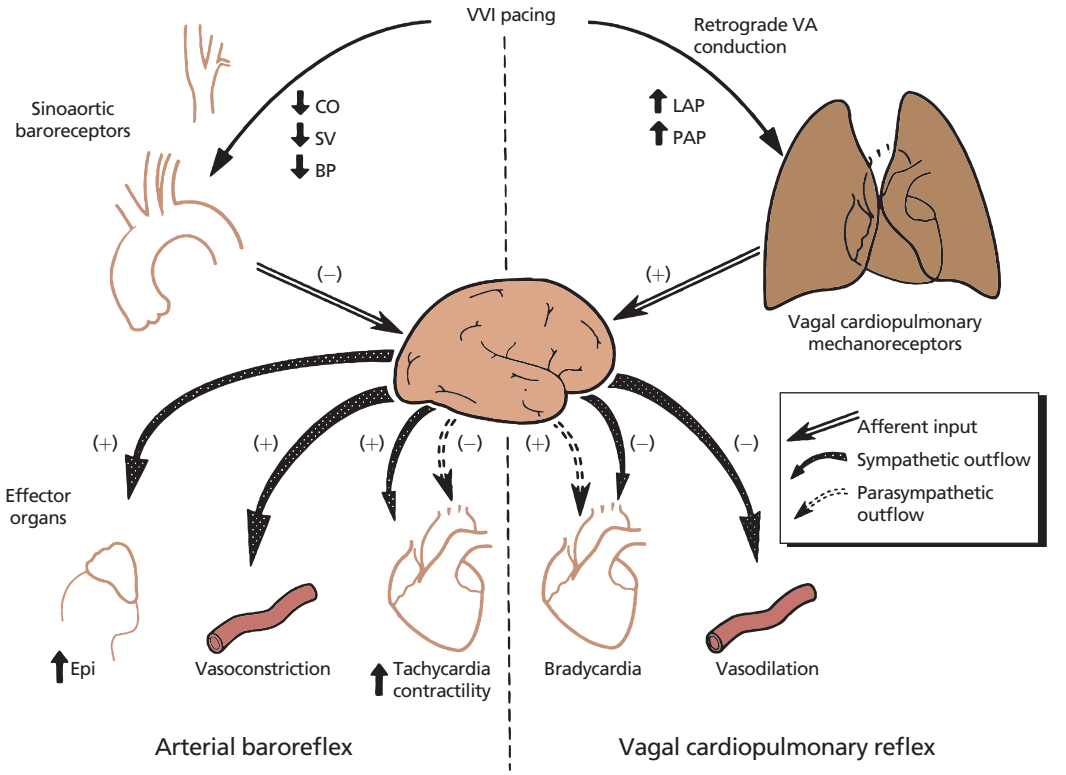


Figure 3.32 Schematic of the multiple reflex pathways involved in pacemaker syndrome. The arterial baroreflexes detect a decrease in stroke volume when atrioventricular (AV) dyssynchrony occurs, leading to sympathetic activation and vasoconstriction. Conversely, AV dyssynchrony leads to increased atrial wall tension and activation of reflex pathways, leading to vagally-mediated vasodilation as well as release of humoral substances, such as atrial natriuretic peptide (ANP), which further facilitate baroreflex-mediated vasoconstriction. BP, blood pressure; CO, cardiac output; EPI, epinephrine LAP, left atrial pressure; PAP, pulmonary artery pressure; SV, stroke volume. (Source: Ellenbogen KA, Stambler BS. Pacemaker syndrome. In: *Clinical Cardiac Pacing*, 1st edn. Eds Ellenbogen KA, Kay, Wilkoff, Philadelphia: W.B. Saunders, 1995; 419–31. Reproduced with permission of Elsevier.)

Based on this understanding, it has been speculated that pacemaker syndrome might be predicted by a simple hemodynamic evaluation at the time of pacemaker implant. Pacemaker syndrome may be more likely to result from VVI pacing if systolic blood pressure drops by more than 20 mmHg during ventricular pacing (Figure 3.17). In the PASE trial, need for future cross-over to dual chamber mode was predicted by a decrease in supine systolic blood pressure during VVI pacing at the pacemaker implantation to less than 110 mmHg (relative risk 2.6; 95% CI 1.5, 4.5; $P \leq 0.001$).[61] The sensitivity of a decrease in paced systolic blood pressure to less than 110 mmHg at implantation for predicting intolerance to VVIR pacing was 36%, specificity was 86%, positive predictive power was 48%, and negative predictive power was 79%. In contrast, however, in MOST, systolic blood pressure drop with VVIR pacing at implantation was not associated with the development of pacemaker syndrome.[60]

It is often thought that pacemaker syndrome is more likely to occur and be more severe when retrograde VA conduction is present. In this regard, although retrograde conduction is common, even in patients with complete heart block, it may be intermittent and not consistently present at implant. Thus, absence of retrograde conduction at implant

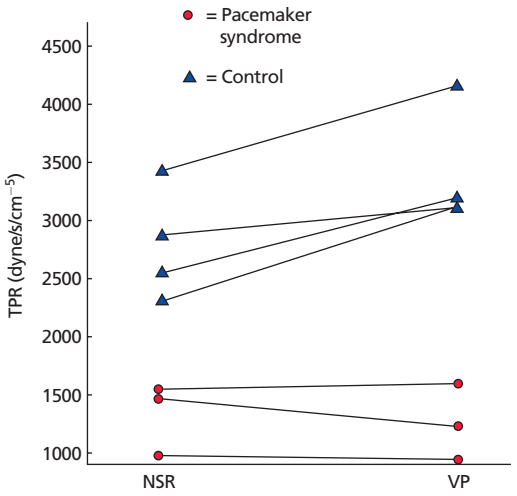


Figure 3.33 Changes in total peripheral vascular resistance (TPR) during normal sinus rhythm (NSR) and ventricular pacing (VP) in four control subjects and three patients with pacemaker syndrome. In the control subjects, there was an approximately 20% increase in peripheral resistance, whereas peripheral resistance failed to increase in the patients with pacemaker syndrome. (Source: Ellenbogen KA, Wood MA, Stambler BS 1993.[58] Reproduced with permission of John Wiley & Sons Ltd.)

during sedation may not preclude subsequent development of signs and symptoms of pacemaker syndrome. In the PASE trial, VA conduction or cannon A waves were present in almost 50% of patients who required crossover from VVIR to DDDR pacing. However, in both the MOST and PASE trials, presence of VA conduction at implant was not a significant predictor of development of intolerance to VVIR pacing.[60,61]

Despite attempts to identify clinical variables that predict intolerance to ventricular pacing, multiple studies have failed to identify any that consistently predict the development of pacemaker syndrome. Therefore, the vast majority of pacemaker implanters have concluded that because prediction of pacemaker syndrome on clinical criteria alone is imprecise, the most effective way to prevent this problem is to implant atrial-based pacemakers in most patients. Undoubtedly, as a consequence of this shift away from the use of VVI/VVIR pacing in clinical practice, there has been a reduced prevalence of pacemaker syndrome.

Management of patients with VVI pacing-induced pacemaker syndrome includes reprogramming or upgrading to DDD pacing, reducing the lower pacing rate to encourage AV conduction or the native rhythm, use of hysteresis, or withdrawal of medications that impair sinus node function. For the rare patient with pacemaker syndrome present with a dual chamber system, appropriate programming to ensure atrial capture and avoidance of atrial non-pacing modes (VDD) or atrial non-tracking modes (DDI or DVI) may be useful.

Detrimental effects of right ventricular pacing

RV pacing can have detrimental effects on myocardial function and result in progression of heart failure, particularly in patients with pre-existing LV dysfunction, and also can result in a modest detrimental effect on LV function in patients who have normal systolic function.[1]

RV pacing produces an asynchronous pattern of activation, contraction, and relaxation within and between the left and right ventricles. RV pacing impairs systolic and diastolic function. These hemodynamic derangements occur whether or not normal AV synchrony is present and may be most pronounced when the ventricular pacing site is the RV apex.[62] Ventricular pacing may compromise effective forward stroke volume further by inducing functional MR.[63] RV pacing results in significant regional differences in perfusion and oxygen consumption, and reduced myocardial mechanical efficiency.[64]

Asynchronous activation during chronic RV apical pacing leads to long-term adaptations of the myocardium, referred to as remodeling. Experimental and clinical studies have shown that chronic RV pacing induces ventricular dilation, asymmetric LV hypertrophy and thinning, altered perfusion distribution, increased myocardial catecholamine concentrations, abnormal histological changes, including myofiber disarray, and impairment of LV function.[65–68] These alterations are due to the LV dyssynchronous contraction present during chronic RV apical pacing. Thus, when normal AV conduction remains intact, preservation of a physiological ventricular activation sequence during permanent cardiac pacing is of importance for optimization of hemodynamic function.

Several studies have observed a high prevalence of asymptomatic LV dysfunction in pacemaker patients undergoing stimulation from the RV.[69–71] In a single-center study, a history of having a permanent pacemaker with a RV pacing lead was the strongest predictor (HR 6.6, $P = 0.002$) of a decrease in LVEF (of >7 points) over 18 months' follow-up.[70] In patients with complete AV block and normal ventricular function at permanent lead implantation, chronic RV pacing induced regional myocardial perfusion defects and wall motion abnormalities, and impaired LV systolic and diastolic function.[72]

In the MOST trial among a pacemaker population with sinus node disease, there was an association between percent of ventricular pacing (in either single or dual chamber modes) and development of heart failure.[30,69] Chronic RV pacing also was associated with an increased risk of AF. Ventricular pacing in the VVIR mode of greater than 80% of the time was associated with increased heart failure risk, and RV pacing in the DDDR mode of greater than 40% conferred a 2.6-fold increased risk of heart failure. In absolute terms, the average risk of heart failure in those receiving RV pacing was approximately 10%; however, the risk was approximately 2% if RV pacing was minimal (<10% of the time). The risk of AF increased linearly with cumulative RV pacing in both groups. From these data, it was concluded that both heart failure progression and AF can be reduced by implementing strategies that minimize ventricular pacing and preserve normal ventricular activation. Consistent with this notion; the Search AV Extension and Managed Ventricular Pacing for Promoting Atrioventricular Conduction (SAVE PACE) trial evaluated a pacing algorithm that minimizes RV pacing in patients with sinus node disease and reported a 40% reduction in persistent AF in those randomized to dual chamber minimal ventricular pacing (median percent ventricular pacing: 9.1%) compared with those with conventional dual chamber pacing (median percent ventricular pacing: 99.0%).[73] However, there were no differences in rates of heart failure or mortality.

Notably, most patients with sinus node dysfunction have normal LV function and tolerate even frequent RV pacing without an increased risk of developing heart failure during long-term follow-up.[1,74,75] Although RV pacing may result in ~6–7% absolute decline in LVEF, the risk for clinical heart failure due to RV pacing among patients with pacemakers who have sinus node disease is quite low (approximately 1.2% at 2 years after pacemaker implantation).[1,76] Furthermore, whether there is a percent of RV pacing that may result in a higher risk of heart failure or AF in patients with sinus node disease also is controversial. Although the aforementioned data from MOST suggest that risk may be increased when RV pacing is greater than 40–50%, in contrast, in the Danish Multicenter Randomized Trial on Single Lead Atrial Pacing versus Dual-Chamber Pacing in Sick Sinus Syndrome (DANPACE), no significant association was detected between percent ventricular pacing and the risk of AF or heart failure.[57,74,75]

In patients with structural heart disease and compromised LV function, the deleterious effects of RV pacing appear to have greater clinical consequences. Clinical evidence of the deleterious effects of chronic and frequent RV pacing in this population was demonstrated in the Dual Chamber and VVI Implantable Defibrillator (DAVID) trial.[55] DAVID tested the hypothesis that dual chamber pacing for rate support would be more efficacious than back-up pacing in patients with impaired ventricular systolic function receiving a dual chamber ICD. The trial was a multicenter study of patients with standard indications for ICD implantation (ventricular tachycardia/ventricular fibrillation, LVEF <40%), but without indications for bradycardia pacing. All patients had a dual chamber, rate-adaptive pacing ICD implanted and were randomized to ventricular back-up pacing (VVI 40 bpm) or dual chamber rate-adaptive pacing (DDDR 70 bpm, average AV delay 180 ms). The study was prematurely discontinued because of increased mortality and hospitalization in patients treated with dual chamber pacing (73.3% 1-year survival and 22.6% requiring hospitalization) compared with back-up ventricular pacing (83.9% survival and 13.3% hospitalization). A subsequent analysis of the DAVID trial and confirmatory observations from other studies demonstrated that percent RV pacing predicted the primary clinical outcomes (composite

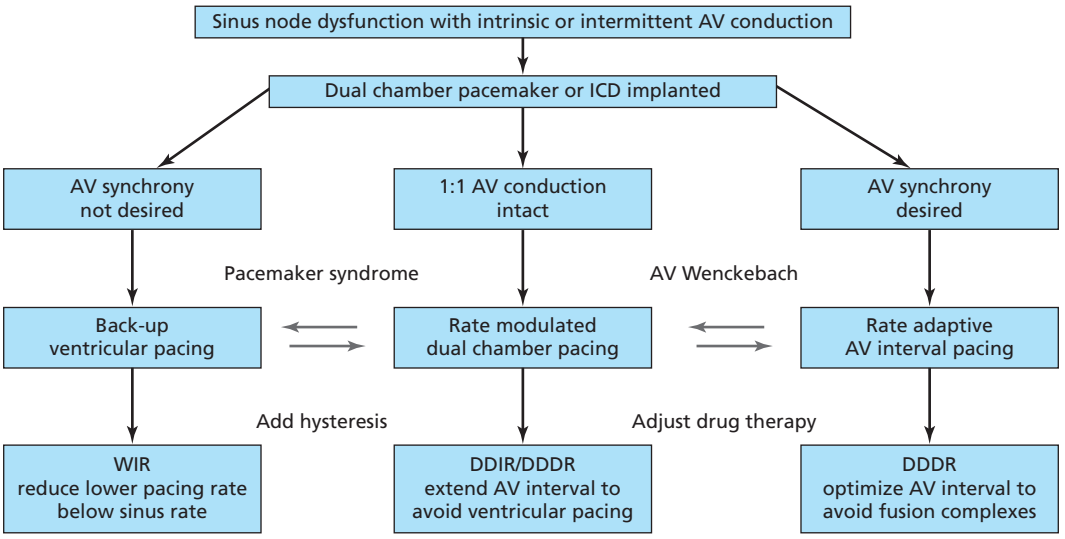


Figure 3.34 Minimal ventricular pacing strategy to promote intrinsic atrioventricular (AV) conduction after implant of a dual chamber pacemaker or ICD for treatment of sinus node dysfunction with impaired AV conduction (present or anticipated). Left: Back-up VVIR pacing is used if AV synchrony is not required. The lower pacing rate is programmed below sinus rate and rest hysteresis is added when appropriate. Change to dual chamber pacing if pacemaker syndrome develops (due to retrograde VA conduction). Middle: Rate-modulated dual chamber pacing is preferred for patients with intrinsic AV conduction. The programmed AV interval is extended to promote normal ventricular activation in patients capable of maintaining 1:1 AV conduction. Discontinue or adjust drugs that affect AV conduction when appropriate. Add rate-adaptive pacing if the patient is symptomatic with extended AV delays. Right: Rate-adaptive AV interval pacing is used for patients requiring physiological AV intervals. During programming, sensed and paced AV intervals should be optimized to avoid ventricular fusion complexes.

end-point of death or hospitalization for congestive heart failure) in patients with LV dysfunction receiving ICDs.[77] Patients with DDDR RV pacing of less than 40% had similar or better outcomes compared with the VVI back-up group (mean RV pacing <4%), whereas outcomes were worse among patients with DDDR RV pacing of greater than 40%.[78] The DAVID II trial, which compared AAI pacing at 70 bpm with VVI pacing at 40 bpm in a second group of patients who required ICD but not pacemaker therapy, found no difference between the two groups, effectively excluding the higher base rate pacing as the cause of the worsened outcomes in the DDDR 70-bpm group in the original DAVID trial.

Strategies to minimize right ventricular pacing

Because of evidence that a high proportion of RV pacing, particularly in patients with some degree of LV systolic dysfunction, may be detrimental, there is a growing trend to minimize RV pacing as much as possible. The risks of frequent or continuous RV stimulation may be reduced by using "minimal ventricular pacing" strategies that use back-up ventricular pacing (VVI or VVIR) modes when AV synchrony is not required, or extended AV intervals during dual chamber pacing, to allow for intrinsic ventricular activation (see Figure 3.34).

Simple measures often employed to reduce ventricular pacing include lengthening programmed AV intervals, programming a lower pacing rate below the sinus rate, adding rate hysteresis for periods of inactivity, and adjusting drugs that affect AV nodal conduction. Rate-adaptive AV delay programming can allow long AV delays to be programmed at lower heart rates, but more appropriate AV intervals at higher rates. To further minimize potentially unnecessary ventricular pacing, rate-adaptive AV interval pacing can be

reserved for patients who are symptomatic with long AV delays or high-grade AV block.

The strategies suggested above may be the only means available in older device technology to reduce unnecessary RV pacing, but may have limitations. Many dual chamber pacemakers impose limitations on maximum allowable AV intervals in order to maintain atrial tracking at elevated rates and adequate sensing windows for atrial tachyarrhythmia mode switch algorithms. In ICDs, allowable AV intervals are more restricted to prevent VT underdetection due to cross-chamber blanking periods. Furthermore, long AV delays increase risk of pacemaker-mediated tachycardias. Finally, if RV pacing continues to occur at long programmed AV delays (>300 ms), this imposes both AV and ventricular desynchronization.

To deal with issues and limitations related to DDD/R pacing with long AV delays, minimal ventricular pacing algorithms have become available that essentially provide atrial [AAI(R)] pacing with ventricular monitoring and back-up ventricular support [DDD(R)] pacing should high-grade AV block develop.[79] These algorithms can extend AV delays beyond 300 ms to avoid ventricular pacing unless high-grade AV block is present. These algorithms are effective in promoting intrinsic AV conduction and reducing ventricular pacing frequency to very low levels (<5–10%).[80] A clinical trial (SAVE-PACE) evaluating one of these algorithms in patients with sinus node disease reported a reduced risk of AF without an increased risk of heart failure or mortality.[1,73]

Another approach to minimize RV pacing has been the use of paced and sensed AV delay hysteresis algorithms that enable prolongation of the AV delay after a predetermined number of atrial beats to look for spontaneous AV conduction. The Inhibition of Unnecessary RV Pacing With AVSH in ICDs (INTRINSIC RV) trial among ICD recipients with LV systolic dysfunction included use of AV search hysteresis (AVSH) during DDD programming to reduce RV pacing percent.[81] This trial found that lowest rates of adverse clinical events occurred with RV pacing between 10% and 19%.[82] The event rates (death or heart failure hospitalization) in this group were lower than in those with increasing levels of RV pacing, but interestingly also were lower than in the group with the least amount of RV pacing (0–9%). Thus, some degree of RV pacing is permissible and may even be beneficial in patients with ICDs.

As noted above, patients with normal hearts usually tolerate some degree of RV pacing without developing heart failure and may benefit from optimized AV synchrony. Notably in contrast to the conclusions of MOST, the DANPACE study in patients with sinus node disease found no difference in mortality, and incidence of chronic AF, stroke, and heart failure between single lead atrial and dual chamber pacing groups, even though ventricular pacing percent in the latter group was 65 ± 33%. In addition, paroxysmal AF occurred more frequently in the AAIR group. In DANPACE, the AV interval was 140–160 ms if no intrinsic conduction was present at an AV interval of greater than 220 ms, but an AV delay hysteresis algorithm was enabled to allow automatic search for intrinsic AV conduction. This algorithm minimized unnecessary ventricular pacing, but reduced it to a percent that was substantially higher than that in the DDDR group who had managed ventricular pacing (MVP) enabled in the SAVE-PACE trial (RV pacing percent: 9%), but lower than that in the DDD(R) groups with fixed, short AV delays in SAVE-PACE (RV pacing percent: 99%) and MOST (RV pacing percent: 90%). Thus, it seems that strategies to reduce unnecessary RV pacing are appropriate, but it may be best to have optimized AV synchrony by avoiding either very short or long AV conduction intervals.

Alternative site right ventricular pacing

In patients with AV conduction disease in whom reducing the percent of ventricular pacing is not feasible because of the requirement for frequent or continuous ventricular pacing support, more physiological alternatives to RV apical pacing should be considered. Pacing from the para-Hisian region, RV outflow tract (RVOT), or RV septum may offer theoretical advantages over the RV apex that could result in a more synchronous ventricular activation sequence. Despite these potential advantages, the clinical benefits of alternative site RV pacing have not been demonstrated conclusively.[83]

His bundle pacing

The bundle of His, a rapid conduction path for both ventricles, is an obvious target for alternative site pacing, but is fraught with technical difficulties. Several small studies have investigated the feasibility of permanent Hisian pacing to produce a narrow paced QRS complex identical to that in intrinsic rhythm.[84–88] Criteria for direct His bundle pacing include 12-lead ECG equivalence between native and paced QRS, and His–ventricular (HV) interval of spontaneous rhythm equal to the pace ventricular interval.

Successful His bundle pacing results in better hemodynamic performance and more uniform distribution of perfusion when compared with RV pacing.[84,86] A less obvious role is for correction of underlying left bundle branch block (LBBB) to resynchronize LV contraction. The theory of longitudinal dissociation of the His explains how His pacing can correct some LBBBs.[89] Direct and exclusive stimulation of predestined fibers to the LBB within the Hisian trunk, below a lesion within the Hisian bundle responsible for the conduction deficit, causes QRS normalization, with resumption of electrical and mechanical LV synchrony. In one study, patients meeting CRT implant indications but treated with His pacing sustained significant improvement in LV function.[90] However, little is known of the proportion of heart failure patients with LBBB in whom LBBB is a His bundle-based ("central") lesion rather than a reflection of peripheral myocardial conduction deficits that may not be corrected in this manner.

Although it has been demonstrated that permanent pacing of the His bundle can be performed in some patients, the major disadvantages of this approach that hinder its widespread application are the technical limitations in being able to achieve permanent His bundle pacing in more than 90% of patients. Among five published studies that included 126 patients, direct His bundle pacing was achieved in less than 70% of patients in whom it was attempted.

Non-apical right ventricular pacing

Most studies of alternative RV site pacing have focused on the RVOT, and in particular on the septal portion of the outflow tract. It is speculated that RVOT or mid-septal pacing will not be associated with the deleterious effects on hemodynamic function seen with RV apical pacing. Most of the data comparing alternative pacing sites to RV apical pacing, however, have been equivocal. Some studies have found significant acute hemodynamic advantages, but several randomized controlled chronic studies have demonstrated either modest or negligible benefit of RVOT compared with RV apical pacing.[91–97] It should be noted that among numerous acute and chronic clinical studies, only in one study was RVOT pacing hemodynamically worse than RV apical pacing.

One of the difficulties in evaluating the potential benefits of RVOT pacing is that this region, at least up until recently, has been difficult to identify using fluoroscopy and therefore is not standardized anatomically with respect to pacing sites. Thus, confirmation of anatomical lead location remains challenging and not well validated. In addition, many studies of alternative site RV pacing are difficult to interpret because of the small number of patients, wide range of baseline LV function, varying spectrum of underlying heart disease, and varying durations of follow-up. Few randomized trials comparing RV apical pacing with alternative RV sites have followed patients over extended periods beyond 1 year. The benefits that may accrue from RVOT pacing seem primarily related to prevention of deterioration of LV function that develops in some patients undergoing RV apical pacing, rather than improvement in function associated with RVOT pacing.

A meta-analysis of randomized trials comparing RV apical versus non-apical pacing concluded that LVEF is higher with non-apical than apical pacing (weighted mean difference of LVEF: 4.27%, 95% CI 1.15%, 7.40%), but only in trials with follow-up of 12 months or longer and in those conducted in patients with a baseline LVEF of 40–45% or less.[98] No significant difference in LVEF was observed in trials of patients whose baseline ejection fraction was preserved. Importantly, available data for endpoints other than ejection fraction, including exercise capacity, functional class, quality of life, and survival, are limited and inconclusive.

Further complicating the evaluation of alternative RV pacing sites, some studies have suggested that the hemodynamically optimal RV pacing site may vary from patient to patient and may not

always reside on the RV septum.[95,99] One study in 14 patients has attempted to find the best RV pacing site, defined as the site with the shortest paced QRS duration.[95] The study found that a shorter QRS duration positively correlated with a higher LVEF, but that the RV septal pacing site did not necessarily produce the shortest QRS or consistently result in improved LV function. QRS duration was shorter in nine patients, longer in four patients, and no different in one patient between RV septal and apical pacing. Overall, the QRS duration was not significantly different between RV septal and apical pacing (156 ± 10 vs. 166 ± 18 ms, respectively). Thus, anatomical lead optimization may not be as critical as hemodynamic lead optimization, and the optimal RV site may not be anatomically defined but may vary from patient to patient.

In summary, whether the detrimental hemodynamic effects of RV apical pacing can be attenuated by selecting a more optimal RV pacing site continues to be of clinical interest, but still remains to be determined definitively. Ongoing pacemaker studies continue to evaluate this issue. Notably however, the results of recent prospective mortality-driven clinical trials comparing biventricular pacing to conventional RV pacing in subjects with bradyarrhythmia, but without heart failure indications for biventricular pacing, have an impact in this area (discussed below).[100,101] These trials provide guidance on the best means to optimally pace the ventricles when bradycardia support is required in clinical practice.

Left ventricular pacing and cardiac resynchronization therapy

CRT is an established therapy in heart failure patients with LV systolic dysfunction and a wide QRS duration. Clinical trials demonstrated benefits of CRT incremental to optimized medical therapy on quality of life, exercise tolerance, and heart failure symptoms, functional class, and hospitalization. Moreover, CRT confers survival benefit.[102,103] Original trial populations targeted severely reduced LV systolic function, refractory heart failure, markedly prolonged QRS durations (usually due to LBBB), and no bradycardia indication for pacing. More recent studies show benefits extending to patients with NYHA class I/II level of symptoms.[104] CRT is therefore an important interventional therapy in this high-risk population.

The concept underlying CRT is that in patients with prolonged QRS duration, delayed LV activation leads to LV mechanical dysfunction, but may be corrected by appropriately timed LV stimulation.[105] The hemodynamic deficit provoked by abnormal pathways of ventricular activation deviating from synchronous ventricular electrical activation (i.e. rapid impulse conduction through the His–Purkinje system) has been known for decades.[106] Chronic effects due to LBBB (and with RV pacing which mimics several aspects of LBBB) in heart failure are manifest by LV remodeling and symptoms of heart failure with increased mortality.[107] Mechanical dysfunction results from dyssynchronous contraction—both interventricular and intra-LV conduction delays may impair contraction. Regions of the ventricle still actively contracting while other regions are relaxing and filling in diastole (i.e. reciprocated stretching) creates mechanical inefficiency.[108] The result is that part of the contractile effort does not wholly contribute to cardiac ejection.

CRT aims to reverse this sequence of adverse events. Its effects may be assessed hemodynamically, both acutely by measurement of contractile function (e.g. ejection fraction) and chronically through remodeling (e.g. changes in LV dimension). These effects may be modulated by variations in both underlying electrical substrate and responses to pacing. By stimulating both the right and left ventricles, CRT results in a more synchronous electrical activation sequence and mechanical contraction. CRT resynchronizes the severely uncoordinated and dysfunctional patterns of ventricular contraction in patients with prolonged native QRS complexes. CRT improves systolic function acutely within one beat of initiation of pacing, with immediate improvements in LV contractility, cardiac output, and arterial pulse pressure. Chronic therapy is required to produce reverse remodeling with reduction in end-diastolic volume and improvement in LVEF.

Atrio-biventricular pacing

Attempts to restore coordinated contraction generally use ventricular-based pacing, coordinated with

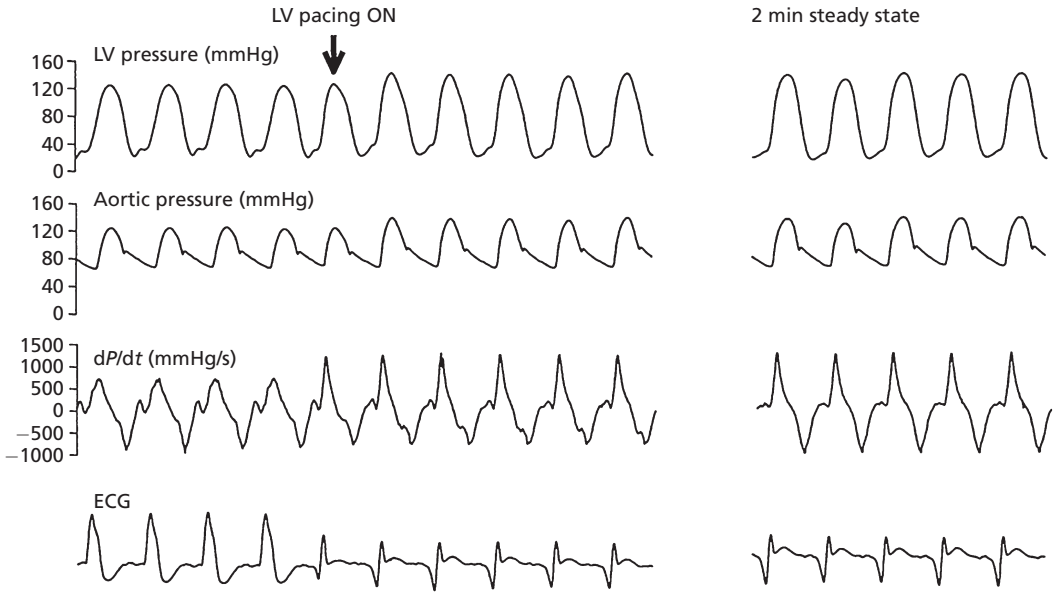


Figure 3.35 Raw data tracings before, immediately on initiation of left ventricular (LV) electrical stimulation, and after 2 min of steady-state LV stimulation in a patient with dilated cardiomyopathy and discoordinate contraction due to left bundle branch block. Stimulation of the LV free wall rapidly increased aortic and ventricular systolic pressures, aortic pulse amplitude, and maximal d*P*/d*t*. These increases changed very little after 2 min of steady-state stimulation. (Source: Nelson GS *et al*. 2000.[112] Reproduced with permission of Wolters Kluwer Health.)

atrial contraction when possible, to correct VV, intra-LV, and also AV dyssynchronies. CRT conventionally involves ventricular stimulation of both the right and left ventricles (biventricular pacing). Biventricular devices incorporate pacing leads capable of stimulating the RV and LV via the coronary sinus transvenously or from the epicardium surgically, in conjunction with an atrial electrode to maintain AV synchrony. Initial case reports were followed by systematic investigation and reported positive acute hemodynamic effects.[109–111] Improvements could be perceived immediately on initiation of pacing (Figure 3.35), manifest in improvements in systolic function, LV contractility, cardiac output, and arterial pulse pressure, not seen with RV pacing alone. Both LV free wall and biventricular pacing reduced end-systolic volume and increased stroke volume (Figure 3.36). These results indicated that ventricular mechanics could be improved dramatically by pre-excited LV pacing to reduce existing conduction delay. This inotropic effect was metabolically efficient as measured in terms of conversion of myocardial oxygen consumption to mechanical work.[112]

Atrial synchronization by modulating AV intervals may affect LV pump function. The relationship between AV delay and LV d*P*/d*t* max among patients with acute improvement in contractile response to simultaneous biventricular pacing demonstrated peak effect at approximately 50% of native PR interval.[109] Effects were diminished at very short AV delays (truncated filling times) or very long AV delays. Thus, routine optimization with acute echocardiographic measures (e.g. VTI, mitral inflow) offers no significant advantage over empirical settings (100–130 ms) except in non-responders. However, regularly adjusted AV intervals by means of a hemodynamic surrogate sensor measuring peak endocardial acceleration may offer some advantages.[113]

A further significant hemodynamic benefit of CRT observed in many patients is reduction in functional MR. The following mechanisms may be involved. Optimization of AV timing and shortening of contraction sequence prolongs diastolic filling time and reduces diastolic MR. Acutely, ventricular resynchronization may restore interpapillary muscle coordination. Ventricular

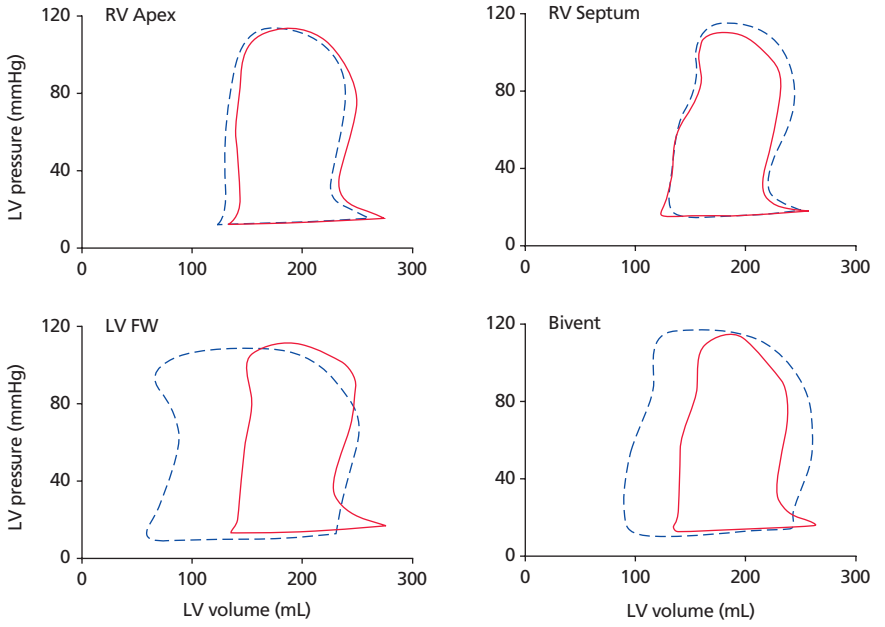


Figure 3.36 Pressure–volume loops from a patient with baseline left bundle branch block as a function of varying pacing site. Data are shown for the optimal atrioventricular (AV) interval at each site. Solid line indicates normal sinus rhythm (NRS)—control; dashed line indicates VDD pacing. There was negligible effect from right ventricular (RV) apical or sensory pacing. However, LV pacing produced loops with greater area (stroke work) and width (stroke volume) and a reduced systolic volume. The latter is consistent with increased contractile function and thus with elevation of d*P*/d*tmax*. LV FW, left ventricular free wall. (Source: Kass 1999.[111] Reproduced with permission of Wolters Kluwer Health.)

remodeling effects may further improve valve function. In several large-scale trials, sustained hemodynamic improvements led to reverse volumetric LV remodeling with reduced sphericity and improvement in ejection fraction. The magnitude of reduction in end-systolic volume observed ranges between 10% and 30%. This remodeling process may be evident as early as 4 weeks after implementing therapy and reverses with its withdrawal.[114] Further discussion is found in Chapter 9.

Univentricular left ventricular pacing

CRT with LV-based pacing (i.e. without RV pacing) demonstrated acute hemodynamic benefits that were similar (if not superior to) biventricular pacing[111] (Figure 3.36). Resynchronization may result from fusion between a wavefront produced by intrinsic conduction down the AV node and intact right bundle and a second wavefront stimulated by LV pacing. Avoidance of RV pacing in this manner avoids RV hemodynamic deficit seen with simultaneous biventricular pacing modes.[115] RV pacing-induced changes in activation sequence and prolongation of activation duration may all potentially perturb the normal sequential pattern of RV inflow-to-outflow contraction.[116] These alterations in RV activation and thus interventricular dyssynchrony may interfere with ventricular coupling and pump function. These effects may be avoided by LV pacing alone, with critically timed AV delays resulting in fusion of the propagated paced wavefront with intrinsic conduction via an intact right bundle. The long-term effects of univentricular LV pacing have been comparatively less well studied compared with evaluations of biventricular resynchronization pacing. Studies to date show no superiority to conventional biventricular stimulation. Thus, chronic programming based on acute hemodynamic effects showed that LV and biventricular pacing were equvialent.[117,118] Acute benefits observed with an algorithm to promote fusion pacing showed no long-term benefits.[48,52] However, maintaining fusion pacing consistently

on a near beat-to-beat basis may offer long-term advantages in select patients.[119]

Left ventricular endocardial pacing

LV endocardial pacing sites usually render better hemodynamic performance than RV endocardial pacing sites and conventional epicardial sites accessed via coronary sinus (CS) tributaries.[120,121] This approach offers the advantage of access to a great variety of LV pacing sites, removing constraints of CS tributary availability. The hemodynamics have been best studied experimentally. In normal hearts, pacing at the left side of the interventricular septum (LV septum) induced a near normal sequence of activation, characterized by rapid spread of depolarization from the pacing site around the LV circumference.[122] LV systolic function was near normal with minimal dyssynchrony. The rapidly conducting superficial endomyocardial layer may be responsible for this effect.[123] Importantly, results were equivalent to biventricular pacing.[124] LV septal pacing differs greatly from RV septal pacing in electric activation and hemodynamic effects—trans-septal conduction occurs rightwardly but with simultaneous circumferential LV endocardial conduction, thus reducing total LV activation time. Therefore, both the interventricular and intraventricular asynchronies are reduced. However, direct LV pacing is potentially hazardous, introducing risks of trans-septal puncture, mitral valve trauma, thromboembolism, and infection with risk of extraction. Novel techniques to deliver this pacing mode include deployment of electrodes to the LV aspect of the septum from the *right* septum with extended screws.[122,124] Safety and feasibility remain to be determined.

Suboptimal response to cardiac resynchronization therapy

Despite the consistent demonstration of CRT benefits across several large-scale trials, individual responses are variable with as many as one-third of patients considered to be non-responders. Therefore, enhancing CRT response is an important but challenging goal. Efforts using various echocardiographic mechanical measures of delay have been ineffective. This emphasizes the importance of retaining electrical measures of LV depolarization delay, which, despite their imperfections, continue to be QRS duration and morphology. Enhanced CRT benefit is gained when QRS is greater than 150 ms and in the presence of LBBB morphology compared to RBBB or intraventricular conduction delay (IVCD).[104,125,126] This is instructive since QRS duration in LBBB is tightly linked to the extent of underlying LV conduction delay.[127] Acute hemodynamic response to biventricular pacing increased progressively with increasing QRS complex duration in LBBB.[111,128] This makes intuitive sense since CRT is understood to work by correction of LV conduction delay, and thus response should be more likely when LV conduction delay is greater. Chronically, a delay of greater than 95 ms (Q–LV) recorded at LV pacing sites was associated with improved CRT response,[129] and this value is present in all patients with LBBB in whom QRS duration exceeds 150 ms.[127] Hence, probability of response encountered in a population of CRT recipients may reflect the prevalence of electrical delay in the population. This reasoning may explain why patients with RBBB derive less (if any) benefit from CRT, since severe LV conduction abnormalities similar to LBBB occur infrequently.[127,130]

Although variability in the prevalence of LV conduction delays may contribute to inconsistent CRT response among and within heart failure groups selected merely by QRS configuration, other electrical factors may also contribute to CRT hemodynamic response. Novel mapping techniques have demonstrated that LBBB in CRT patients is not a uniform lesion, but rather encompasses a variety of different LV activation patterns.[131] A large area of late-activated tissue heralded superior hemodynamic response to LV stimulation.[132] A U-shaped LV activation ("type II") pattern was more likely to respond to CRT.[121,133] Furthermore, LV- and RV-paced wavefronts generated by CRT can be modulated by complex conduction barriers, sometimes developing in response to pacing (i.e. functional mechanism) and not predictable from intrinsic conduction problems. Thus, posterolateral transmural scar was reported to negate CRT effect, presumably due to inexcitability of this target area, although electrical activation was not investigated.[134] Disordered electrical activation may not consistently match scar distribution,[135] i.e.

variations in propagation may occur in non-scar areas. Thus, prolonged propagation of depolarization correlated with poorer hemodynamic response to pacing compared to rapid global activation.[136] Hemodynamics improved when these "slow conduction" areas were avoided and paced wavefronts were permitted to emerge and recruit adequate tissue mass. Chronic persistence of these conduction barriers was noted in responders versus non-responders using non-invasive ECG imaging (ECGI) (Figure 3.37). Accordingly, LV-paced wavefronts differed considerably among patients. This inconsistency in being able to achieve rapid confluent LV depolarization, even in appropriately selected CRT candidates, further affects ultimate CRT response.

Given the range of individual variability in electrical substrate and LV activation, pacing from multiple sites has been advocated to overcome suboptimal response. This includes pacing from multiple areas along a single CS branch with multipolar electrodes or with different electrodes deployed to different CS branches. Preliminary data suggest improved hemodynamics in some patients.[121,137]

In summary, there is definitive evidence that LV-based ventricular pacing improves the outcome of heart failure patients with significant LV electrical delay and avoids the detrimental effects of RV pacing. Recent trials have extended CRT to patients with ambulatory class I/II heart failure and prolonged QRS duration. It is likely that future use of CRT will continue to expand in patients who require any form of ventricular-based pacing. A more complete discussion of biventricular and LV pacing is provided in Chapter 9.

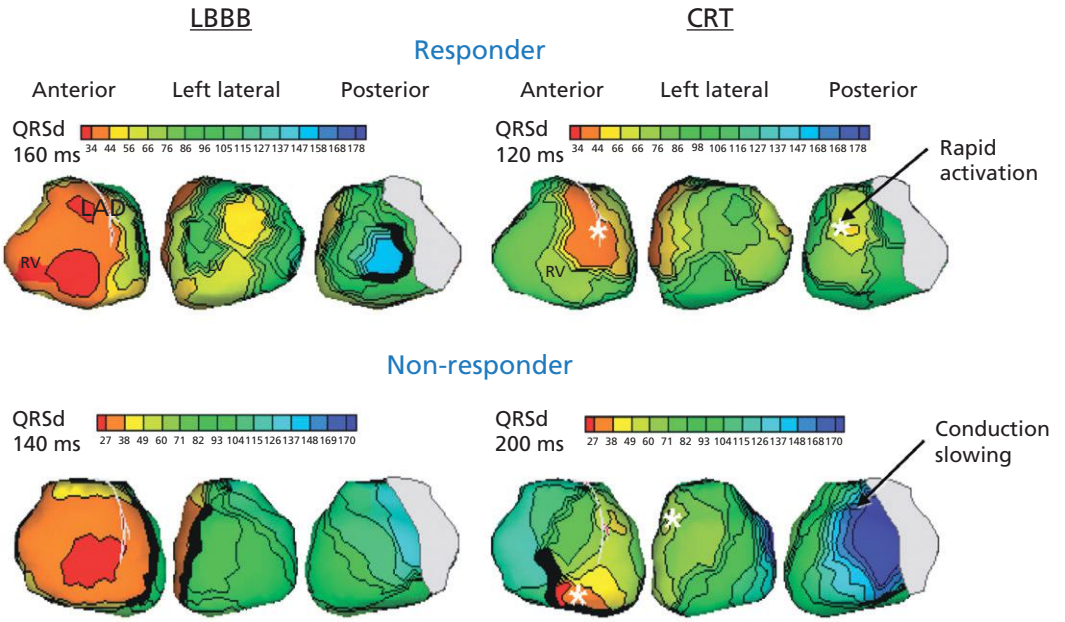


Figure 3.37 Ventricular epicardial isochrone activation using non-invasive electroanatomic mapping (ECGI) in heart failure patients with left bundle branch block (LBBB). Left ventricular (LV) electrical effects are contrasted in two patients: a responder and a non-responder to therapy. Variations in LV activation during intrinsic conduction (left panels) and biventricular pacing (right panels) are illustrated. Epicardial surfaces of both ventricles are displayed in three views: front, left, and back. There is overlap between adjacent views. The left anterior descending (LAD) coronary artery is shown. Thick black markings indicate line/region of conduction block. Pacing sites are marked by asterisks. Posterolateral regions of LV activation delay (blue) during intrinsic conduction (left) are resolved (right top) or aggravated (bottom right) by LV pacing. Similar effects may be observed acutely and correlate with hemodynamic responses to cardiac resynchronization therapy (CRT).[136] Lack of intended electrical effect of LV pacing severely limited paced wavefront propagation and may have presaged CRT failure. QRSd, QRS delay. (Source: Jia 2006.[135] Reproduced with permission of Elsevier.)

Pacing in hypertrophic obstructive cardiomyopathy

In the past some clinicians advocated a therapeutic role for cardiac pacing in selected patients with hypertrophic obstructive cardiomyopathy (HOCM). These patients have obstruction to LV outflow caused by hypertrophy of the interventricular septum, typically in the subaortic valve area, combined with systolic anterior motion of the mitral valve. In this select subset of patients with LV outflow tract (LVOT) obstruction and refractory symptoms despite pharmacological therapy, it was proposed that DDD pacing with a short AV delay would be of benefit. It was speculated that by producing dyssynchrony of LV contraction and paradoxical septal movement, dual chamber pacing with ventricular pacing from the RV apex will reduce the degree of outflow obstruction and symptoms. An AV delay of less than 100 ms is usually necessary to ensure full RV apical pre-excitation. Shorter AV delays allow for more complete apical pre-excitation and minimal basal septal activation through the His–Purkinje system. Apical pre-excitation with short AV delays must be maintained at higher heart rates and during exercise.

Retrospective studies suggested that AV synchronous pacing with a short AV delay decreases LVOT gradient and symptoms. An example of modest improvement in LV outflow gradient in such a patient is shown in Figure 3.38. AV delays ranging from 80 to 100 ms may be optimal for gradient reduction. Other investigators documented subjective as well as objective improvement in such parameters as oxygen consumption at peak exercise. These studies generated interest in the role of pacing in HOCM, but subsequent prospective studies of dual chamber pacing yielded conflicting results.[138–140] Results varied from patient to patient and were inconsistent. Some patients had marginal benefit, whereas others obtained complete gradient abolition. Part of the reason for this variability may be that AV delays that are too short can be detrimental to diastolic filling and can worsen symptoms. If interatrial conduction is impaired, then short AV delays will result in LA contraction occurring after mitral valve closure, which can elevate LA pressure and promote atrial arrhythmias. Reduction in LVOT gradient may require AV interval optimization with Doppler echocardiographic guidance assessing both LV outflow gradient and mitral inflow velocities.

At least three randomized, controlled, cross-over trials of pacing in HOCM patients refractory to medical therapy have been performed and found that the benefit of this therapy is less than suggested by earlier reports. These studies included a total of about 140 patients and suggested that pacing can reduce LVOT gradient and lead to a modest reduction in symptoms, but does not improve exercise capacity. The North American M-PATHY trial was a randomized, double-blind, cross-over multicenter trial of 48 patients with drug-refractory HOCM.[140] An average reduction in LVOT gradient of 40 mmHg was seen, but no significant effect on quality of life, exercise capacity, peak oxygen consumption, or septal wall thickness. A small subgroup of patients over the age of 65 years showed consistent improvement in functional capacity. Likewise, the European Pacing in Cardiomyopathy (PIC) study also suggested that elderly patients (>65 years) are most likely to respond to pacing.[139] However, the placebo effect of pacing system implantation appears to play an important role in overall subjective improvement. Therefore, pacing cannot be regarded as primary therapy for obstruction because of inconsistent results.

A non-randomized comparison of dual chamber pacing and septal myectomy for patients with drug-refractory symptoms analyzed LVOT gradients, symptoms, and exercise testing in 39 patients who underwent surgery or pacemaker implantation based on physician preference.[141] Although both groups showed subjective improvement, myectomy patients had a greater reduction in LVOT gradients and larger improvements in functional status.

Despite observations that some patients derive benefit, DDD pacing with short AV delays cannot be regarded as a primary treatment modality for LVOT obstruction in HOCM and is not routinely indicated for the alleviation of symptoms. There may be benefit of pacing therapy in selected subgroups, such as those older than 65 years or patients who are not candidates for myectomy or septal ablation because of co-morbidities. American College of Cardiology/American Heart Association/Heart Rhythm Society guidelines give pacing in

patients with HOCM who are refractory to pharmacological therapy a class IIb indication.[142] Pacing is indicated in HOCM patients with sinus node dysfunction or AV block, and may have utility in preventing bradycardia and allowing more aggressive drug therapy with β-blockers or verapamil. The European Society of Cardiology guidelines give pacing in patients with drug-refractory HOCM a class IIb indication.[143] There is no evidence that pacing reduces the risk of sudden death or overall mortality in HOCM.[144] Whether incorporating DDD pacing with short AV delays into implantable defibrillators plays a role in the treatment of HOCM patients is not well defined. Pacing therapy has not been shown to be beneficial in patients with minimal intraventricular gradients or

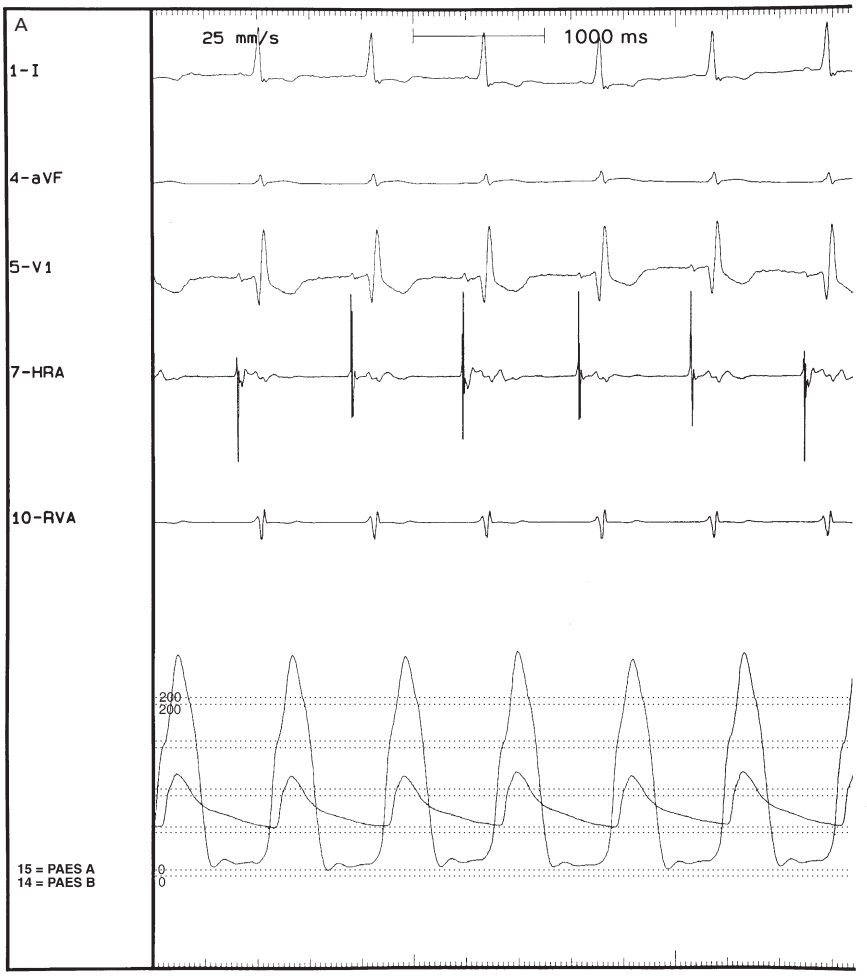


Figure 3.38 Tracings showing the impact of atrioventricular (AV) sequential pacing on left ventricular and femoral arterial pressure in a selected patient with hypertrophic obstructive cardiomyopathy. (A) The presence of a nearly 150-mmHg pressure gradient at baseline during sinus rhythm. (B) With AV sequential pacing at an AV interval of 75 ms, the pressure gradient decreases to 50–90 mmHg. The beat-to-beat variability of the measurement of this gradient is highlighted by the bottom tracing. Top to bottom: I, aVf; V_1, surface ECG leads; RA, right atrial intracardiac recording; RV, right ventricular intracardiac recording; and femoral and left ventricular pressure tracings (in mmHg) superimposed on each other. (Source: Sweeney MO, Ellenbogen KA. Implantable devices for the electrical management of heart disease: overview of indications for therapy and selected recent advances. In: Antman EM, ed. *Cardiovascular Therapeutics*, 2nd edn. Philadelphia: WB Saunders, 2002. Reproduced with permission of Elsevier.)

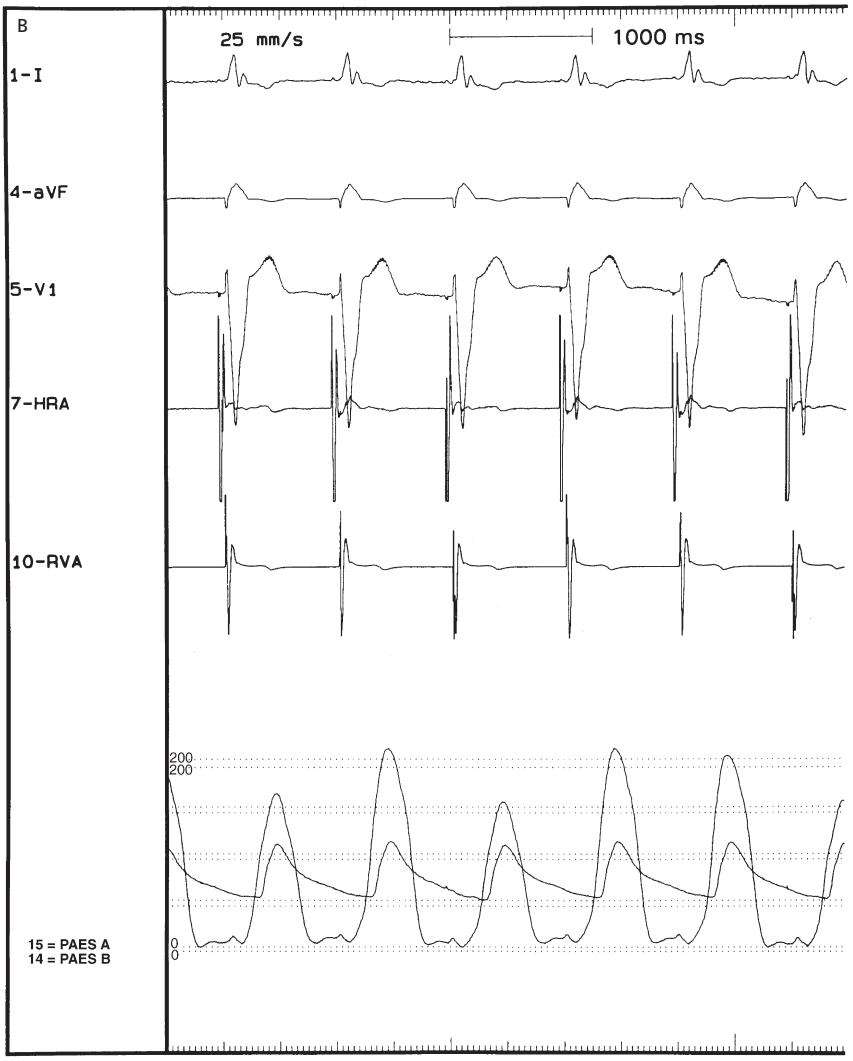


Figure 3.38 (*Continued*)

in those with non-obstructive hypertrophic cardiomyopathy, and is not indicated in the absence of bradycardia.

Pacemaker mode selection

A logical approach to pacemaker mode selection is to choose a mode that targets the underlying bradycardia and to avoid modes that electrically stimulate chambers that have appropriate intrinsic electrical and conduction properties. Selection of the appropriate pacing mode should fit the patient's electrical and hemodynamic status. This decision should incorporate consideration of the patient's electrical conduction status, including the atrial rhythm, AV conduction, ventricular conduction (i.e. QRS duration), chronotropic competence, and hemodynamic status, including the patient's LV systolic function and whether there is a history of heart failure. Pacemaker mode selection should be consistent with evidence from clinical trials indicating at least a lack of harm of a particular pacing mode and preferably supporting a potential benefit on important clinical outcomes. Striving to provide

AV synchrony, rate modulation, and CRT when clinical evidence supports their benefits, assists in this decision-making process.[145] Pacemaker mode selection algorithms in sinus node disease and AV block are shown in Figure 3.39 and Figure 3.40.

In pure sinus node dysfunction with normal AV conduction, atrial pacing should be the primary pacing mode and RV stimulation should be avoided as much as possible. This can be accomplished either using atrial pacing (AAI) alone or with a dual chamber pacing (DDD) system, preferably one that incorporates an algorithm that reduces frequency of unnecessary ventricular pacing. These pacing mode selections are supported by evidence from clinical trials indicating a reduction in incidence of AF and progression to chronic AF, a lower risk of developing pacemaker syndrome, and small improvements in quality of life with atrial-based compared with single chamber RV pacing (see Table 3.1).

About 20% of patients with sinus node dysfunction will have some degree of AV conduction disturbance at baseline.[30] Within 5 years following pacemaker implantation, the risk of developing AV block is 3–35%.[34] Pre-existing PR interval prolongation (>200 ms), LBBB, or a low Wenckebach rate (<100 bpm) are predictors for subsequent requirement for implantation of a ventricular lead.[146–149] Notably, trials have not demonstrated a beneficial effect on long-term clinical outcomes comparing atrial with dual-chamber pacing. However, there is an incremental risk of a complication associated with an operative revision from single chamber atrial to dual chamber pacing necessitated by the development of AV block in this population. Therefore, most implanters prefer to implant a dual chamber rather than an AAI-only pacing system in patients with sinus node disease, even in the presence of normal AV conduction. An AAI pacing system might still be considered on occasion in carefully selected, younger patients who are expected to require decades of pacemaker therapy in the presence of sinus node disease, but who show no evidence of AV or ventricular conduction abnormality. The 2012 HRS/ACCF Expert Consensus Statement on Pacemaker Device and Mode Selection support these recommendations.[34]

In patients with AV block, any pacing mode that provides ventricular pacing support (i.e. single chamber ventricular, single lead VDD, dual chamber or biventricular) will prevent bradycardia.[34] However, single chamber ventricular pacing will not maintain AV synchrony and non-CRT pacing modes will not prevent the potential deleterious effects of long-term RV pacing. The optimal pacing mode for patients with AV conduction disease has been the subject of a number of clinical trials and remains an area of debate. Trials have investigated the need for dual chamber rather than single chamber ventricular pacing in elderly patients and the need for biventricular pacing in patients with LV ejection fractions above 35–40%.[31,100,101] Most implanters prefer dual chamber pacing over single chamber ventricular pacing for patients with AV block due to a desire to preserve AV synchrony and chronotropic response driven by the sinus node rather than by an artificial rate-adaptation sensor. This may be most important in younger or more physically active patients and in those with any degree of systolic and/or diastolic dysfunction in whom the maintenance of AV synchrony is needed for preserving optimal hemodynamics. The atrial arrhythmia detection features in dual chamber pacemakers may have the added benefit of detection of atrial tachyarrhythmias that may result in therapeutic interventions, including therapy for stroke prevention. Single chamber ventricular pacing is chosen primarily for patients with AV conduction disease who have permanent AF or longstanding persistent AF if no attempt to restore sinus rhythm is contemplated, or in whom pacing would rarely be required.

Because of the need for ventricular pacing support in patients with advanced AV conduction disease, alternatives to RV apical pacing should be considered to address the issue of forced ventricular desynchronization. If it is anticipated that frequent ventricular pacing will be required (>40%) in a patient with AV block and symptomatic, LV dysfunction (NYHA class II–IV and LVEF ≤35%), then CRT should be utilized. For patients with AV block and normal or mildly impaired LV systolic function (LVEF >35%), alternative RV pacing sites (His, RV septum) may be considered. However, existing clinical data are equivocal in support of alternative RV pacing sites; there is no evidence to suggest an increase in

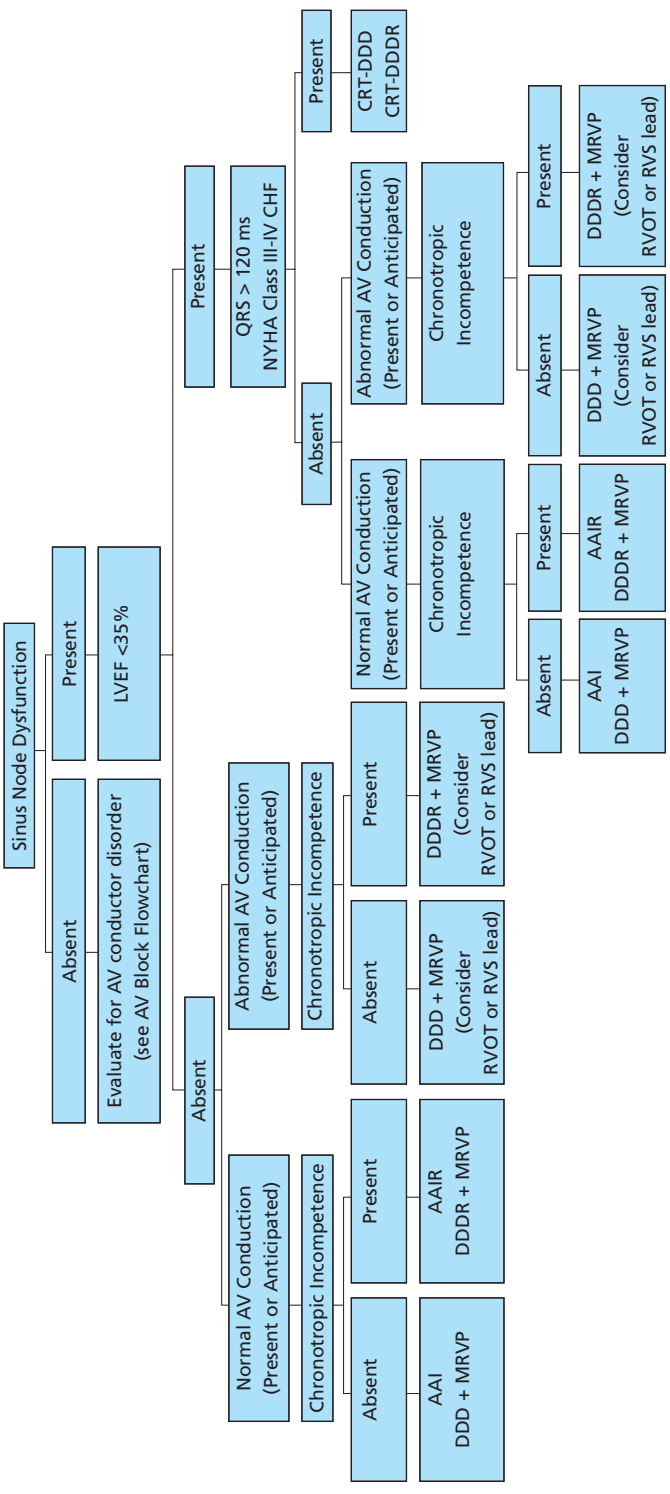


Figure 3.39 Pacemaker mode selection algorithm for sinus node dysfunction. AAI, atrial demand pacing; AAIR, atrial demand rate-adaptive pacing; AV, atrioventricular; CHF, congestive heart failure; CRT, cardiac resynchronization therapy; DDD, dual chamber pacing; DDDR, dual chamber rate-adaptive pacing; LVEF, left ventricular ejection fraction; MRVP, minimize right ventricular pacing; NYHA, New York Heart Association; RVOT, right ventricular outflow tract; RVS, right ventricular septal. Pacemaker codes are discussed in detail in Chapter 6.

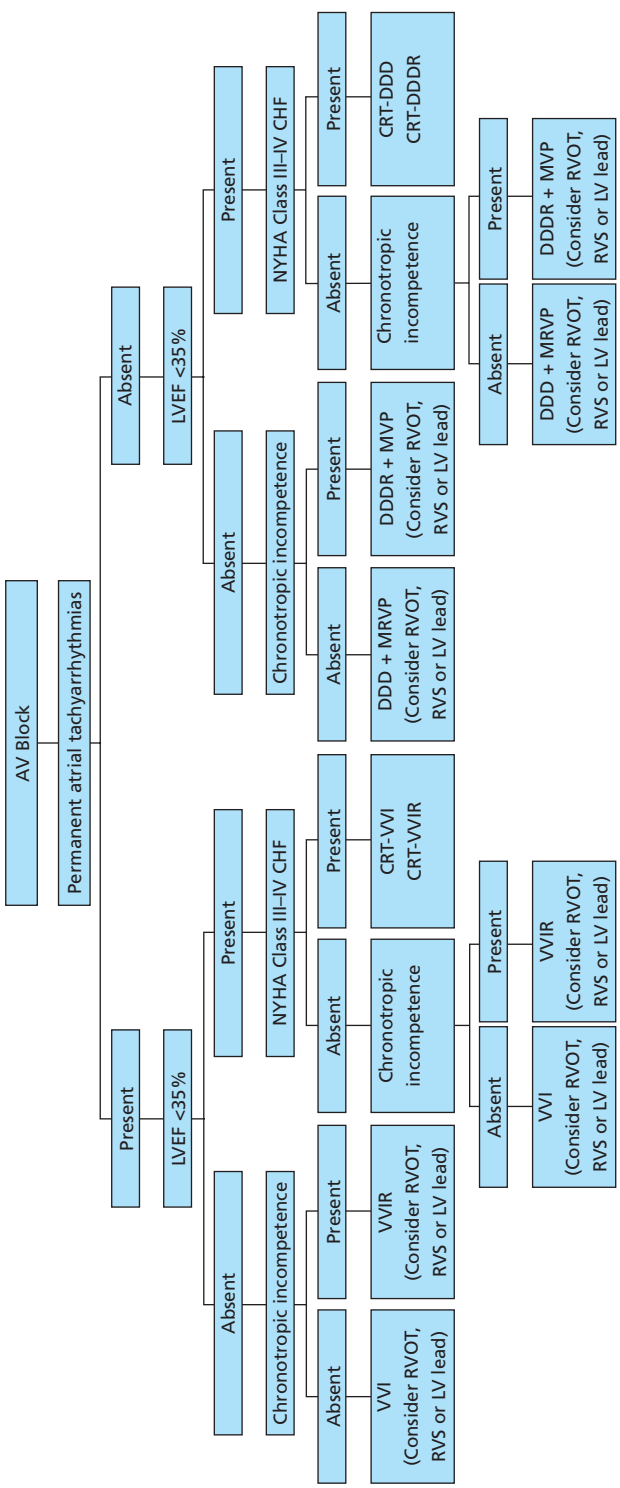


Figure 3.40 Pacemaker mode selection algorithm for atrioventricular block. AV, atrioventricular; CHF, congestive heart failure; CRT, cardiac resynchronization therapy; DDD, dual chamber pacing; DDDR, dual chamber rate-adaptive pacing; LV, left ventricular; LVEF, left ventricular ejection fraction; NYHA, New York Heart Association; MRVP, minimize right ventricular pacing; RVOT, right ventricular outflow tract; RVS, right ventricular septal; VVI, ventricular demand pacing; VVIR, ventricular demand rate-adaptive pacing. Pacemaker codes are discussed in detail in Chapter 6.

detrimental effects, but no definitive evidence of improved clinical outcomes over the RV apex. Notably, atrio-biventricular pacing may be the optimal pacing mode for hemodynamic indications in patients who require frequent ventricular pacing, regardless of baseline ejection fraction. However, guidelines do not yet recommend this therapy in patients in whom LVEF is greater than 35–40%.

Several trials of biventricular pacing in patients requiring pacing for bradycardia have been completed recently. In a study of patients with bradycardia and a normal ejection fraction, patients randomized to RV pacing had a lower mean LVEF ($55 \pm 9\%$ vs. $62 \pm 7\%$; $P < .001$) and a larger LV end-systolic volume (36 ± 16 mL vs. 28 ± 10 mL; $P < .001$) than patients in the biventricular pacing group at 12 months.[100] Results from the Biventricular versus RV Pacing in Heart Failure Patients with Atrioventricular Block (BLOCK HF) study comparing RV with biventricular pacing in patients with AV block requiring ventricular pacing and mild-to-moderate LV dysfunction and heart failure (LVEF $\leq$50%, NYHA class I–III) demonstrated that biventricular pacing led to a 26% reduction in the combined end-point of mortality, heart failure-related urgent care, and increase in end-systolic volume index.[101]

When chronotropic incompetence accompanies sinus node dysfunction or AV block, as it often does in the pacemaker population, then rate-adaptive pacing might be considered. However, the rate-adaptive pacing mode should not be programmed at the expense of a greater frequency of ventricular pacing and promotion of ventricular dyssynchrony. Rate-adaptive pacing may promote ventricular pacing, particularly if rate-adaptive AV delays are programmed. Furthermore, it must be recognized that there is an absence of conclusive data showing that DDDR pacing is superior to DDD with regard to improved quality of life and reduced symptoms.[145] Thus, rate-adaptive pacing should not be used routinely in pacemaker patients unless there is a strong clinical need (i.e. highly symptomatic patients with inadequate chronotropic response to exercise). Furthermore, the sinus node should be given priority as the primary modulator of heart rate when its chronotropic function is unimpaired. Thus, for patients with complete AV block and preserved sinoatrial nodal function, an artificial sensor is not required for rate-adaptive pacing. The VDD and DDD pacing modes provide rate modulation and AV synchrony in this setting. Patients with sinus node dysfunction and an inadequate chronotropic response to exercise are candidates for AAIR or DDDR pacemakers, depending on AV conduction status. For patients with paroxysmal or chronic atrial arrhythmias, a rate-adaptive pacing system is often preferred. Patients with chronic AF or flutter and inappropriately slow ventricular rates during exercise are managed best with VVIR pacing.

References

1 Sweeney MO, Hellkamp AS. Heart failure during cardiac pacing. *Circulation* 2006; 113: 2082–2088.
2 Sowton E. Haemodynamic studies in patients with artificial pacemakers. *Br Heart J* 1964; 26: 737–746.
3 Narahara KA, Blettel ML. Effect of rate on left ventricular volumes and ejection fraction during chronic ventricular pacing. *Circulation* 1983; 67: 323–329.
4 Leung SK, Lau CP. Developments in sensor-driven pacing. *Cardiol Clin* 2000; 18: 113–155.
5 Astrand PO, Rodahl K. *Textbook of Work Physiology*, 2nd edn. New York: McGraw-Hill, 1977.
6 Linnarsson D. Dynamics of pulmonary gas exchange and heart rate changes at start and end of exercise. *Acta Physiol Scand* 1974; 415: 1–68.
7 Ellestad MH, Wan MKC. Predictive implications of stress testing: follow-up of 2700 subjects after maximum treadmill testing. *Circulation* 1975; 51: 363–369.
8 Wilkoff BL, Corey J, Blackburn G. A mathematical model of the cardiac chronotropic response to exercise. *J Electrophysiol* 1989; 3: 176–80.
9 Melzer C, Witte J, Reibis R, *et al.* Predictors of chronotropic incompetence in the pacemaker patient population. *Europace* 2006; 8: 70–75.
10 Dresing TJ, Blackstone EH, Pashkow FJ, Snader CE, Marwick TH, Lauer MS. Usefulness of impaired chronotropic response to exercise as a predictor of mortality, independent of the severity of coronary artery disease. *Am J Cardiol* 2000; 86: 602–609.
11 Brubaker PH, Kitzman DW. Prevalence and management of chronotropic incompetence in heart failure. *Curr Cardiol Rep* 2007; 9: 229–235.
12 Bellocci F, Spampinato A, Ricci R, *et al.* Antiarrhythmic benefits of dual chamber stimulation with rate-response in patients with paroxysmal atrial fibrillation and chronotropic incompetence: a prospective, multicentre study. *Europace* 1999; 1: 220–225.

13 Pena JL, Hussein SJ, Lamas GA, *et al.* A comparison of clinical events in a randomized clinical trial of DDDR versus DDD pacing. *Heart Rhythm* 2005; 2: S172 (abstract).
14 Lamas GA, Knight JD, Sweeney MO, *et al.* Impact of rate-modulated pacing on quality of life and exercise capacity—evidence from the Advanced Elements of Pacing Randomized Controlled Trial (ADEPT). *Heart Rhythm* 2007; 4: 1125–1132.
15 Shukla HH, Flaker GC, Hellkamp AS, *et al.* Clinical and quality of life comparison of accelerometer, piezoelectric crystal, and blended sensors in DDDR-paced patients with sinus node dysfunction in the mode selection trial (MOST). *Pacing Clin Electrophysiol* 2005; 28: 762–770.
16 Furman S. The present status of cardiac pacing. *Hertz* 1991; 16: 171–181.
17 Lamas GA. Physiological consequences of normal atrioventricular conduction: applicability to modern cardiac pacing. *J Card Surg* 1989; 4: 89–98.
18 Panidis IP, Ross J, Munley B, *et al.* Diastolic mitral regurgitation in patients with atrio-ventricular conduction abnormalities: a common finding by Doppler echocardiography. *J Am Coll Cardiol* 1986; 7: 768–774.
19 Timek T, Dagum P, Lai DT, *et al.* The role of atrial contraction in mitral valve closure. *J Heart Valve Dis* 2001; 10: 312–319.
20 Barold SS, Ovsyshcher IE. Pacemaker-induced mitral regurgitation. *Pacing Clin Electrophysiol* 2005; 28: 357–60.
21 Salukhe TV, Henein MY, Sutton R. Pacing in heart failure: patient and pacing mode selection. *Eur Heart J* 2003; 24: 977–986.
22 Hauser J, Behnke IM, Zervan K, Pees C. Noninvasive measurement of atrial contribution to the cardiac output in children and adolescents with congenital complete atrioventricular block treated with dual-chamber pacemakers. *Am J Cardiol* 2010; 107: 92–95.
23 Gold MR, Brockman R, Peters RW, Olsovsky MR, Shorofsky SR. Acute hemodynamic effects of right ventricular pacing site and pacing mode in patients with congestive heart failure secondary to either ischemic or idiopathic dilated cardiomyopathy. *Am J Cardiol* 2000; 85: 1106–1109.
24 Reynolds DW, Wilson MF, Burow RD, *et al.* Hemodynamic evaluation of atrioventricular sequential vs. ventricular pacing in patients with normal and poor ventricular function at variable heart rates and posture. *J Am Coll Cardiol* 1983; 1: 636 (abstract).
25 Taylor JA, Morillo CA, Eckberg DL, Ellenbogen KA. Higher sympathetic nerve activity during ventricular (VVI) than during dual-chamber (DDD) pacing. *J Am Coll Cardiol* 1996; 28: 1753–1758.
26 Horie H, Tsutamoto T, Ishimoto N, *et al.* Plasma brain natriuretic peptide as a biochemical marker for atrioventricular sequence in patients with pacemakers. *Pacing Clin Electrophysiol* 1999; 22: 282–290.
27 Andersen HR, Nielsen JC, Thomsen PE, *et al.* Long-term follow-up of patients from a randomized trial of atrial versus ventricular pacing for sick-sinus syndrome. *Lancet* 1997; 350: 1210–1216.
28 Lamas GA, Orav EJ, Stambler BS, *et al.* for the PASE Investigators. Quality of life and clinical outcomes in elderly patients treated with ventricular pacing as compared with dual-chamber pacing. *N Engl J Med* 1998; 338: 1097–1104.
29 Connolly SJ, Kerr CR, Gent M, *et al.* Effects of physiologic pacing versus ventricular pacing on the risk of stroke and death due to cardiovascular causes. Canadian Trial of Physiologic Pacing Investigators. *N Engl J Med* 2000; 342: 1385–1391.
30 Lamas GA, Lee KL, Sweeney MO, *et al.* Ventricular pacing or dual-chamber pacing for sinus-node dysfunction. *N Engl J Med* 2002; 346: 1854–1862.
31 Tofff WD, Camm AJ, Skehan JD, for the United Kingdom Pacing and Cardiovascular Events Trial (UKPACE) Investigators. Single chamber versus dual-chamber pacing for high-grade atrioventricular block. *N Engl J Med* 2005; 353: 145–155.
32 Healey JS, Toff WD, Lamas GA, *et al.* Cardiovascular outcomes with atrial-based pacing compared with ventricular pacing: meta-analysis of randomized trials, using individual patient data. *Circulation* 2006; 114; 11–17.
33 Fleischmann KE, Orav EJ, Lamas GA *et al.* Pacemaker implantation and quality of life in the Mode Selection Trial (MOST). *Heart Rhythm* 2006; 3: 653–659.
34 Gillis AM, Russo AM, Ellenbogen KA, *et al.* HRS/ACCF expert consensus statement on pacemaker device and mode selection. *J Am Coll Cardiol* 2012; 60: 682–703.
35 Crystal E, Ovsyshcher IE. Cardiac output-based versus empirically programmed AV interval—how different are they? *Europace* 1999; 1: 121–125.
36 Ovsyshcher IE. Toward physiological pacing: optimization of cardiac hemodynamics by AV delay adjustment. *Pacing Clin Electrophysiol* 1997; 20: 861–865.
37 Meisner JS, McQueen DM, Ishida Y, *et al.* Effects of timing of atrial systole on LV filling and mitral valve closure: computer and dog studies. *Am J Physiol* 1985; 249(3 Pt 2): H604–619.
38 Rossi R, Muia N Jr, Turco V, *et al.* Short atrioventricular delay reduces the degree of mitral regurgitation in patients with a sequential dual-chamber pacemaker. *Am J Cardiol* 1997; 80: 901.
39 Shinbane JS, Chu E, DeMarco T, *et al.* Evaluation of acute dual-chamber pacing with a range of

atrioventricular delays on cardiac performance in refractory heart failure. *J Am Coll Cardiol* 1997; 30: 1295.

40 Capucci A, Romano S, Puglisi A, *et al*. Dual chamber pacing with optimal AV delay in congestive heart failure: a randomized study. *Europace* 1999; 1: 174.

41 Brecker SJ, Xiao HB, Sparrow J, Gibson DG. Effects of dual-chamber pacing with short atrioventricular delay in dilated cardiomyopathy. *Lancet* 1992; 340(8831): 1308–1312.

42 Nishimura RA, Hayes DL, Holmes DR Jr, Tajik AJ. Mechanism of hemodynamic improvement by dual-chamber pacing for severe left ventricular dysfunction: an acute Doppler and catheterization hemodynamic study. *J Am Coll Cardiol* 1995; 25: 281–288.

43 Gold MR, Feliciano Z, Gottlieb SS, Fisher ML. Dual-chamber pacing with a short atrioventricular delay in congestive heart failure: a randomized study. *J Am Coll Cardiol* 1995; 26: 967–973.

44 Barold SS, Ilercil A, Leonelli F, Herweg B. First-degree atrioventricular block: clinical manifestations, indications for pacing, pacemaker management & consequences during cardiac resynchronization. *J Interv Card Electrophysiol* 2006; 17: 139.

45 Strohmer B, Pichler M, Froemmel M, Migschitz M, Hintringer F; ELVIS Study Group. Evaluation of atrial conduction time at various sites of right atrial pacing and influence on atrioventricular delay optimization by surface electrocardiography. *Pacing Clin Electrophysiol* 2004; 27: 468–474.

46 Chirife R, Pastori J, Mosto H, Arrascaite M, Sambelashvili A. Prediction of interatrial and interventricular electromechanical delays from P/QRS measurements: Value for pacemaker timing optimization. *Pacing Clin Electrophysiol* 2008; 31: 177–183.

47 Sorajja D, Bhakta MD, Scott LRP, Gregory T Altemose GT, Srivathsan K. Utilization of electrocardiographic P-wave duration for AV interval optimization in dual-chamber pacemakers. *Indian Pacing Electrophysiol J* 2010; 10: 383–392.

48 Gold MR, Niazi I, Giudici M, *et al*. A prospective comparison of AV delay programming methods for hemodynamic optimization during cardiac resynchronization therapy. *J Cardiovasc Electrophysiol* 2007; 18: 490–496.

49 Jansen AHBF, van Dantzig JM, van der Voort PH, Aarnoudse W, Van Gelder BM, Peels KH. Correlation of echo-Doppler optimization of atrioventricular delay in cardiac resynchronization therapy with invasive hemodynamics in patients with heart failure secondary to ischemic or idiopathic dilated cardiomyopathy. *Am J Cardiol* 2006; 97: 552–557.

50 Kedia NNK, Apperson-Hansen C, Wang C, Tchou P, Wilkoff BL, Grimm RA. Usefulness of atrioventricular delay optimization using Doppler assessment of mitral inflow in patients undergoing cardiac resynchronization therapy. *Am J Cardiol* 2006; 98: 780–785.

51 Gorcsan J III, Abraham T Agler DA, *et al*. Echocardiography for cardiac resynchronization therapy: recommendations for performance and reporting-a report from the American society of echocardiography dyssynchrony writing group endorsed by the heart rhythm society. *J Am Soc Echocardiogr* 2008; 21: 191–213.

52 Ellenbogen KA, Gold MR, Meyer TE, *et al*. Primary results from the SmartDelay determined AV optimization: a comparison to other AV delay methods used in cardiac resynchronization therapy (SMART-AV) trial: a randomized trial comparing empirical, echocardiography-guided, and algorithmic atrioventricular delay programming in cardiac resynchronization therapy. *Circulation* 2010; 122: 2660–2668.

53 Cheng A, Gold MR, Waggoner AD, *et al*. Potential mechanisms underlying the effect of gender on response to cardiac resynchronization therapy: insights from the SMART-AV multicenter trial. *Heart Rhythm* 2012; 9: 736–741.

54 Daubert C, Ritter P, Mabo P, *et al.* AV delay optimization in DDD and DDDR pacing. In: Barold SS, Mugica J, eds. *New Perspectives in Cardiac Pacing 3*. Mt Kisco, NY: Futura, 1993: 259–287.

55 Wilkoff BL, Cook JR, Epstein AE, *et al.* Dual-chamber pacing or ventricular backup pacing in patients with an implantable defibrillator: the Dual Chamber and VVI Implantable Defibrillator (DAVID) Trial. *JAMA* 2002; 288: 3115–3123.

56 Steinberg JS, Fischer A, Wang P, *et al.* The clinical implications of cumulative right ventricular pacing in the multicenter automatic defibrillator trial II. *J Cardiovasc Electrophysiol* 2005; 16: 359–365.

57 Nielsen JC, Thomsen PE, Højberg S, *et al.*; DANPACE investigators. Atrial fibrillation in patients with sick sinus syndrome: the association with PQ-interval and percentage of ventricular pacing. *Europace* 2012; 14: 682–689.

58 Ellenbogen KA, Wood MA, Stambler BS. Pacemaker syndrome: clinical, hemodynamic and neurohumoral features. In: Barold SS, Mugica J, eds. *New Perspectives in Cardiac Pacing 3*. Armonk, NY: Futura Publishing, 1993: 85–112.

59 Ellenbogen KA, Gilligan DM, Wood MA, Morillo C, Barold SS. The pacemaker syndrome—a matter of definition. *Am J Cardiol* 1997; 79: 1226–1229.

60 Link MS, Hellkamp AS, Estes NA 3rd, *et al.*; MOST Study Investigators. High incidence of pacemaker syndrome in patients with sinus node dysfunction treated with ventricular-based pacing in the Mode Selection Trial (MOST). *J Am Coll Cardiol* 2004; 43: 2066–2071.

61 Ellenbogen KA, Stambler BS, Orav EJ, *et al.* Clinical characteristics of patients intolerant to VVIR pacing. *Am J Cardiol* 2000; 86: 59–63.
62 Sanagala T, Johnston SL, Groot GD, Rhine DK, Varma N. Left atrial mechanical responses to right ventricular pacing in heart failure patients: Implications for atrial fibrillation. *J Cardiovasc Electrophysiol* 2011; 22: 866–874.
63 Sassone B, De Simone N, Parlangeli G, Tortorici R, Biancoli S, Di Pasquale G. Pacemaker-induced mitral regurgitation: prominent role of abnormal ventricular activation-sequence versus altered atrioventricular synchrony. *Ital Heart J* 2001; 2: 441–448.
64 Nielsen JC, Bottcher M, Nielsen T, *et al.* Regional myocardial blood flow in patients with sick sinus syndrome randomized to long-term single chamber atrial or dual chamber pacing—effect of pacing mode and rate. *J Am Coll Cardiol* 2000; 35: 1453–1461.
65 Van Oosterhout MF, Prinzen FW, Arts T, *et al.* Asynchronous electrical activation induces inhomogeneous hypertrophy of the left ventricular wall. *Circulation* 1998; 98: 588–595.
66 Prinzen FW, Cheriex EM, Delhaas T, *et al.* Asymmetric thickness of the left ventricular wall resulting from asynchronous electrical activation. A study in patients with left bundle branch block and in dogs with ventricular pacing. *Am Heart J* 1995; 130: 1045–1053.
67 Lee MA, Dae MW, Langberg JJ, *et al.* Effects of long-term right ventricular apical pacing on left ventricular perfusion, innervation, function and histology. *J Am Coll Cardiol* 1994; 24: 225–232.
68 Tantengco MV, Thomas RL, Karpawich PP. Left ventricular dysfunction after long-term right ventricular apical pacing in the young. *J Am Coll Cardiol* 2001; 37: 2093–2100.
69 Sweeney MO, Hellkamp AS, Ellenbogen KA, *et al.* Adverse effect of ventricular pacing on heart failure and atrial fibrillation among patients with normal baseline QRS duration in a clinical trial of pacemaker therapy for sinus node dysfunction. *Circulation* 2003; 107: 2932–2937.
70 O'Keefe JH Jr, Abuissa H, Jones PG, *et al.* Effect of chronic right ventricular apical pacing on left ventricular function. *Am J Cardiol* 2005; 95: 771–773.
71 Freudenberger RS, Wilson AC, Lawrence-Nelson J, Hare JM, Kostis JB. Permanent pacing is a risk factor for the development of heart failure. *Am J Cardiol* 2005; 95: 671–675.
72 Tse H-F, Lau C-P. Long-term effect of right ventricular pacing on myocardial perfusion and function. *J Am Coll Cardiol* 1997; 29: 744–749.
73 Sweeney MO, Bank AJ, Nsah E, *et al.*, the Search AV Extension and Managed Ventricular Pacing for Promoting Atrioventricular Conduction (SAVE PACe) Trial. Minimizing ventricular pacing to reduce atrial fibrillation in sinus-node disease. *N Engl J Med* 2007; 357: 1000–1008.
74 Nielsen JC, Thomsen PE, Hojberg S, *et al.* A comparison of single-lead atrial pacing with dual-chamber pacing in sick sinus syndrome. *Eur Heart J* 2011; 32: 686–696.
75 Riahi S, Nielsen JC, Hjortshøj S, *et al.*; DANPACE Investigators. Heart failure in patients with sick sinus syndrome treated with single lead atrial or dual-chamber pacing: no association with pacing mode or right ventricular pacing site. *Europace* 2012; 14: 1475–1482.
76 Yu CM, Chan JY, Zhang Q, *et al.* Biventricular pacing in patients with bradycardia and normal ejection fraction. *N Engl J Med* 2009; 361: 2123–2134.
77 Sharma AD, Rizo-Patron C, Hallstrom AP, *et al.*; DAVID Investigators. Percent right ventricular pacing predicts outcomes in the DAVID trial. *Heart Rhythm* 2005; 2: 830–834.
78 Steinberg JS, Fischer A, Wang P, *et al.* The clinical implications of cumulative right ventricular pacing in the multicenter automatic defibrillator trial II. *J Cardiovasc Electrophysiol* 2005; 16: 359–365.
79 Sweeney MO, Shea JV, Fox V, *et al.* Randomized trial of a new minimal ventricular pacing mode in patients with dual chamber ICDs. *Pacing Clin Electrophysiol* 2003; 26: 973 (abstract).
80 Sweeney MO, Shea JB, Fox V, *et al.* Randomized pilot study of a new atrial-based minimal ventricular pacing mode in dual-chamber implantable cardioverter-defibrillators. *Heart Rhythm* 2004; 1: 160–167.
81 Olshansky B, Day JD, Moore S, *et al.* Is dual-chamber programming inferior to single-chamber programming in an implantable cardioverter-defibrillator? Results of the INTRINSIC RV (Inhibition of Unnecessary RV Pacing With AVSH in ICDs) study. *Circulation* 2007; 115: 9–16.
82 Olshansky B, Day JD, Lerew DR, Brown S, Stolen KQ. Eliminating right ventricular pacing may not be best for patients requiring implantable cardioverter defibrillators. *Heart Rhythm* 2007; 4: 886–891.
83 Kaye G, Stambler BS, Yee R. Search for the optimal right ventricular pacing site: Design and implementation of three randomized multicenter clinical trials. *Pacing Clin Electrophysiol* 2009; 32: 426–433.
84 Deshmukh P, Casavant DA, Romanyshyn M, Anderson K. Permanent direct His-bundle pacing: a novel approach to cardiac pacing in patients with normal His–Purkinje activation. *Circulation* 2000; 101: 869–77.
85 Morina Vazquez P, Barba Pichardo R, Venegas Gamero J, *et al.* Permanent pacing of the bundle of His after radiofrequency atrioventricular node ablation in

patients with suprahisian conduction disturbances. *Rev Esp Cardiol* 2001; 54: 1385–1393.

86 Deshmukh PM, Romanyshyn M. Direct His-bundle pacing: present and future. *Pacing Clin Electrophysiol* 2004; 27(6 Pt 2): 862–870.

87 Zanon F, Baracca E, Aggio S, *et al.* A feasible approach for direct his-bundle pacing using a new steerable catheter to facilitate precise lead placement. *J Cardiovasc Electrophysiol* 2006; 17: 29–33.

88 Occhetta E, Bortnik M, Magnani A, *et al.* Prevention of ventricular desynchronization by permanent para-Hisian pacing after atrioventricular node ablation in chronic atrial fibrillation: a crossover, blinded, randomized study versus apical right ventricular pacing. *J Am Coll Cardiol* 2006; 47: 1938–1945.

89 Narula OS. Longitudinal dissociation in the His bundle. Bundle branch block due to asynchronous conduction within the His bundle in man. *Circulation* 1977; 56: 996–1006.

90 Barba-Pichardo R, Manovel A, Fernández-Gómez F, Moriña-Vázquez P, Venegas-Gamero J, Herrera-Carranza H. Ventricular resynchronization therapy by direct His-bundle pacing with internal cardioverter defibrillator. *Europace* 2013; 15: 83–88.

91 Gold MR, Brockman R, Peters RW, *et al.* Acute hemodynamic effects of right ventricular pacing site and pacing mode in patients with congestive heart failure secondary to either ischemic or idiopathic dilated cardiomyopathy. *Am J Cardiol* 2000; 85: 1106–1109.

92 Gold MR, Shorofsky SR, Metcalf MD, *et al.* The acute hemodynamic effects of right ventricular septal pacing in patients with congestive heart failure secondary to ischemic or idiopathic dilated cardiomyopathy. *Am J Cardiol* 1997; 79: 679–681.

93 Giudici MC, Thornburg GA, Buck DL, *et al.* Comparison of right ventricular outflow tract and apical lead permanent pacing on cardiac output. *Am J Cardiol* 1997; 79: 209–212.

94 Bourke JP, Hawkins T, Keavey P, *et al.* Evolution of ventricular function during permanent pacing from either right ventricular apex or outflow tract following AV-junctional ablation for atrial fibrillation. *Europace* 2002; 4: 219–228.

95 Schwaab B, Frohlig G, Alexander C, *et al.* Influence of right ventricular stimulation site on left ventricular function in atrial synchronous ventricular pacing. *J Am Coll Cardiol* 1999; 33: 317–323.

96 Tse HF, Yu C, Wong KK, *et al.* Functional abnormalities in patients with permanent right ventricular pacing: the effect of sites of electrical stimulation. *J Am Coll Cardiol* 2002; 40: 1451–1458.

97 Stambler BS, Ellenbogen K, Zhang X, *et al.* Right ventricular outflow versus apical pacing in pacemaker patients with congestive heart failure and atrial fibrillation. *J Cardiovasc Electrophysiol* 2003; 14: 1180–1186.

98 Shimony A, Eisenberg MJ, Filion KB, Amit G. Beneficial effects of right ventricular non-apical vs. apical pacing: a systematic review and meta-analysis of randomized-controlled trials. *Europace* 2012; 14(1): 81–91.

99 Lieberman R, Padeletti L, Schreuder J, *et al.* Ventricular pacing lead location alters systemic hemodynamics and left ventricular function in patients with and without reduced ejection fraction. *J Am Coll Cardiol* 2006; 48: 1634–1641.

100 Yu CM, Chan JY, Zhang Q, *et al.* Biventricular pacing in patients with bradycardia and normal ejection fraction. *N Engl J Med* 2009; 361: 2123–2134.

101 Curtis AB, Worley SJ, Adamson PB, *et al.* Biventricular pacing for atrioventricular block and systolic dysfunction. *N Engl J Med* 2013; 368: 1585–1593.

102 Bristow MR, Saxon LA, Boehmer J, *et al.* Cardiac-resynchronization therapy with or without an implantable defibrillator in advanced chronic heart failure. *N Engl J Med* 2004; 350: 2140–2150.

103 Cleland JG, Daubert JC, Erdmann E, *et al.* The effect of cardiac resynchronization on morbidity and mortality in heart failure. *N Engl J Med* 2005; 352: 1539–1549.

104 Moss AJ, Hall WJ, Cannom DS, *et al.* Cardiac-resynchronization therapy for the prevention of heart-failure events. *N Engl J Med* 2009; 361: 1329–1338.

105 Leclerq C KD. Retiming the failing heart: principles and current clinical status of cardiac resynchronization. *J Am Coll Cardiol* 1999; 39: 194–201.

106 Wiggers CJ. Dynamics of ventricular contraction under abnormal conditions. *Circulation* 1952; 5: 321–348.

107 Baldasseroni S, Opasich C, Gorini M, *et al.* Left bundle-branch block is associated with increased 1-year sudden and total mortality rate in 5517 outpatients with congestive heart failure: a report from the Italian network on congestive heart failure. *Am Heart J* 2002; 143: 398–405.

108 Prinzen FW, Hunter WC, Wyman BT, McVeigh ER. Mapping of regional myocardial strain and work during ventricular pacing: experimental study using magnetic resonance imaging tagging. *J Am Coll Cardiol* 1999; 33: 1735–1742.

109 Auricchio A, Stellbrink C, Block M, *et al.* Effect of pacing chamber and atrioventricular delay on acute systolic function of paced patients with congestive heart failure. The pacing therapies for congestive heart failure study group. *Circulation* 1999; 99: 2993–3001.

110 Blanc JJ, Etienne Y, Gilard M, *et al.* Evaluation of different ventricular pacing sites in patients with severe heart failure: results of an acute hemodynamic study. *Circulation* 1997; 96: 3273–3277.

111 Kass DA, Chen CH, Curry C, *et al*. Improved left ventricular mechanics from acute VDD pacing in patients with dilated cardiomyopathy and ventricular conduction delay. *Circulation* 1999; 99: 1567–1573.

112 Nelson GS, Berger RD, Fetics BJ, *et al*. Left ventricular or biventricular pacing improves cardiac function at diminished energy cost in patients with dilated cardiomyopathy and left bundle-branch block. *Circulation* 2000; 102: 3053–3059.

113 Ritter P, Delnoy PP, Padeletti L, *et al*. A randomized pilot study of optimization of cardiac resynchronization therapy in sinus rhythm patients using a peak endocardial acceleration sensor vs. standard methods. *Europace* 2012; 14: 1324–1333.

114 Yu CM, Fung JW, Zhang Q, *et al*. Tissue Doppler imaging is superior to strain rate imaging and postsystolic shortening on the prediction of reverse remodeling in both ischemic and nonischemic heart failure after cardiac resynchronization therapy. *Circulation* 2004; 110: 66–73.

115 Lee KL, Burnes JE, Mullen TJ, Hettrick DA, Tse HF, Lau CP. Avoidance of right ventricular pacing in cardiac resynchronization therapy improves right ventricular hemodynamics in heart failure patients. *J Cardiovasc Electrophysiol* 2007; 18: 497–504.

116 Varma N, Jia P, Ramanathan C, Rudy Y. RV electrical activation in heart failure during right, left, and biventricular pacing. *JACC Cardiovasc Imaging* 2010; 3: 567–575.

117 Auricchio A, Stellbrink C, Sack S, *et al*. Long-term clinical effect of hemodynamically optimized cardiac resynchronization therapy in patients with heart failure and ventricular conduction delay. *J Am Coll Cardiol* 2002; 39: 2026–2033.

118 Auricchio A, Stellbrink C, Butter C, *et al*. Clinical efficacy of cardiac resynchronization therapy using left ventricular pacing in heart failure patients stratified by severity of ventricular conduction delay. *J Am Coll Cardiol* 2003; 42: 2109–2116.

119 Martin DO, Lemke B, Birnie D, *et al*. Investigation of a novel algorithm for synchronized left-ventricular pacing and ambulatory optimization of cardiac resynchronization therapy: results of the adaptive CRT trial. *Heart Rhythm* 2012; 9: 1807–1814.

120 Derval N, Steendijk P, Gula LJ, *et al*. Optimizing hemodynamics in heart failure patients by systematic screening of left ventricular pacing sites: the lateral left ventricular wall and the coronary sinus are rarely the best sites. *J Am Coll Cardiol* 2010; 55: 566–575.

121 Ginks MR, Shetty AK, Lambiase PD, *et al*. Benefits of endocardial and multisite pacing are dependent on the type of left ventricular electric activation pattern and presence of ischemic heart disease: insights from electroanatomic mapping. *Circ Arrhythm Electrophysiol* 2012; 5: 889–897.

122 Mills RW, Cornelussen RN, Mulligan LJ, *et al*. Left ventricular septal and left ventricular apical pacing chronically maintain cardiac contractile coordination, pump function and efficiency. *Circ Arrhythm Electrophysiol* 2009; 2: 571–579.

123 Myerburg RJ, Gelband H, Nilsson K, Castellanos A, Morales AR, Bassett AL. The role of canine superficial ventricular muscle fibers in endocardial impulse distribution. *Circ Res* 1978; 42: 27–35.

124 Strik M, Rademakers LM, van Deursen CJ, *et al*. Endocardial left ventricular pacing improves cardiac resynchronization therapy in chronic asynchronous infarction and heart failure models. *Circ Arrhythm Electrophysiol* 2012; 5: 191–200.

125 Bilchick KC, Kamath S, Dimarco JP, Stukenborg GJ. Bundle-branch block morphology and other predictors of outcome after cardiac resynchronization therapy in Medicare patients. *Circulation* 2010; 122: 2022–2030.

126 Sipahi I, Carrigan TP, Rowland DY, Stambler BS, Fang JC. Impact of QRS duration on clinical event reduction with cardiac resynchronization therapy: meta-analysis of randomized controlled trials. *Arch Intern Med* 2011; 171: 1454–1462.

127 Varma N. Left ventricular conduction delays and relation to QRS configuration in patients with left ventricular dysfunction. *Am J Cardiol* 2009; 103: 1578–1585.

128 Ploux S, Whinnett Z, Lumens J, *et al*. Acute hemodynamic response to biventricular pacing in heart failure patients with narrow, moderately, and severely prolonged QRS duration. *Heart Rhythm* 2012; 9: 1247–1250.

129 Gold MR, Birgersdotter-Green U, Singh JP, *et al*. The relationship between ventricular electrical delay and left ventricular remodelling with cardiac resynchronization therapy. *Eur Heart J* 2011; 32: 2516–2524.

130 Zareba W, Klein H, Cygankiewicz I, *et al*. Effectiveness of cardiac resynchronization therapy by QRS morphology in the Multicenter Automatic Defibrillator Implantation Trial-Cardiac Resynchronization Therapy (MADIT-CRT). *Circulation* 2011; 123: 1061–1072.

131 Varma N, Jia P, Rudy Y. Electrocardiographic imaging of patients with heart failure with left bundle branch block and response to cardiac resynchronization therapy. *J Electrocardiol* 2007; 40: S174–178.

132 Tse HF, Lee KL, Wan SH, *et al*. Area of left ventricular regional conduction delay and preserved myocardium predict responses to cardiac resynchronization therapy. *J Cardiovasc Electrophysiol* 2005; 16: 690–5.

133 Fung JW, Chan JY, Yip GW, *et al*. Effect of left ventricular endocardial activation pattern on echocardiographic

and clinical response to cardiac resynchronization therapy. *Heart* 2007; 93: 432–437.

134 Bleeker GB, Kaandorp TA, Lamb HJ, *et al.* Effect of posterolateral scar tissue on clinical and echocardiographic improvement after cardiac resynchronization therapy. *Circulation* 2006; 113: 969–976.

135 Jia P, Ramanathan C, Ghanem RN, Ryu K, Varma N, Rudy Y. Electrocardiographic imaging of cardiac resynchronization therapy in heart failure: observation of variable electrophysiologic responses. *Heart Rhythm* 2006; 3: 296–310.

136 Lambiase PD, Rinaldi A, Hauck J, *et al.* Non-contact left ventricular endocardial mapping in cardiac resynchronisation therapy. *Heart* 2004; 90: 44–51.

137 Leclercq C, Gadler F, Kranig W, *et al.* A randomized comparison of triple-site versus dual-site ventricular stimulation in patients with congestive heart failure. *J Am Coll Cardiol* 2008; 51: 1455–1462.

138 Nishimura RA, Trusty JM, Hayes DL, *et al.* Dual-chamber pacing for hypertrophic cardiomyopathy: a randomized, double-blind, crossover trial. *J Am Coll Cardiol* 1997; 29: 435–441.

139 Kappenberger L, Linde C, Daubert C *et al.* Pacing in hypertrophic obstructive cardio-myopathy. A randomized crossover study. PIC Study Group. *Eur Heart J* 1997; 18: 1249–1256.

140 Maron BJ, Nishimura RA, McKenna WJ, *et al.* Assessment of permanent dual-chamber pacing as a treatment for drug-refractory symptomatic patients with obstructive hypertrophic cardiomyopathy. A randomized, double blind, crossover study (M-PATHY). *Circulation* 1999; 99: 2927–2933.

141 Ommen SR, Nishimura RA, Squires RW, Schaff HV, Danielson GK, Tajik AJ. Comparison of dual-chamber pacing versus septal myectomy for the treatment of patients with hypertrophic obstructive cardiomyopathy: a comparison of objective hemodynamic and exercise end points. *J Am Coll Cardiol* 1999; 34: 191–196.

142 Gregoratos G, Abrams J, Epstein AE, *et al.* ACC/AHA/NASPE 2002 guideline update for implantation of cardiac pacemakers and antiarrhythmia devices: summary article: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (ACC/AHA/NASPE Committee to Update the 1998 Pacemaker Guidelines). *Circulation* 2002; 106: 2145–2161.

143 Vardas PE, Auricchio A, Blanc JJ, *et al.* Guidelines for cardiac pacing and cardiac resynchronization therapy. The Task Force for Cardiac Pacing and Cardiac Resynchronization Therapy of the European Society of Cardiology. *Europace* 2007; 9: 959–98.

144 Maron BJ, Olivotto I, Spirito P, *et al.* Epidemiology of hypertrophic cardiomyopathy related death: revisited in a large non-referral-based patient population. *Circulation* 2000; 102: 858–864.

145 Lamas GA, Ellenbogen KA, Hennekens CH, Montanez A. Evidence base for pacemaker mode selection from physiology and randomized trials. *Circulation* 2004; 109: 443–451.

146 Nielsen JC, Kristensen L, Andersen HR, Mortensen PT, Pedersen OL, Pedersen AK. A randomized comparison of atrial and dual-chamber pacing in 177 consecutive patients with sick sinus syndrome: echocardiographic and clinical outcome. *J Am Coll Cardiol* 2003; 42: 614–623.

147 Clarke KW, Connelly DT, Charles RG. Single-chamber atrial pacing: an underused and cost-effective pacing modality in sinus node disease. *Heart* 1998; 80: 387–389.

148 Tripp IG, Armstrong GP, Stewart JT, Hood MA, Smith WM. Atrial pacing should be used more frequently in sinus node disease. *Pacing Clin Electrophysiol* 2005; 28: 291–294.

149 Kristensen L, Nielsen JC, Pedersen AK, Mortensen PT, Andersen HR. AV block and changes in pacing mode during long-term follow-up of 399 consecutive patients with sick sinus syndrome treated with an AAI/AAIR pacemaker. *Pacing Clin Electrophysiol* 2001; 24: 358–65.

4

CHAPTER 4

Temporary cardiac pacing

T. Jared Bunch, Jeffrey S. Osborn, and John D. Day
Intermountain Heart Institute, Intermountain Medical Center, Murray, UT, USA

Introduction

Temporary cardiac pacing is a commonly used tool in the practice of cardiovascular and intensive care medicine. Temporary cardiac pacing is typically used to treat a bradyarrhythmia until it resolves or a permanent pacing solution can be applied. Temporary pacing can be lifesaving in maintaining cardiovascular and hemodynamic function. Although temporary pacing can be used to treat tachyarrhythmias, the most common use is for significant, life-threatening bradyarrhythmias. Temporary pacing is required in approximately 20% of patients presenting to the emergency department with symptomatic bradycardia.[1] This chapter will focus on the use of temporary pacing in cardiopulmonary resuscitation and reversible causes of significant bradyarrhythmias, and then highlight current temporary pacing options and approaches.

Cardiopulmonary resuscitation

Symptomatic bradycardia can present with hypotension, signs of heart failure or cardiac ischemia, or electrical instability (Figure 4.1). There have been two randomized trials comparing temporary (transcutaneous) pacing versus drug therapy in patients who have symptomatic bradycardia with a pulse. Unfortunately, neither study demonstrated a clear survival benefit and as such, current guidelines suggest that pacing be considered only in those patients who do not respond to pharmacological approaches such as atropine.[2–4] However, in patients who do not respond to pharmacological approaches, pacing is indicated.

In general, temporary pacing is not recommended for patients who present in asystole. Three randomized controlled trials have failed to show an improvement in survival to hospital admission or discharge with pacing in patients who had an asystolic cardiac arrest.[5–8] In these patients, pharmacological approaches remain the mainstay of therapy, but if a patient is resuscitated to a bradyarrhythmia, temporary pacing may re-enter the resuscitation algorithm.

Reversible causes of severe bradycardia

Temporary pacing is indicated for symptomatic bradycardia that stems from acute and reversible causes of cardiac instability. In these scenarios, temporary pacing may serve as a bridge to placement of a permanent pacemaker, or merely as a means to bypass this need while the reversible conditions are addressed. There are many potential reversible and/or acute causes of bradycardia that may require temporary pacing (Table 4.1). Unfortunately, although Table 4.1 details many potential reversible causes of injury, in some cases, despite removal or treatment of the offending

Cardiac Pacing and ICDs, Sixth Edition. Edited by Kenneth A. Ellenbogen and Karoly Kaszala.
© 2014 John Wiley & Sons, Ltd. Published 2014 by John Wiley & Sons, Ltd.

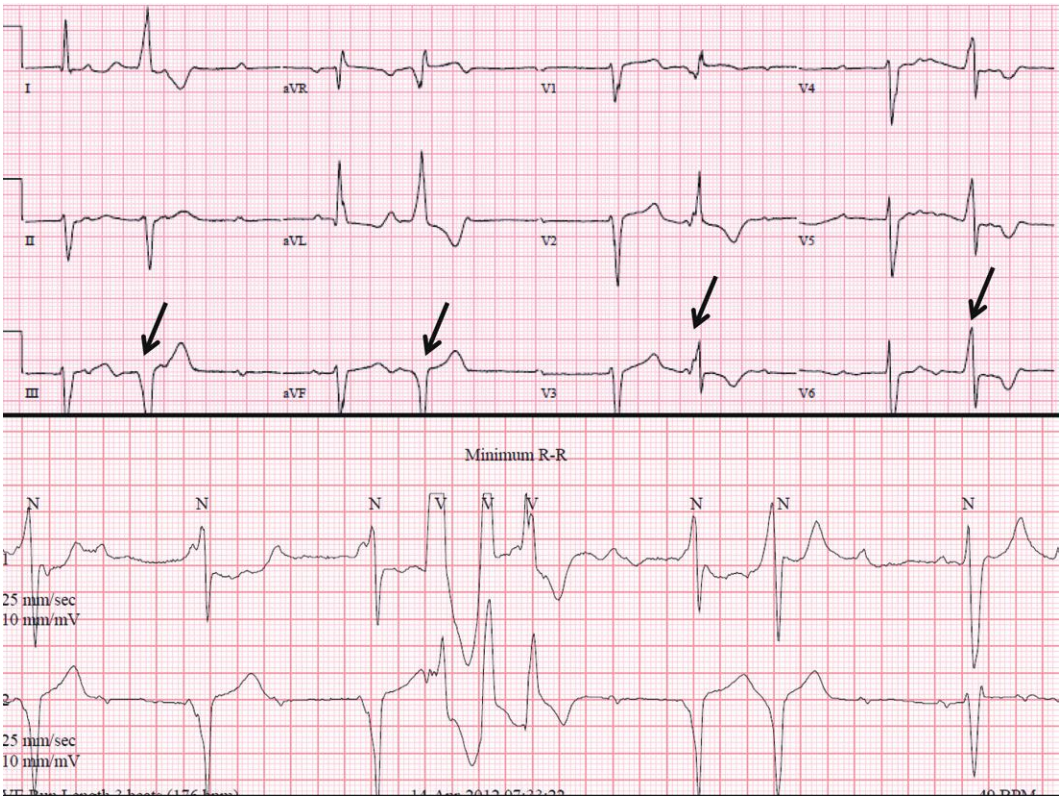


Figure 4.1 Sinus rhythm with complete heart block. Top: There are coupled premature ventricular beats (arrows) in a bigeminal pattern. Bottom: In the setting of severe bradycardia with prolongation of the QT interval, these premature ventricular beats can induce polymorphic ventricular tachycardia. Bradycardia-induced polymorphic ventricular tachycardia is an indication for temporary or permanent pacing independent of the presence of other symptoms.

source, long-term need for pacing may persist. Nonetheless, a careful patient history and laboratory investigation is required to exclude reversible causes of bradyarrhythmia, before committing the patient to long-term pacing. During the investigation of potential reversible causes of bradycardia there may be a need for temporary pacing. An algorithm is provided in Figure 4.2 to show our approach in a patient who presents with symptomatic bradycardia.

Temporary pacing options

Transcutaneous pacing

The ability to pace transcutaneously was first described in the 1950s by Zoll.[9] Dr Zoll reported the successful treatment in two patients of asystole with subcutaneous needle electrodes. Since the establishment of the utility of this concept, transcutaneous pacing has been an integral part of the treatment of bradyarrhythmias in the emergency setting.

The successful application of transcutaneous pacing requires pacemaker pads and cables, a pulse generator unit, electrocardiogram (ECG) patches, monitoring equipment, and analgesia/sedation (Figure 4.3). Placement of the pads, as shown in Figure 4.3, is typically done by using one of two configurations. One option is an anterior and posterior placement. The anterior pad is placed on the left chest over the heart and the posterior patch immediately behind this pad on the left upper quadrant of the back. Another option is to place one pad on the right upper chest and the other pad

Table 4.1 Examples of potentially reversible causes of symptomatic bradycardia

Metabolic/electrolyte
Drug-induced/toxic:
Digoxin
Antiarrhythmic drugs
β-Adrenergic blockers
Calcium channel blockers
Clonidine
Cardiac ischemia
Injury to the sinus node and/or atrioventricular (AV) node during cardiac surgery
Post cardiac transplant
Central nervous system injury
Infectious:
Lyme carditis
Bacterial endocarditis
Influenza
Trauma to the AV node or His–Purkinje system during a cardiac procedure:
Electrophysiology study of catheter placement
Catheter ablation near the sinus node, AV node, or His bundle
Right heart catheterization
Cardiac pacing
Transcutaneous aortic valve placement/valvuloplasty
Ethanol ablation for hypertrophic cardiomyopathy
Paroxysmal atrial tachyarrhythmias
Autonomically-mediated syndromes

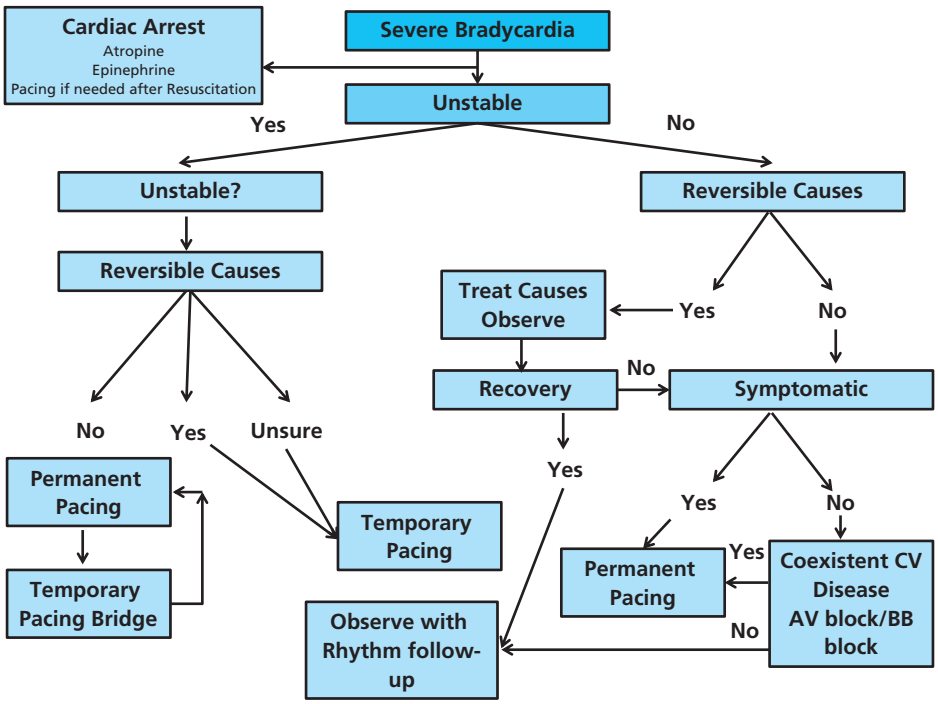


Figure 4.2 An algorithm to consider in the treatment of a patient with severe bradycardia, including when to consider temporary and/or permanent pacing. BB, bundle branch block.

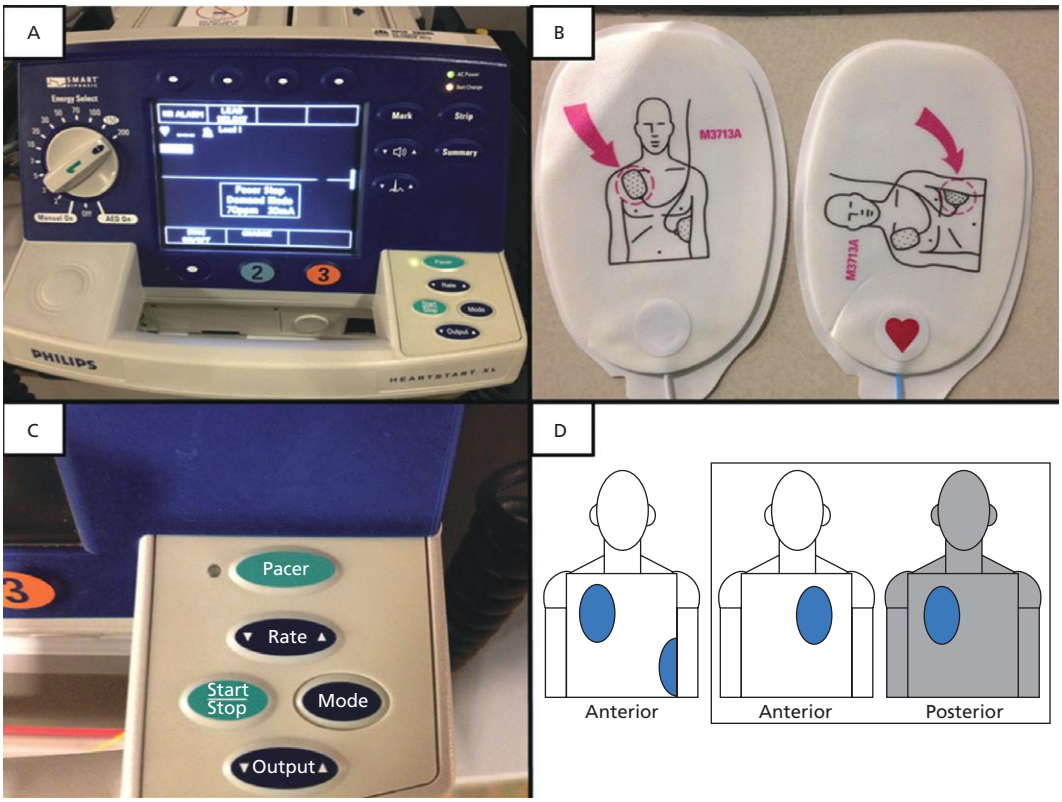


Figure 4.3 Components required for transcutaneous pacing. (A) An automated external defibrillator/pacemaker. (B) The gelatinous pads that are applied to deliver transcutaneous pacing in the anticipated positions highlighted in D. (C) A close-up view of the control panel highlighting the pacemaker function and controls to adjust rate and current delivery.

lateral over the region of the anticipated apex of the heart.

Initially the pacing rate is often set between 70 and 80 bpm. The generator current is increased until there is capture of the myocardium and then typically increased by an additional 10 mA above this capture threshold. The transcutaneous pacing threshold is variable amongst patients and their disease state, typically between 40 and 80 mA, and lowest in healthier individuals.[10–12] Care must be taken to confirm that stable and complete capture of the myocardium has been accomplished as the transcutaneous pacing will result in pacemaker spikes on telemetry monitoring; a finding that may not necessarily confirm that capture has also been accomplished. Adequate capture may be verified with palpation of the femoral or carotid pulse, or by observing arterial pressure waveform (if an arterial line is present). Careful monitoring of the ECG with evidence of temporary transcutaneous electrical capture is shown in Figure 4.4;[13] there is initiation of pacing, followed by fusion with the native sinus complexes, and ultimately complete ventricular capture. In patients with co-existent sepsis or hypotension, additional confirmation of pacing capture may be required with echocardiography.[14] Table 4.2 outlines common causes of failure to capture during transcutaneous pacing and the respective solution to consider.

Transcutaneous pacing is painful. Sedation and analgesia are often required, and at levels that may necessitate general anesthesia with intubation. Furthermore, the side effects of these medications can impact hemodynamic stability in an already compromised patient. In addition, there can be a mild reduction in cardiac function and stroke index due

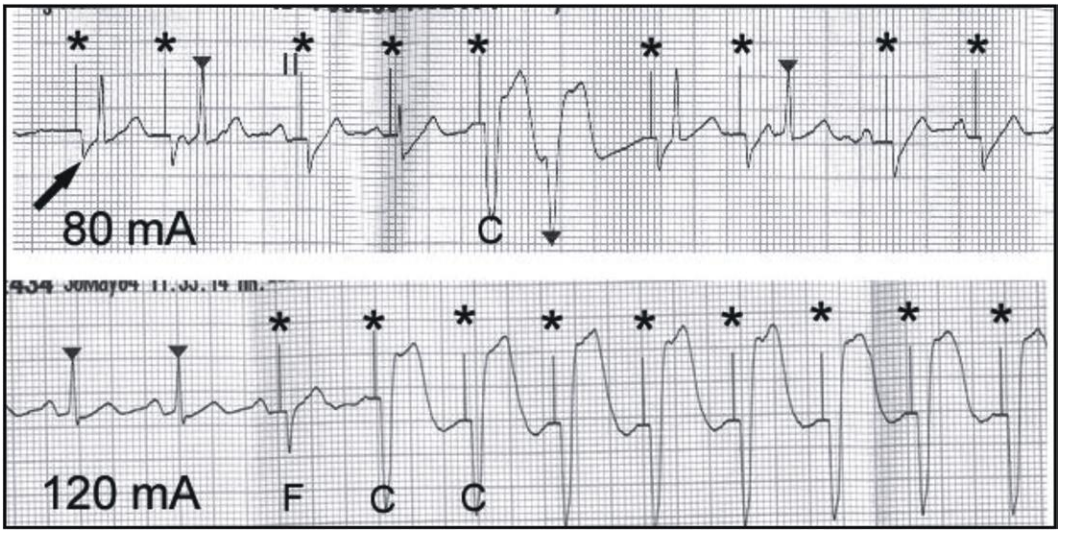


Figure 4.4 Transcutaneous pacing in an intubated 400-lb patient with recurrent episodes of sinus arrest. The tracings are obtained from the pacing generator itself. Top: Subthreshold stimulation. At 80-mA output, the pacing stimuli (*) are followed by a polarization artifact (arrow), but there is no ventricular capture except for the fifth stimulus (C). The polarization artifact may be confused with an evoked QRS complex. Note the demand pacing mode with intrinsic complexes (arrowheads). Bottom: At 120-mA output, ventricular capture (C) begins with the first pacing stimulus (*). This first complex shows fusion (F). (Source: Adapted from Wood MA 2008.[13] Reproduced with permission of John Wiley & Sons Ltd.)

Table 4.2 Failure to capture during transcutaneous pacing[13]

Cause	*Solution*
Suboptimal lead position	Reposition leads, avoiding scapula, sternum, and spine
Negative electrode placed posteriorly	Place negative electrode anteriorly over apex or V3
Poor skin–electrode contact	Clean skin of sweat and debris; shave body hair
Faulty electrical contacts	Check electrical connections
Generator battery depletion	Charge battery or plug-in generator
Increased intrathoracic air	Reduce positive pressure ventilation; relieve pneumothorax
Pericardial effusion	Drain pericardial effusion
Myocardial ischemia/metabolic	Cardiopulmonary resuscitation, ventilation, correct acidosis/hypoxia/derangements electrolyte abnormalities
High threshold	Shave hair beneath electrodes, apply pressure to patches, apply patches with fresh gel

to atrioventricular (AV) dyssynchrony during transcutaneous pacing.[15] As such, transcutaneous pacing largely is used as a temporary bridge to either permanent pacing or a more stable and tolerable endovascular temporary pacing modality.

Temporary endocardial pacing

Transvenous endocardial pacing is the most stable means to provide temporary pacing. There are various types of electrode catheters available for temporary pacing. Unlike transcutaneous pacing, once transvenous pacing is initiated, it is typically well tolerated. As such, transvenous pacing can be applied for extended periods of time, unlike transcutaneous pacing. Furthermore, depending on the type of electrode catheter used, patients can remain ambulatory.

The tools required for temporary endocardial pacing continue to evolve. Initially, transvenous electrode catheters are inserted through a large

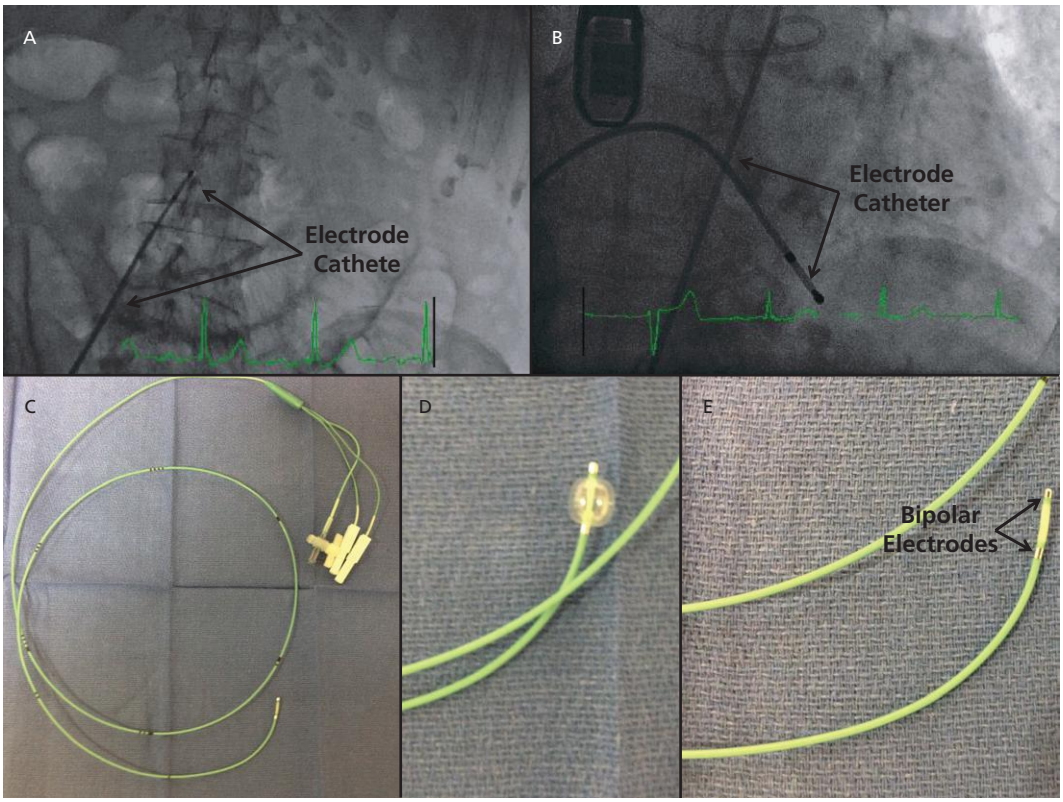


Figure 4.5 Delivery of a 5-Fr transvenous passive fixation pacing electrode catheter. (A) Initial advancement of the catheter through the common femoral and iliac veins. (B) Final location of the electrode catheter in the right ventricular apex. There is a bend in the catheter in the region of the tricuspid annulus that is consistent with the pressure required to minimize lead dislodgement. (C) The complete electrode catheter. There is a central lumen connected to a tip balloon that has not been inflated and two pacemaker wires at the distal end. (D) Inflated tip balloon. This balloon enhances migration through the veins and facilitates movement towards the right ventricle. (E) A magnified image of the catheter tip showing the spacing and characteristics of the bipolar system.

vein, typically the femoral vein, using a modified Seldinger technique (Figure 4.5). The catheters can be balloon tipped to allow easier and safer navigation into the right ventricle (RV).[16] There are different catheter sizes and shapes that enhance their stability in the right atrium and ventricle. However, typically, an atrial catheter is not inserted as the procedure is largely viewed as temporary for a reversible condition and control of the ventricular rate provides the quickest avenue towards stability. At times dual chamber pacing may be helpful. These potential scenarios will be discussed later in this chapter.

Figure 4.5 shows the insertion of a 5-Fr balloon-tipped, relatively stiff temporary electrode catheter via a transfemoral approach. In this case, the electrode catheter was placed as a precaution at the time of a transcutaneous aortic valve placement in case high-grade AV block developed during the procedure. A femoral venous approach offers a rapid, stable access for temporary pacing.[17] Other venous access sites such as the subclavian or internal jugular vein are better options if pacing is anticipated for an extended period as these allow ambulation and reduce infection risk. Typically, these catheters are inserted using fluoroscopy, and we recommend fluoroscopy in all settings whenever possible. In the rare setting where fluoroscopy is not available, ECG guidance can be used. A balloon-tipped catheter is carefully advanced into

the central circulation. The distal electrode of the catheter is connected to lead V_1 of a standard ECG recorder. Once inside the cardiac chambers, the pacing location can be assessed using the intracardiac electrograms (Figure 4.6).[13] Once the tip is in the ventricle, the balloon is deflated to avoid its migration into the pulmonary artery. Once the patient is stabilized, we recommend confirming the location of the catheter with fluoroscopy to minimize both the risk of dislodgement or perforation. The latter can be due to application of excessive force to the shaft and tip of the catheter while urgently placing the catheter in the ventricle. Examples of less desirable temporary lead placements from a femoral approach as determined by fluoroscopy are shown in Figure 4.7.[13]

The surface ECG can serve as a tool to assist in catheter tip localization (Table 4.3). The paced QRS complexes originating from the RV apex should demonstrate left bundle branch block (LBBB)

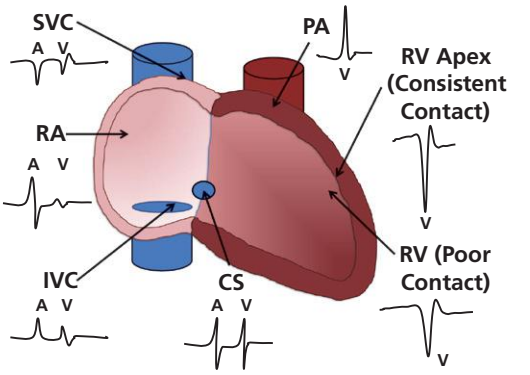


Figure 4.6 Unipolar electrograms obtained by connecting the distal electrode of a temporary pacing catheter to lead V1 of a standard ECG machine. A, atrial electrogram; CS, coronary sinus; IVC, inferior vena cava; PA, pulmonary artery; RA, right atrium; SRV, right ventricle (with display of transition from a near field, sharp ECG with contact that becomes less sharp, or far field with poor contact); V, ventricular electrogram; VC, superior vena cava. (Source: Adapted from Wood MA 2008.[13] Reproduced with permission of John Wiley & Sons Ltd.)

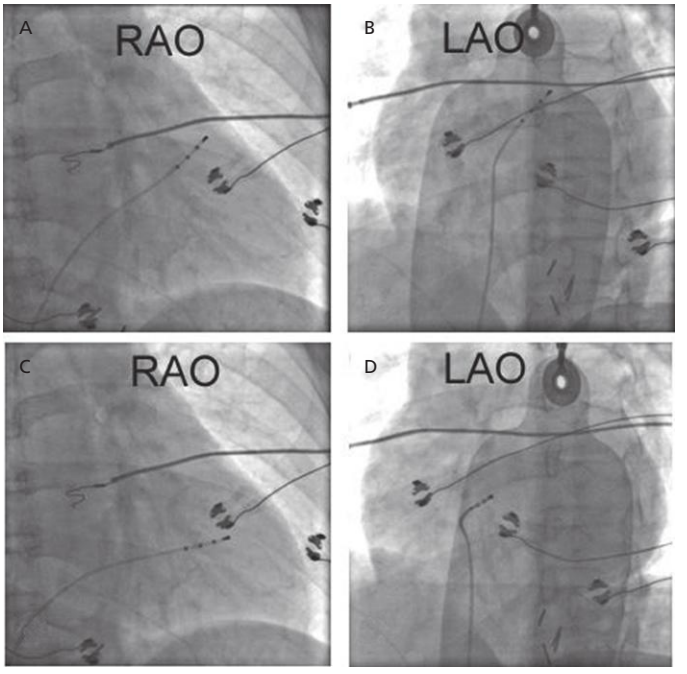


Figure 4.7 Temporary pacing lead malposition through an atrial septal defect. (A) In right anterior oblique view (RAO), the lead appears to be in the right ventricular outflow tract. (B) In left anterior oblique view (LAO), however, the lead courses posteriorly. (C) The lead has been repositioned in the right ventricular septum in RAO and in LAO (D) the lead no longer crosses posteriorly. (Source: Adapted from Wood MA 2008.[13] Reproduced with permission of John Wiley & Sons Ltd.)

Table 4.3 Paced QRS morphology from various electrode positions

Lead position	*Typical QRS morphology QRS axis*
Right ventricular apex	LBBB superior
Right ventricular inflow tract	LBBB normal
Right ventricular outflow tract	LBBB inferior or right
Mid or high left ventricle	RBBB inferior or right
Inferior left ventricle	RBBB superior
Coronary sinus	RBBB inferior

LBBB, left bundle branch block; RBBB, right bundle branch block.

morphology with a superior axis. A right bundle branch block (RBBB) pattern during pacing usually indicates left ventricular or coronary sinus pacing. Rarely, RV apical pacing can produce a pattern of a RBBB with an R wave transition between V2 and V3. Placing V_1 and V_2 electrodes one intercostal space below the standard position usually reveals a LBBB paced pattern and confirms RV pacing.

With electrode systems such as the one shown in Figure 4.5, the target location for the catheter is in the RV. As shown in Figure 4.5, enough pressure is required to create a slight bend along the region of the tricuspid annulus to minimize risk of lead dislodgement. Pressure on the tip of the catheter increases risk of perforation and tamponade. The risk of perforation is variable and depends upon operator experience and patient characteristics, but in general is estimated at approximately 3%.[18] Unfortunately, despite initial proper placement of the electrode, lead dislodgement risk remains high with passively placed temporary catheters (16% in one series[18]).

There are many alternative transvenous temporary electrode catheters, all sharing the common characteristics of active fixation technologies and a less stiff structure. These may reduce risk of perforation and dislodgement. Figure 4.8 shows a 3-Fr temporary active fixation electrode. This more compliant system is delivered through a sheath that can be deformed to allow the electrode to be placed in different locations in the right atrium or ventricle.

In patients who will require long-term pacing, but are not candidates for this due to a reversible condition that may take days to weeks to resolve, we favor a more durable solution to pacing needs that minimizes risk of lead dislodgement but allows the patient to fully ambulate, which is particularly important if rehabilitation is required. Figure 4.9 demonstrates such an approach. We use an externalized permanent pacemaker generator that can be resterilized after each use. We then use a permanent bipolar pacemaker lead that can be inserted into a jugular or subclavian vein through a 6–7-Fr sheath placed via a modified Seldinger technique. The lead is connected externally to a pacemaker and the complete system held in place against the chest wall using silk sutures and a tight sterile dressing. Since this approach uses standard pacemaker lead technologies and their respective tools that assist in placement, these leads can be placed into the RV, coronary sinus, or right atrium depending on need.

Similar to cutaneous pacing, there are many potential causes of failure to pace. These and their respective potential solutions are listed in Table 4.4. Operators who implant temporary pacemakers must be confident with recognizing pacing malfunctions and identifying the mechanism for this, and be able to quickly correct the problem.

Temporary epicardial pacing

Epicardial pacing leads are frequently used as they are a common aspect of postoperative management of patients who undergo various types of cardiac surgery. These small, flexible, externally placed epicardial leads are typically bipolar. These leads are inserted into the epicardium in an orientation that allows easy removal with simple traction on the externalized wires. Figure 4.10 shows the placement of bipolar epicardial leads in the right atrium and ventricle during cardiovascular surgery. The pacemaker lead wires are tunneled through the skin and then connected to a temporary external transvenous pacing generator. The generators used for temporary pacemaker leads are capable of demand and asynchronous pacing modes.

Transesophageal pacing

Due to the proximity of the esophagus and left atrium, a transesophageal pacemaker lead can be used for atrial pacing. The lead requires placement through the nose or mouth. Since contact

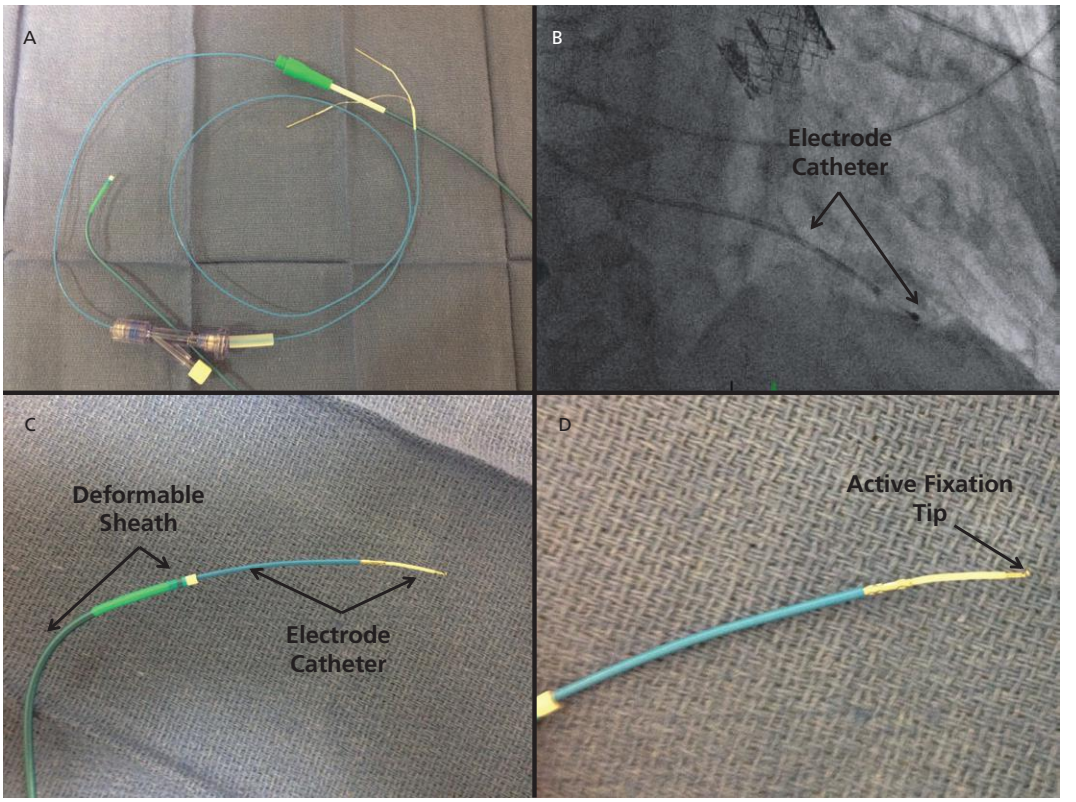


Figure 4.8 Delivery of a 3-Fr transvenous passive fixation pacing electrode catheter through the right internal jugular vein. (A) The complete system with delivery sheath and active fixation pacing electrode catheter. (B) The final location of the electrode catheter in the right ventricular apex. There is a bend in the catheter in the region of the tricuspid annulus that is consistent with the pressure required to minimize lead dislodgement. (C) The catheter image is magnified and the deformable delivery sheath and active fixation electrode catheter are labeled. (D) A magnified image of the electrode catheter tip showing the active fixation mechanism.

in the esophagus can be variable, capture consistency is not reliable and high current and broad pulse widths are required, which can be painful. In our practice, transesophageal pacing approaches are largely used only for diagnostic approaches to discern the atrial arrhythmia when other non-invasive diagnostic methods have been unsuccessful.

Temporary dual chamber pacing

Patients with an intact sinus node with high-grade AV block are at risk of pacemaker syndrome with ventricular pacing only. These patients may exhibit an adverse hemodynamic profile, such as a decrease in blood pressure with ventricular pacing alone. Commonly, these patients have underlying moderate-to-severe impairment in diastolic function. Since the need for temporary pacing is often brief, these patients can typically be stabilized with ventricular pacing alone but rarely, dual chamber pacing is required. Two venous cannulations are required, with placement of either permanent pacemaker leads in the right atrium and ventricle connected to an externalized permanent pacemaker generator, or two active fixation 3-Fr leads in the right atrium and ventricle connected to an external transvenous pacing generator. Figure 4.11 shows an example of a temporary dual chamber pacemaker system that was implanted in a patient with restrictive filling and complete heart block after placement of a transfemoral aortic valve.

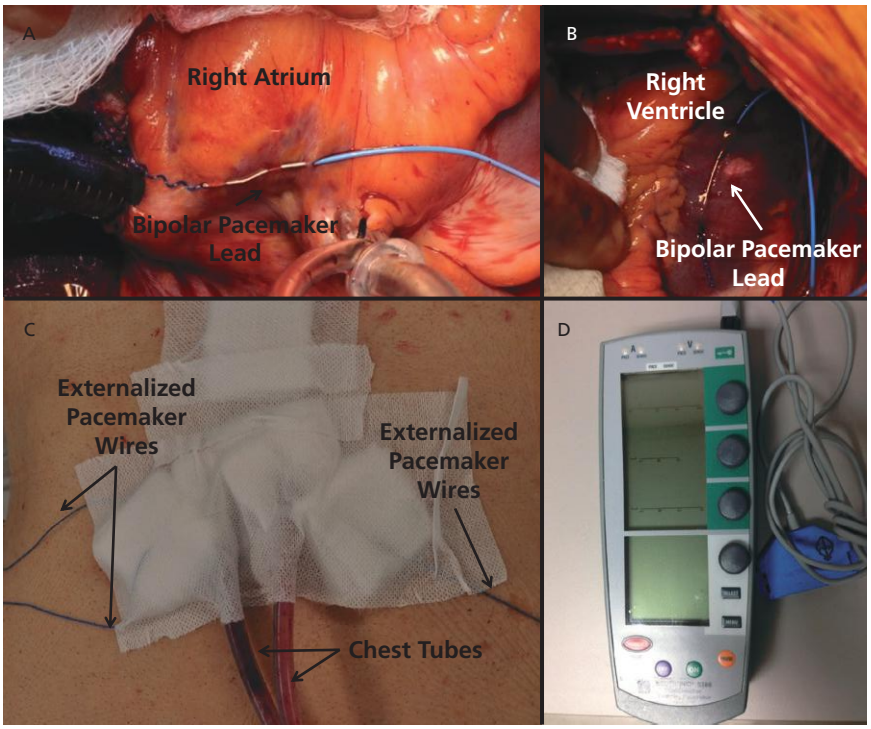


Figure 4.9 An epicardial pacing system placed during cardiac surgery. (A) The epicardial pacemaker lead in the right atrium. The bypass cannula inserted into the right atrium is seen in the lower aspect of the image. (B) The epicardial pacemaker lead in the right ventricle. (C) The external manifestation of the epicardial pacemaker system with the wires tunneled and externalized to be connected to a temporary transvenous pacemaker generator (D).

Table 4.4 Loss of capture during temporary transvenous cardiac pacing

Cause	*Evaluation*	*Solution*
Catheter dislodgement	Check morphology of surface Electrocardiogram (ECG)	Reposition lead Increase output
Perforation	Check morphology of surface ECG, echocardiogram ± pericardiocentesis	Reposition lead
Local myocardial necrosis/ischemia	Rule out perforation Check ECG for acute ischemia	Reposition lead under fluoroscopy Change to an active fixation lead
Hypoxia/acidosis/electrolyte disturbance/drug effect (type Ia and Ic antiarrhythmics)	Serum electrolytes, arterial blood gas, lactate level	Correct reversible causes Increase output
Unstable electrical connections/battery failure	Assess system power source Check connections	Secure connections Change power source
Failure to sense with secondary	Check ECG/telemetry to assure capture failure is due to pacing during the ventricular refractory period	Reposition lead
Oversensing, with failure to pace	Check ECG Determine cause Assure adequate connections	Myopotentials (decrease sensitivity) Electromagnetic interference (decrease sensitivity or remove source) T or P wave oversensing (decrease sensitivity or reposition lead)

Other means of pacing

Other methods for temporary pacing can be considered when the above options are not available. For example, percussion- or fist-based pacing can be attempted.[19] This largely represents a variant of cardiopulmonary resuscitation. However, it remains a means to provide perfusion in a patient who is severely compromised. Clearly, this method should only be used in those who are in or near cardiac arrest.

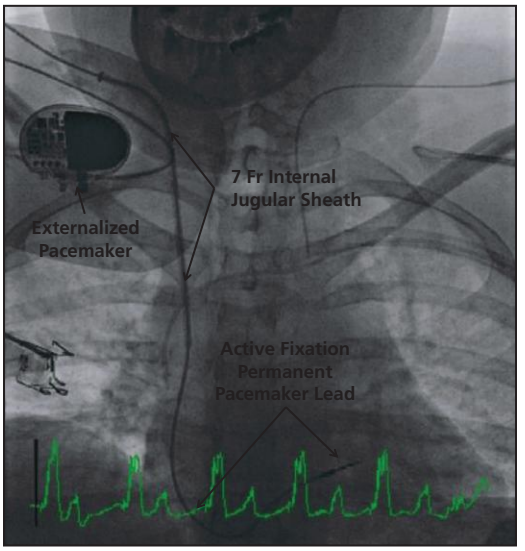


Figure 4.10 A permanent bipolar pacemaker lead placed in the right ventricle through the right internal jugular vein. The pacemaker lead is connected to an externalized reusable pacemaker generator.

Insertion of an endovascular temporary pacemaker

Physicians who consider placing a temporary pacemaker must be familiar with venous anatomy and be confident with access using the jugular, subclavian, and femoral veins. If a physician is not confident with obtaining venous access and managing temporary pacing leads, we recommend use of a transcutaneous system to gain stability acutely and until an experienced operator is available to provide access and placement of the pacing catheter.

The guidelines for training in adult cardiovascular medicine, Core Cardiology Training Symposium (COCATS), recommend a minimum of five supervised temporary pacemaker implants for level 1 training in cardiology.[20] To safely and rapidly perform the procedure, however, additional experience is required with catheter access from both the jugular and femoral venous routes. Without this extensive experience the risk versus benefit of placing an endocardial system compared to

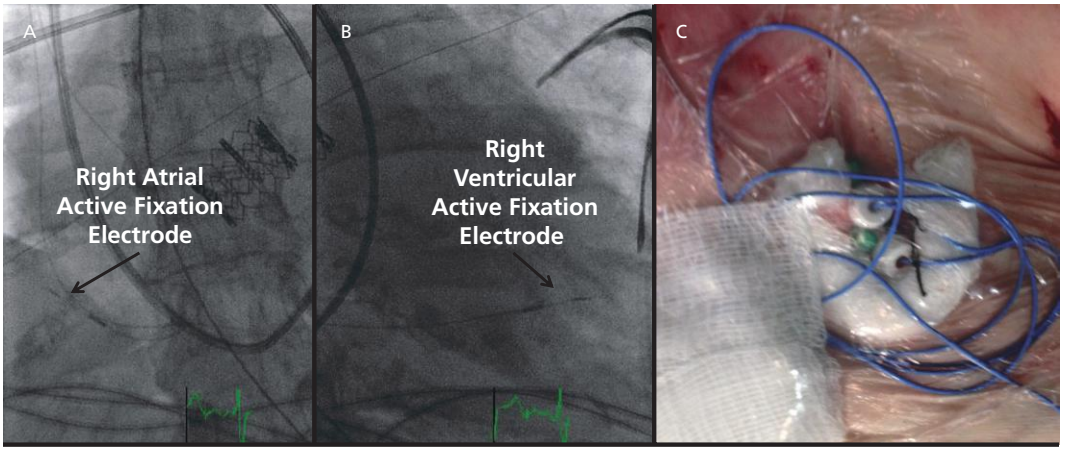


Figure 4.11 Placement of 3-Fr active fixation electrode catheters placed in the right atrium (A) and ventricle (B) to allow atrioventricular synchrony in a patient with heart block following transfemoral aortic valve replacement. (C) The double access and sheath placement approach in the extrathoracic subclavian vein for insertion of the two electrode catheters. The catheters are subsequently connected to a temporary transvenous pacemaker generator.

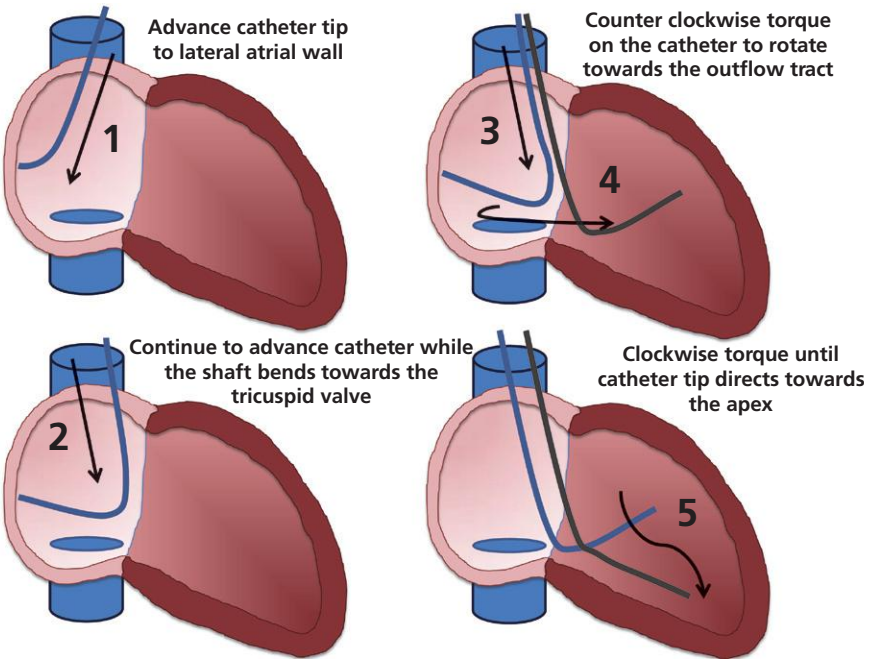


Figure 4.12 A common superior venous approach toward placement of a endovascular temporary pacing catheter, most commonly from the right internal jugular or subclavian vein.

a transcutaneous system is swayed towards utilizing the latter until an experienced operator is available.

Figure 4.12 illustrates how to place a temporary endovascular catheter from a superior approach, either a jugular or subclavian vein. This approach and technique require fluoroscopy guidance. The catheter tip is advanced to the lateral right atrial wall. Once the wall is encountered, additional forward force is applied, resulting in shaft bending of the catheter in an interior/anterior direction. As the catheter shaft bends, torque is applied to direct it into in the RV and ultimately the RV apex.

Figure 4.13 illustrates how to place a temporary endovascular catheter from an inferior approach. The approach is similar to that using a superior approach, with initial direction of the catheter toward the lateral right atrium or orifice of the hepatic vein. Additional forward force bends the shaft in a superior and anterior direction. Torque on the catheter is then applied to direct it towards the RV.

These stiffer, steerable, temporary pacing catheters are passive fixation catheters and as such they require the patient to remain on bedrest to minimize risk of lead dislodgement and perforation. In addition, a plan is required to minimize the time a temporary catheter will be in place, and to avoid both infection and thrombosis. Studies that have examined the incidence of femoral vein thrombosis in patients with catheters placed through the femoral vein report that up to 39% of patients develop a clot despite use of anticoagulation.[21,22]

Complications

Although temporary cardiac pacing is typically indicated in an emergent situation to retain cardiovascular stability, a number of complications can be encountered (Table 4.5).[17,21,23,24] The most common is lead dislodgement, followed by systemic infection and lead perforation.

Appropriate lead placement under fluoroscopy helps decrease the risk of dislodgement. Careful attention to sterile technique and minimizing the length of time the temporary pacemaker is in place is the best practice to reduce the risk of systemic infection. Regarding perforation, placement

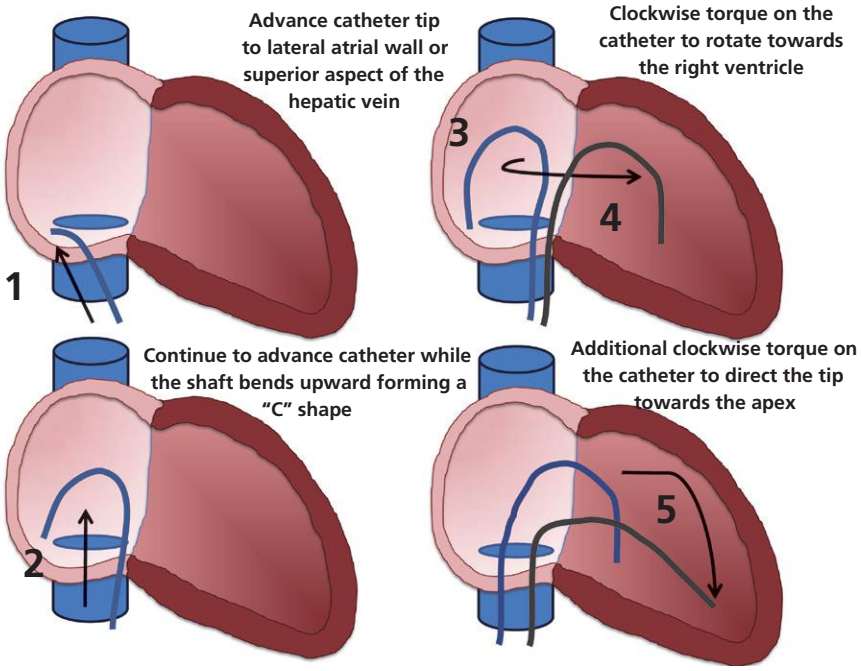


Figure 4.13 A common inferior venous approach toward placement of an endovascular temporary pacing catheter, most commonly from the right femoral vein.

Table 4.5 Complications encountered during placement of a transvenous temporary pacing system

Pneumothorax and/or hemothorax
Hemopericardium
Lead displacement/dislodgement
Local infection
Systemic infection
Induction of ventricular fibrillation or ventricular tachycardia
Air embolism
Deep venous thrombosis
Thromboembolism/pulmonary embolism
Inadvertent arterial puncture:
Arterial pseudoaneurysm
Arterial–venous fistula
Retroperitoneal bleed
Hematoma

technique, location, and type of catheter tip technology may help to curtail this risk. In the event of a perforation, echocardiography is urgently required to monitor the pericardial space and assess for tamponade physiology. The patient needs to be prepped for a sterile access to the pericardial space if required. The catheter is then drawn back slowly out of the pericardium. The intracardiac electrograms can be used as a guide to determine when the distal tip of the catheter moves from the epicardial to endocardial space (Figure 4.14).[13]

In addition, catheter migration, dislodgement, and undersensing can complicate the pacing system even after successful placement. Less stable atrial or ventricular catheters can provoke supraventricular and ventricular arrhythmias, respectively. In addition, failure to sense in the ventricle may provoke ventricular arrhythmias by pacing at a vulnerable period. Ventricular arrhythmias during temporary pacing are more common in the setting of myocardial ischemia or infarction, hypoxia, catecholamine administration, vagal stimulation, and with certain anesthesia agents.[25]

Patients who require temporary pacing due to sinus pauses or second-degree heart block with a LBBB require careful attention during pacing catheter insertion. Mechanical trauma to the right bundle branch in these patients may cause acute complete heart block. Transcutaneous pacing must

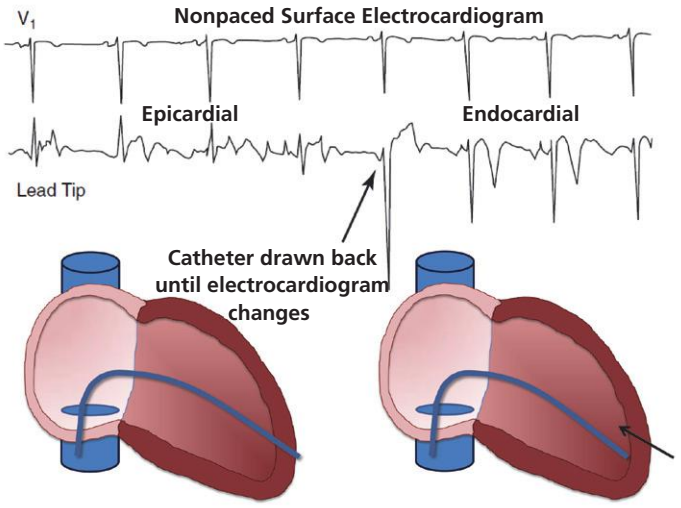


Figure 4.14 Continuous unipolar recording from the distal electrode of a perforated ventricular pacing catheter in an elderly woman. The surface ECG lead V_1 is also shown. Perforation into the pericardial space was clinically suspected 24 h after catheter placement. The first three complexes show a predominantly positive morphology to the unipolar electrogram recorded from the distal electrode. As the catheter is withdrawn, the fourth unipolar electrogram becomes biphasic and then is negative (arrow) as the distal electrode moves from an epicardial to endocardial position. This finding confirms the diagnosis of myocardial perforation. This maneuver should only be performed with echocardiographic guidance to monitor the pericardial space with the patient prepped for urgent pericardiocentesis. (Source: Adapted from Wood MA 2008.[13] Reproduced with permission of John Wiley & Sons Ltd.)

therefore be immediately available to provide pacing until the endovascular lead can be successfully positioned. It is our practice to have the transcutaneous pacemaker pads placed and connected to a generator before inserting the endovascular catheter.

Active fixation electrode catheters or leads should decrease the risk of the most common complications. For systemic infection, regardless of the technology used, we try to avoid leaving the pacemaker system in place for longer than 1 week. Finally, since less stiff electrode catheters can be placed in locations other than the RV apex, we anticipate these will reduce the perforation risk.

Clinical application

Table 4.6 compares the various temporary pacemaker technologies discussed within this chapter. For emergent situations involving cardiac arrest, transcutaneous pacing is the dominant utility given its ease of use and time required for application. In patients who are more stable but require temporary pacing due to symptomatic bradycardia, the available options depend upon the time required for application, dislodgement risk, and chambers that require pacing.

In our practice, for patients requiring urgent/emergent pacing due to non-reversible causes, we generally implant a permanent pacemaker as the initial procedure, even during off hours, rather than initially performing temporary pacing only for the patient to undergo permanent pacing at a later time. In our experience, with a readily available catheterization lab and personnel, patients can undergo a definitive procedure with minimal risk of lead dislodgement or complications from multiple procedures. This type of strategy can be particularly helpful in minimizing the long-term infection risk associated with temporary endocardial pacing systems.

Conclusion

Temporary pacing is part of the armamentarium of emergency room, critical care, cardiovascular surgery, and cardiovascular medicine physicians. Temporary pacing can provide immediate

Table 4.6 Comparison of temporary pacing technologies

Variable	*Transcutaneous*	*Transvenous passive fixation*	*Transvenous active fixation*	*Transvenous permanent pacing lead*	*Epicardial*
Chambers	Ventricle	Primarily ventricle	Atrium/ventricle	Atrium/ventricle	Atrium/ventricle
Time to initiate	Minimal	5–10 min	5–10 min	5–10 min	Minimal (CV surgery)
Training	Minimal	Moderate	Moderate–extensive	Extensive	Extensive
Stability	+	++	+++	++++	+++/++++
Long-term use	–	–	+	++	++
Infection risk	–	+	+	+	–
Perforation risk	–	++	+	+	–
Cardiac arrest	+	±	–	–	–

CV, cardiovascular.

cardiovascular stabilization in patients with severe symptomatic bradycardia. Technologies have evolved to enhance lead stability and minimize risk, allowing temporary pacing to provide a bridge to permanent pacing or until the reversible condition resolves, even when this requires weeks. Although specialized training and equipment are required, temporary pacing remains fundamental to the cardiac care of patients.

References

1 Sodeck GH, Domanovits H, Meron G, *et al*. Compromising bradycardia: management in the emergency department. *Resuscitation* 2007; 73(1): 96–102.

2 Link MS, Atkins DL, Passman RS, *et al*. Part 6: electrical therapies: automated external defibrillators, defibrillation, cardioversion, and pacing: 2010 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care. *Circulation* 2010; 122(18 Suppl 3): S706–719.

3 Smith I, Monk TG, White PF. Comparison of transesophageal atrial pacing with anticholinergic drugs for the treatment of intraoperative bradycardia. *Anesth Analg* 1994; 78(2): 245–252.

4 Morrison LJ, Long J, Vermeulen M, *et al*. A randomized controlled feasibility trial comparing safety and effectiveness of prehospital pacing versus conventional treatment: 'PrePACE'. *Resuscitation* 2008; 76(3): 341–349.

5 Field JM, Hazinski MF, Sayre MR, *et al*. Part 1: executive summary: 2010 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care. *Circulation* 2010; 122(18 Suppl 3): S640–656.

6 Hedges JR, Syverud SA, Dalsey WC, Feero S, Easter R, Shultz B. Prehospital trial of emergency transcutaneous cardiac pacing. *Circulation* 1987; 76(6): 1337–1343.

7 Barthell E, Troiano P, Olson D, Stueven HA, Hendley G. Prehospital external cardiac pacing: a prospective, controlled clinical trial. *Ann Emerg Med* 1988; 17(11): 1221–1226.

8 Cummins RO, Graves JR, Larsen MP, *et al*. Out-of-hospital transcutaneous pacing by emergency medical technicians in patients with asystolic cardiac arrest. *N Engl J Med* 1993; 328(19): 1377–1382.

9 Zoll PM, Linenthal AJ, Norman LR. Treatment of Stokes-Adams disease by external electric stimulation of the heart. *Circulation* 1954; 9(4): 482–493.

10 Zoll PM, Zoll RH, Falk RH, Clinton JE, Eitel DR, Antman EM. External noninvasive temporary cardiac pacing: clinical trials. *Circulation* 1985; 71(5): 937–944.

11 Klein LS, Miles WM, Heger JJ, Zipes DP. Transcutaneous pacing: patient tolerance, strength-interval relations and feasibility for programmed electrical stimulation. *Am J Cardiol* 1988; 62(16): 1126–1129.

12 Kelly JS, Royster RL, Angert KC, Case LD. Efficacy of noninvasive transcutaneous cardiac pacing patients undergoing cardiac surgery. *Anesthesiology* 1989; 70(5): 747–751.

13 Wood MA. Temporary cardiac pacing. In: Ellenbogen KA, Wood MA, eds. *Cardiac Pacing and ICDs*, 5th edn. Oxford: Blackwell Publishing, 2008.

14 Ettin D, Cook T. Using ultrasound to determine external pacer capture. *J Emerg Med* 1999; 17(6): 1007–1009.

15 Trigano JA, Remond JM, Mourot F, Birkui P, Levy S. Left ventricular pressure measurement during noninvasive transcutaneous cardiac pacing. *Pacing Clin Electrophysiol* 1989; 12(11): 1717–1719.
16 Schnitzler RN, Caracta AR, Damato AN. "Floating" catheter for temporary transvenous ventricular pacing. *Am J Cardiol* 1973; 31(3): 351–354.
17 Austin JL, Preis LK, Crampton RS, Beller GA, Martin RP. Analysis of pacemaker malfunction and complications of temporary pacing in the coronary care unit. *Am J Cardiol* 1982; 49(2): 301–306.
18 Betts TR. Regional survey of temporary transvenous pacing procedures and complications. *Postgrad Med J* 2003; 79(934): 463–465.
19 Eich C, Bleckmann A, Schwarz SK. Percussion pacing–an almost forgotten procedure for haemodynamically unstable bradycardias? A report of three case studies and review of the literature. *Br J Anaesth* 2007; 98(4): 429–433.
20 Josephson ME, Maloney JD, Barold SS, *et al*. Guidelines for training in adult cardiovascular medicine. Core Cardiology Training Symposium (COCATS). Task Force 6: training in specialized electrophysiology, cardiac pacing and arrhythmia management. *J Am Coll Cardiol* 1995; 25(1): 23–26.
21 Nolewajka AJ, Goddard MD, Brown TC. Temporary transvenous pacing and femoral vein thrombosis. *Circulation* 1980; 62(3): 646–650.
22 Sanders P, Farouque O, Ashby DT, Mahar LJ, Young GD. Effects of anticoagulation on the occurrence of deep venous thrombosis associated with temporary transvenous femoral pacemakers. *Am J Cardiol* 2001; 88: 798–801.
23 McLeod AA, Jokhi PP. Pacemaker induced ventricular fibrillation in coronary care units. *BMJ* 2004; 328(7450): 1249–1250.
24 Hill PE. Complications of permanent transvenous cardiac pacing: a 14-year review of all transvenous pacemakers inserted at one community hospital. *Pacing Clin Electrophysiol* 1987; 10(3 Pt 1): 564–570.
25 Mooss AN, Ross WB, Esterbrooks DJ, Nair C, Mohiuddin S, Sketch MH. Ventricular fibrillation complicating pacemaker insertion in acute myocardial infarction. *Cathet Cardiovasc Diagn* 1982; 8(3): 253–259.

5

CHAPTER 5

Techniques of pacemaker implantation and removal

Joseph E. Marine and Jeffrey A. Brinker
Johns Hopkins University School of Medicine, Baltimore, MD, USA

Introduction

A permanent pacing system consists of a pacemaker generator and one or more leads that connect it to the endocardial or epicardial surface of the heart. Considerable evolution in technique and hardware has occurred over the past several decades, which has simplified the implantation procedure. Associated with this evolution has been a miniaturization of the power source and circuitry of the generator, and near-universal use of smaller and more flexible transvenous leads.

Compared with such tasks as optimization of programming and interpretation of complex pacemaker electrograms, the implantation of a modern pacemaker may now be the least challenging aspect of cardiac pacing. However, it would be inappropriate to create the impression that all pacemaker implantation is easy. Implanters should be dedicated to lifelong continuous improvement of their skills and knowledge, learning from their own challenging cases as well as those of colleagues.

In this chapter, transvenous single and dual chamber pacemaker implantation is examined from a broad perspective that emphasizes the practical considerations influencing the safety and efficacy of this procedure. In addition, the indications for and methodology of removing implanted pacing devices are reviewed.

Physician qualifications

Pacemaker implantation is performed by physicians from a variety of specialties, including cardiothoracic surgeons, non-electrophysiology cardiologists, and electrophysiologists. Formal training in the implantation of arrhythmia management devices is most extensive in clinical cardiac electrophysiology fellowship programs. Despite the growth in numbers of trained electrophysiologists, many non-electrophysiology cardiologists continue to implant pacemakers either alone or as part of a surgical team. In addition, many electrophysiologists and cardiologists call upon their surgical colleagues for assistance in more complicated implantations, such as submammary or subpectoral dissections.

Procedural success and safety are determined in large part by the skill and experience of the operator. Although the degree of "surgery" required for a routine transvenous implantation is modest, good surgical technique is essential. Experience is also necessary to ensure proper positioning of leads so that optimal stability and long-term performance are obtained. A physician wishing to implant pacing systems independently should perform a sufficient number of procedures under the supervision of an accomplished operator to gain the skill and confidence necessary for independent work.

Cardiac Pacing and ICDs, Sixth Edition. Edited by Kenneth A. Ellenbogen and Karoly Kaszala.
© 2014 John Wiley & Sons, Ltd. Published 2014 by John Wiley & Sons, Ltd.

The minimal number of cases to credential a physician depends on the physician's prior familiarity with intravascular catheterization, surgical technique, and knowledge of the principles of pacing. This experience should include single and dual chamber systems, and use of both the subclavian/axillary and cephalic approaches for venous access. In addition to this initial training experience, an adequate number of implantations should be performed over time to maintain a level of proficiency. Guidelines for training in pacemaker implantation have been published that may serve as a general model.[1] The guidelines acknowledge the special training necessary for those physicians seeking credentials in biventricular pacing, defibrillator implantation, and lead extraction. Because fluoroscopic imaging is a necessary component of the implantation process, knowledge of the basics of radiation physics and safety is required to minimize risk to the patient, operator, and laboratory personnel.

Specialty assistance may be anticipated before a procedure in some cases, and appropriate consultation should be obtained. Implantation procedures are generally performed under moderate sedation, but on occasion there may be a need for the support of an anesthesiologist. Implanting physicians should be familiar with the principles of moderate sedation and the particular institutional guidelines under which they operate, including the acceptable drugs (dosages, reversibility) and the necessary support personnel, monitoring equipment, and recovery procedures.

Quality assurance has become a necessary part of every hospital's activities, and surgical operations and the physicians who perform them are most thoroughly scrutinized. It is the responsibility of all physicians to be conscious of the quality of their work; those in administrative positions should ensure that proper databases are maintained and performance evaluations are carried out. The objective of these practices is improved quality of care.

Logistical requirements

The logistical requirements for pacemaker implantation are relatively modest. The procedure may be carried out in an operating room, a catheterization laboratory, or a special procedure room with no compromise of success rate or difference in complications. Implantation in the cardiac catheterization laboratory has been shown to result in a significant reduction in the cost and length of hospital stay compared with implants in the operating room by surgeons. This is probably due to the increased flexibility in scheduling in the catheterization laboratory, as well as the use of conscious sedation administered by catheterization laboratory personnel instead of anesthesia staff.

The procedure room should be adequate in size and well lit, and it should comply with all the electrical safety requirements for intravascular catheterization. The radiographic equipment should function within accepted guidelines, and appropriate radiation shielding should be available and used. The room should have appropriate temperature control and ventilation for sterile procedures.

In addition to the operator, the staff should include qualified individuals to monitor the electrocardiogram (ECG) and assist with the imaging equipment. A nurse is required to prepare and administer medications. Often a representative of a pacemaker company is present to provide technical assistance, such as with operating the pacing system analyzer or device programmer. These individuals may be a valuable source of information, but should not be considered a substitute for a nurse or laboratory technologist during the implant procedure. Laboratory personnel should also be trained in adherence to rigorous sterile techniques.

An adequate imaging system is an important requirement of the pacemaker laboratory. The fluoroscopy equipment may be portable or fixed, but must be capable of rotation so that oblique and lateral views of the areas of interest (which may extend from the neck to the groin) can be obtained. A mechanism for magnification is helpful for situations such as confirmation of extension of the helix of active fixation leads, lead removal procedures, and the identification of problems such as fracture of a conductor or "J" retention wire. Digital acquisition and storage capabilities have proven to be advantageous and are widely used. Such technology can be used to road-map or superimpose real-time fluoroscopy on a stored image. Thus, one can bring up a stored image of the

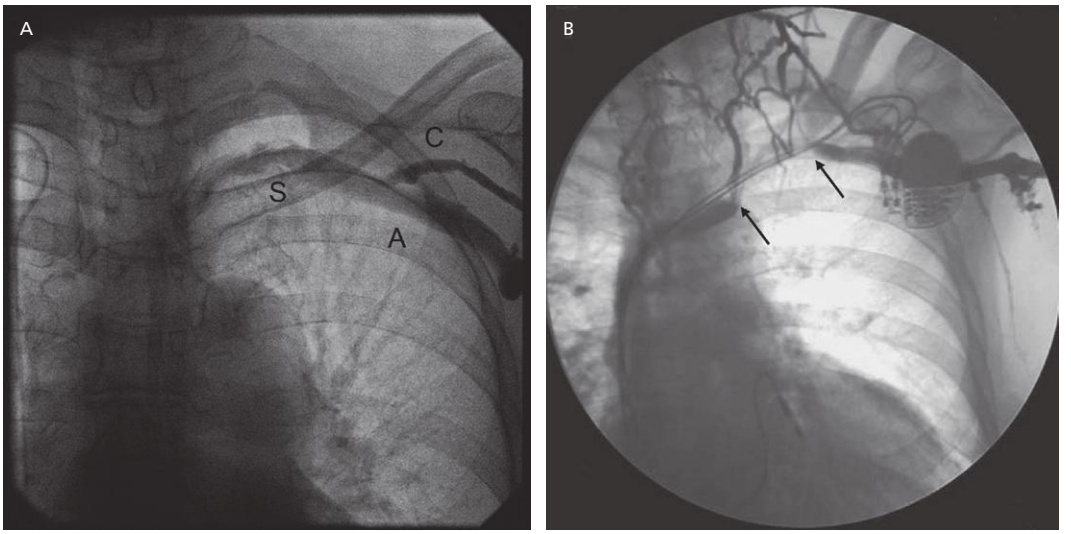


Figure 5.1 Venography may be helpful in documenting the patency of venous structures. (A) A normal left arm venogram. A, axillary portion of the vein; C, cephalic vein; S, subclavian vein. (B) This study shows complete occlusion of the subclavian vein (between the two arrows) with extensive collateral vein formation in a patient with prior pacemaker implantation. This information would clearly be important when planning for procedures requiring new venous access.

subclavian venogram to document the vein patency and to serve as a target for an exploring needle being advanced under fluoroscopic monitoring (Figure 5.1).

The use of pulsed digital fluoroscopy can reduce radiation exposure to the patient and operator, and should be used whenever possible. Frame rates of 7.5 fps are usually adequate for pacemaker implantation, and newer systems may use as little as 3.75 fps. Newer imaging systems may also increase patient safety by providing on-line dose measurements that more accurately reflect radiation exposure than does total fluoroscopy time. The patient table should be flat, radiolucent, and configured in such a way that the operator may work on either side of it. Movement of the imaging system about the support should be unhindered.

It is essential that the ECG be continuously monitored; a simultaneous multilead display that is easily visualized is preferable in order to assess paced QRS axis and morphology. There should be an ability to obtain a hard copy of the monitored rhythm strip as well as a 12-lead tracing if necessary. Leads placed on the chest or back should consist of radiolucent electrodes and wires. The patient should be connected via radiolucent transthoracic electrode patches to an external defibrillator capable of transcutaneous pacing, cardioversion, and defibrillation in case an arrhythmia develops during the procedure. Arterial blood pressure and pulse oximetry should be monitored throughout the procedure. A portable ultrasound device may be helpful in identifying vascular structures and provide guidance for venous access.

The surgical instruments required for the procedure depend on the demands of the particular procedure and operator. A pacemaker tray may be derived from the hospital's surgical cut-down set and supplemented in accordance with the specifics of the case. Add-ons include tear-away vascular introducer sets, appropriate cables to connect to a pacing system analyzer (PSA), suction, and electrocautery. The operator should be familiar with the guidelines for electrocautery use to ensure safety, particularly when oxygen is being administered.

An adequate supply and variety of pacing hardware should be available, including not only pacemaker generators and leads, but also sheaths,

stylets, and lead adaptors. It is good practice to have at least two of every necessary item on hand in case of accidental damage or loss of sterility.

The PSA measures a variety of pacing parameters (capture and sensing threshold, lead impedance, electrograms, slew rate) that assess the adequacy of lead position and integrity. A direct digital readout and the capability to print a hard copy are desirable. Some manufacturers have consolidated products by configuring their programmers to act as PSAs when necessary. Equipment necessary for emergency pericardiocentesis, chest tube insertion, and temporary endocardial pacing must be at hand, and it is advantageous to have prompt access to a two-dimensional echocardiography machine. A crash cart containing resuscitative supplies (including those necessary to establish endotracheal intubation), an adequate supply of all appropriate drugs, and experienced staff should be readily available.

Assessment of the patient

The implantation process begins with a thorough evaluation of the patient. This should include reviewing medical records, obtaining a pertinent history (including current medications, especially anticoagulants and antiplatelet agents, and previous reactions to drugs and contrast media), performing a physical examination, and acquiring the basic laboratory tests.

The indication for pacing should be documented and characterized in accordance with the American College of Cardiology (ACC)/American Heart Association (AHA) guidelines.[2] In some situations, it may be reasonable to offer pacemaker therapy for conditions in which the indication for such therapy is controversial and evolving, such as recurrent neurally-mediated syncope with a prominent cardioinhibitory component. Documentation of the indication for a pacemaker implantation should be made in the patient's chart and supported by a relevant ECG tracing.

Consideration of the type of pacing system to be used should be part of the patient assessment. The choice of mode of pacing (e.g. atrial; ventricular; single chamber, dual chamber, biventricular) is made on the basis of the underlying conduction disturbance, the present and future potential need for pacing, and the hemodynamic and functional status of the patient.[3,4] Other factors that might influence the method of implantation, the operative site, or the type of hardware needed should be considered before the procedure. Examples include: the need for an unusual vascular approach (e.g. iliac vein) or an epicardial lead system in a patient with a previously documented venous anomaly; and employment of an active fixation ventricular lead in a patient with severe tricuspid regurgitation or corrected transposition of the great vessels. These factors comprise an array of choices that should be carefully considered before the patient enters the procedure room (Figure 5.2). Thorough preparation is essential to minimize problems at implantation.

Special issues

Several issues in patient assessment and preparation merit special consideration (Table 5.1).

Infection

Implanters are frequently asked to implant permanent pacemakers semi-urgently in hospitalized patients with co-existing infectious issues. Decision-making regarding the timing of pacemaker implantation in these patients can be complex, and depends on the site of the suspected or documented infection, concern for bacteremia, and indication for cardiac pacing. For example, a patient with complete atrioventricular (AV) block who has asymptomatic bacteriuria with no fever and normal white count can usually be implanted with minimal delay while treating the potential lower urinary tract infection. On the other hand, a patient with bacterial endocarditis and mildly symptomatic sinus node dysfunction is best completely treated and cure proven prior to implantation. Patients with pneumonia without bacteremia can usually be implanted after antibiotic therapy has rendered them afebrile for 2–3 days.

A special population comprises patients with an existing infected cardiovascular implantable electronic device (CIED) that is to be removed. Although temporary pacing may be immediately required for dependent individuals, guidelines for re-implantation of a permanent system require

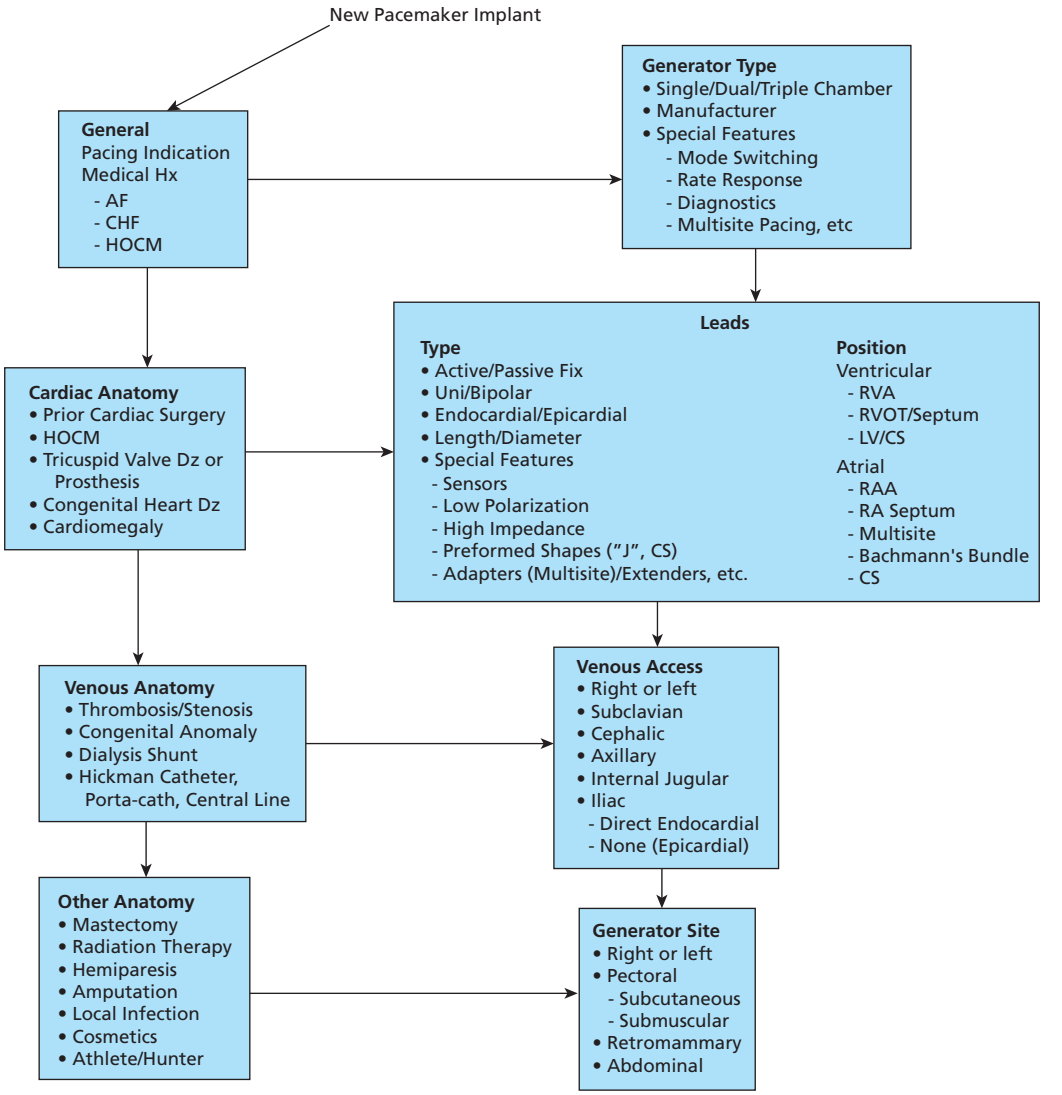


Figure 5.2 Flow chart for decision process surrounding a new pacemaker implant. AF, atrial fibrillation; CHF, congestive heart failure; CS, coronary sinus; Dz, disease; HOCM, hypertrophic obstructive cardiomyopathy; Hx, history; LV, left ventricle; RAA, right atrial appendage; RVA, right ventricular apex; RVOT, right ventricular outflow tract.

evaluation for infective endocarditis and negative blood cultures. In general, the minimum duration between extraction and re-implantation is 3–14 days.[5] In such difficult cases, consultation with infectious disease colleagues regarding duration of antibiotic therapy may be helpful. In considering the timing of implantation, the risk of pacemaker infection needs to be balanced against the risk of delaying pacemaker therapy and of prolonged hospitalization awaiting "ID clearance."

Kidney disease

Patients with chronic kidney disease also merit special consideration. For the patient with end-stage renal disease (ESRD) on dialysis, pacemaker implantation and overnight observation must be coordinated with the outpatient dialysis center to

Table 5.1 Special issues in the assessment of the patient who requires cardiac pacing

Infection
Kidney disease
Anticoagulants and antiplatelet agents
Subclavian vein anomalies
Prior mastectomy
Tricuspid valve disease/prosthesis
Risk for asystole (left bundle branch block, complete atrioventricular block)
Prior central venous lines
Prior clavicular fracture

ensure that dialysis is not disrupted. Implantation is usually scheduled on a non-dialysis day and dialysis is scheduled the next day, either as an inpatient on the morning of discharge or at the outpatient center in the afternoon. In general, implantation should be performed on the side opposite to the functioning dialysis access site, due to elevation of venous pressure on that side (raising risk of bleeding) as well as risk of loss of use of the dialysis access site should subclavian vein stenosis or occlusion result from the pacemaker insertion. In cases where the ipsilateral pectoral site must be used, some advocate use of the supraclavicular or internal jugular approach to minimize these risks. Because the risk of infection is higher in ESRD patients, especially in those receiving catheter-based hemodialysis, some thought might be given to the implantation of an epicardial lead system.

For patients with lesser degrees of renal dysfunction (determined by estimated creatinine clearance), the main issue is whether use of intravenous contrast is anticipated, and if so at what dose. Upper extremity venography can usually be performed with 10–20 mL of diluted contrast, which generally poses little risk. Patients undergoing biventricular pacemaker implantation may occasionally require as much as 80–100 mL of contrast when there is difficulty engaging the coronary sinus (CS) or identifying a suitable tributary for lead placement. In general, we favor use of isosmolar, non-ionic contrast for such patients and make every effort to minimize total contrast dose, using diluted contrast wherever possible. Recent consensus guidelines for prevention of contrast-induced nephropathy have emphasized use of pre- and post-procedure intravenous hydration with normal saline or sodium bicarbonate.[6] Other agents, such as N-acetylcysteine (NAC), have not been found to be uniformly effective for this purpose.

Anticoagulants and antiplatelet agents

Many patients requiring pacemaker implantation take oral anticoagulants for a variety of reasons, including atrial fibrillation, mechanical heart valves, and prior venous thromboembolism. Their peri-implant management is often complicated and related to their indication for anticoagulation. There are three general options. The traditional approach has been to convert the patient to intravenous unfractionated heparin. The latter can be stopped 4–6 h before surgery. Implantation is then performed when the International Normalized Ratio (INR) is 1.5 or less. If necessary, heparin may be restarted 8–12 h after the procedure and warfarin may be re-initiated on the day of the procedure or even the night before. It should be understood that intravenous heparin administered within 24 h after pacer or defibrillator implantation presents a significant risk (up to 20%) of pocket hematoma formation; this risk is five times that encountered in an unanticoagulated patient. Resumption of intravenous anticoagulation should thus be deferred for as long as possible after implant and then only with careful attention to the partial thromboplastin time.

Some operators now favor transitioning patients on oral anticoagulation to subcutaneously administered low-molecular-weight heparin (LMWH), which may be given up until 12–18 h before planned implantation. This approach obviates preprocedural hospitalization and is generally well tolerated. Resumption of warfarin at its maintenance dose post procedure with simultaneous LMWH for 3–5 days allows for the outpatient transition back to oral anticoagulation. The risk of post-procedure bleeding with LMWH is thought to be similar to that experienced with unfractionated heparin, although large-scale experience with its use specifically after pacemaker implantation has not been reported. In addition, there are no randomized controlled trials demonstrating the safety and efficacy of LMWH compared with standard unfractionated heparin for this indication, and

LMWH has not been Food and Drug Administration (FDA)-approved for this purpose. We generally do not favor use of these agents after device implantation because of the impression that they are associated with a higher risk of pocket hematoma formation.

The third, increasingly used option for managing the patient on warfarin is to perform the procedure without reversal of the anticoagulant. Giudici *et al.* reported excellent results with this strategy in a series of 470 patients with a mean INR of 2.6.[7] The authors used meticulous implantation technique and suggest that the risk of pocket bleeding is not prohibitive because hemostasis in these procedures is primarily a function of capillary vasoconstriction and platelet activity. In their study, the rate of pocket hematoma formation was 2.6% and was not significantly different from the rate in the control group of 555 patients implanted with an INR of less than 1.5 (2.2%).

Since this report was published, numerous additional studies have reported similar findings of relative safety of pacemaker implantation with continuation of therapeutic warfarin. Cheng *et al.* conducted a randomized trial of 100 patients on warfarin undergoing pacemaker or implantable cardioverter–defibrillator (ICD) implantation, or generator replacement, comparing a strategy of continuation of warfarin with interruption, and found a strong trend toward fewer complications in the group assigned to continuous warfarin.[8] Ghanbari *et al.* conducted a meta-analysis of eight studies enrolling 2321 patients undergoing pacemaker or ICD implantation in which continuation of warfarin was compared with a heparin bridging strategy.[9] This analysis found that continuation of warfarin was associated with a lower risk of postoperative bleeding and equivalent risk of thromboembolism.

It should be emphasized that pacemaker implantation in the setting of therapeutic warfarin is associated with potential risk and should be carried out by experienced operators who are confident in their implantation skills and ability to manage complications. This strategy appears to be increasingly used, however, as the least problematic solution to the challenging situation of pacemaker implantation in a patient at high risk for periprocedural thromboembolism.

Increasingly, patients with atrial fibrillation are anticoagulated with newer agents such as the direct-acting thrombin inhibitor dabigatran and the oral factor Xa inhibitors rivaroxaban and apixaban. These agents have a prompt anticoagulation effect after being started and half-lives of 8–16 h. No information has been published yet on the safety of continuation of these agents during pacemaker implantation. In general, these agents are held for 2–3 days prior to the procedure and restarted the day afterward.

Increasing use of prolonged dual-antiplatelet therapy in patients who receive intracoronary drug-eluting stents (DESs) poses an additional challenge for the pacemaker implanter. Although low-dose aspirin alone may usually be continued when it is indicated, it is clear that the use of dual antiplatelet therapy (i.e. aspirin plus ticlopidine, clopidogrel, or prasugrel) markedly impairs surgical hemostasis. Tompkins *et al.* reviewed 1388 device implantations at a single large urban health system and found that the combination of aspirin and clopidogrel was associated with a 4.5-fold increased risk of bleeding compared with use of no antiplatelet therapy, and a two-fold increased risk compared with use of aspirin alone.[10] Given that the recommendation for dual-antiplatelet treatment has been increased to 1 year after DES placement, and optimal duration remains undefined, implanting physicians will probably be more frequently asked to implant pacemakers and defibrillators in such patients. If the procedure cannot be postponed and dual-antiplatelet therapy cannot be held, then the pacemaker implanter will need to pay particularly careful attention to pocket hemostasis and perhaps take other steps to minimize bleeding complications, such as use of cephalic vein access.

Subclavian vein anomalies

Patients with potential subclavian vein anomalies require additional pre-procedure planning. In particular, patients with a pre-existing transvenous permanent pacemaker or ICD system have an approximately 25% prevalence of subsequent ipsilateral subclavian vein occlusion. One can usually anticipate a patent, suitable subclavian vein in a patient without prior chest surgery, pacemaker/ICD implantation, or deep venous thrombosis.

Other patients should undergo upper extremity venography prior to the implantation procedure, either on a separate day, or in the pacemaker laboratory prior to the sterile preparation of the patient. Management of a subclavian stenosis or occlusion, if identified, will depend on the degree of stenosis, length of occlusion, and perceived need to place the device on a particular side. If the side opposite to the venous stenosis/occlusion is felt to be unsuitable, various interventional techniques for crossing and dilating these lesions have been described.[11] Of the significant congenital anomalies of the brachiocephalic system, a persistent left superior vena cava (SVC) is the most frequent. It is discussed in more detail under "Site".

Prior mastectomy

With improved survival from breast cancer, the pacemaker implanter is more likely to encounter patients with prior mastectomy who require implantation of a CIED. In general, the side opposite to the mastectomy is used, due to concern for exacerbating arm swelling should subclavian vein stenosis or occlusion follow pacemaker implantation. Breast surgery, however, should not automatically preclude use of the ipsilateral pectoral site if that side is preferred for appropriate reasons. For example, a patient with a partial mastectomy and minimal or no lymph node dissection, good preservation of subcutaneous tissue, and no history of lymphedema or arm swelling could probably undergo ipsilateral implantation with little or no increased risk. If the patient has a history of arm swelling or lymphedema, that side is best avoided. In the unusual patient with bilateral mastectomies, the pectoral site with best preservation of subcutaneous tissue and least degree of ipsilateral arm swelling should be used. Preoperative upper extremity venography should also be performed in this situation.

Tricuspid valve disease

Patients with pre-existing severe tricuspid regurgitation can pose a substantial challenge for the pacemaker implanter, due to both turbulent blood flow from the regurgitation and the resulting right heart enlargement. Active fixation leads are usually required to reduce the risk of dislodgement. Larger-diameter, heavier leads and stiffer stylets are often required to place the right ventricular (RV) lead. Lead stability may need to take priority over best possible lead parameters.

In patients with prosthetic tricuspid valves, it is imperative to determine the type of prosthesis. Transvenous leads cannot be placed through a mechanical prosthesis, and an alternative site for ventricular pacing must be chosen (CS or epicardial). In patients with bioprosthetic valves, transvenous RV leads have been successfully placed, although the long-term effects on prosthetic valve function are not known.[12]

Patients at risk for asystole

The operator should consider whether a temporary pacing wire should be placed at the start of the procedure to provide back-up pacing in the event of prolonged asystole during permanent lead placement. Patients with complete left bundle branch block (LBBB) or AV block with a ventricular escape mechanism are at particular risk for this complication. Patients with isolated sinus node dysfunction without bundle branch block are generally at low risk. Operators with less experience should have a lower threshold for placing a temporary wire prior to permanent pacemaker implantation if potential for severe intraprocedural bradycardia is anticipated. Patients who are pacemaker dependent and undergoing generator replacement or system revision should generally have a temporary pacing wire placed for the procedure. All patients should be connected via adhesive electrode patches to an external defibrillator capable of emergency external pacing; however, this device should not be considered a substitute for a temporary wire in a high-risk patient.

Cost effectiveness

More emphasis is currently being placed on the cost effectiveness of medical care, especially those aspects of care that are procedurally centered. Ideally, attention to cost effectiveness is accompanied by increased quality of care. Hospital administrators have increasingly focused on minimizing length of stay, the cost of specific devices, and increasing the level of patient satisfaction. Mechanisms of clinical practice improvement that

may reduce cost yet increase the quality of care have been used. Practice guidelines, critical pathways, and other methods of standardizing care are likely to become more widespread. Physicians should continue to play a leading role in cost constraint without compromising excellent patient care.

Informed consent

It is generally the implanting physician's responsibility to obtain informed consent from the patient (or the patient's surrogate decision-maker) before the procedure. A candid appraisal of the anticipated risks and benefits, acute and long term, must be undertaken along with an explanation of alternatives. This should be relevant to the particular individual rather than the "average patient." There should be a discussion not only of why pacing is being offered, but also of why a particular mode of pacing is being considered. If the indication for pacing is controversial or investigational, more extensive counseling of the patient and documentation are usually necessary. The need for regular, life-long follow-up evaluations should be noted, and mention should be made of the eventual need for generator replacement for an end-of-service indication. The small but finite possibility of premature failure of the leads and/or generator should also be reviewed. Finally, physical or occupational restrictions imposed by the presence of a pacemaker should be discussed with the patient.

It is good practice for the physician to establish a rapport with the patient and the patient's family. All their questions should be answered and their fears concerning the procedure should be allayed, although it is important that no guarantees regarding outcome be given. The participation of other physicians at the time of implantation or during the follow-up assessments should be described. If the pacemaker follow-up is to be performed by the referring physician, that person should be consulted in advance to determine the most appropriate choice of pacemaker system. The various members of the team should be in agreement about all important aspects of the procedure so that the presentation to the patient is not confused.

Pre-implantation orders

Although outpatient pacemaker implantation can be performed, the usual practice is to admit the patient to the hospital for overnight observation.[13] Many third-party payors consider these stays as 23-h observation stays rather than full admissions for this purpose. Admission may be done on the day of the procedure if the patient's medical condition does not mandate prior hospitalization. Routine pre-implant laboratory tests include a 12-lead ECG, a complete blood cell count (including platelet count), and measures of the prothrombin and activated partial thromboplastin times (aPTT), serum electrolytes, blood urea nitrogen (BUN), and creatinine. It may be helpful to have a recent posteroanterior and lateral chest radiograph to compare with the post-procedure radiographs, particularly in patients with prior chest surgery and/or prior pacemaker or ICD implantation.

Patients usually fast for at least 8 h before the procedure. Hydration is maintained by the establishment of an intravenous line, preferably with a large-bore cannula, in a vein of the upper extremity ipsilateral to the intended implant site. This will facilitate the injection of contrast should difficulty be encountered in achieving venous access. In general, patients are allowed to continue whatever medication they have been taking, with the usual exception of anticoagulants and antiplatelet agents (see "Special issues"). The dosage of insulin or oral hypoglycemic drugs may require temporary alteration, usually holding or reducing the dose on the morning of the procedure.

Antibiotic prophylaxis appears to decrease the incidence of short-term and late pacemaker infection. A meta-analysis of randomized trials that used a systemic antibiotic has supported the use of a prophylactic antibiotic to prevent infection associated with permanent pacemaker implantation.[14] In an accompanying report, the same investigators have suggested that contamination by local flora cultured at the site of implant can result in delayed pacemaker-related infections presenting months later.[15] We routinely give an antibiotic active against *Staphylococcus* (cefazolin, vancomycin, or clindamycin) before and for 24 h after the procedure. It is of obvious importance that the initial antibiotic

dose be completed prior to skin incision, preferably 30–60 min before, to allow for peak tissue concentrations. There are no data to support giving prophylactic antibiotics for more than 24 h after implantation procedures. Quality guidelines for surgical procedures generally call for stopping prophylactic antibiotics within 24 h of clean, sterile procedures, unless there are extenuating circumstances.

The implant site (typically the area from above the nipple line to the angle of the jaw bilaterally) should be cleaned just before the patient's arrival in the pacemaker laboratory. Shaving the surgical site is controversial, and guidelines have been issued recently that argue against shaving in favor of surgical hair clippers that do not abrade the skin. A reliable intravenous line is established in the prep area, preferably ipsilateral to the implant site, and intravenous fluids administered for hydration. Mild preprocedural sedation [e.g. 5–10 mg of diazepam (Valium) and 25–50 mg of diphenhydramine (Benadryl), orally] may be given in the prep area. Sedation is usually augmented by intravenous sedatives/analgesics during the procedure (e.g. 0.5–1 mg of midazolam, 25–50 μg of fentanyl) as needed.

Care should be taken not to oversedate patients, especially the elderly. Drugs to reverse sedation should be readily available: intravenous flumazenil in 0.2-mg increments reverses midazolam; intravenous naloxone in 0.2-mg increments reverses fentanyl and other opiates. For particular patients (such as children or neurologically impaired adults), general anesthesia may be needed and should be arranged in advance.

Patient preparation

On entering the procedure room, the patient is placed supine on the fluoroscopy table in such a way as to facilitate access to the specific operative site. Physiological monitoring (ECG, automated blood pressure, and pulse oximetry) should be quickly established so that rhythm disturbances may be detected and treated. The operative site is thoroughly prepared with an antiseptic solution (usually chlorhexidine or iodine based), which is allowed to dry, and a plastic adhesive sterile field is applied. Disposable towels and drapes are applied to provide a large sterile workplace and to minimize the risk of accidental contamination. A separate adhesive plastic pocket is affixed to the lateral aspect of the procedure site to collect draining fluid and sponges. A sterile plastic cover is placed over the image intensifier and the leaded glass shield (if used) to avoid inadvertent contamination of the sterile field during the procedure.

Implant procedure

Site

Access to the right heart for permanent pacing has been achieved by introducing leads into several veins, including the subclavian, cephalic, internal or external jugular, and iliofemoral. Typically, the choice of venous entry site determines where the generator will be placed, although lead extenders can be used when necessary to allow for remote positioning of the device. In most cases, a cephalic, axillary, or subclavian vein is used, and the pacemaker is placed subcutaneously in the adjacent infraclavicular region. On occasion, however, the generator may be implanted under the pectoral muscle or in an abdominal position. For women in whom there is a concern about cosmetic appearance, an inframammary incision may be performed and the pacemaker placed under the breast. In such circumstances, it may be prudent to enlist the assistance of a plastic surgeon. Patients should be advised that such remote generator implantation sites may make any future lead revisions and generator changes more complicated procedures.

The site of implantation is influenced by the factors listed in Figure 5.2. Most often the left side is chosen because most patients are right handed and there is a less acute angle between the left subclavian and the innominate vein than exists on the right side. A disadvantage of using the left side is the small (0.3–0.5%) incidence of a persistent left SVC with drainage into the CS, which complicates lead positioning. Suspicion of this anomaly may be raised by finding greater distension and a double a wave in the left jugular vein compared with that of the right vein, a left paramediastinal venous crescent on the chest radiograph, and an enlarged CS on echocardiography. Contrast

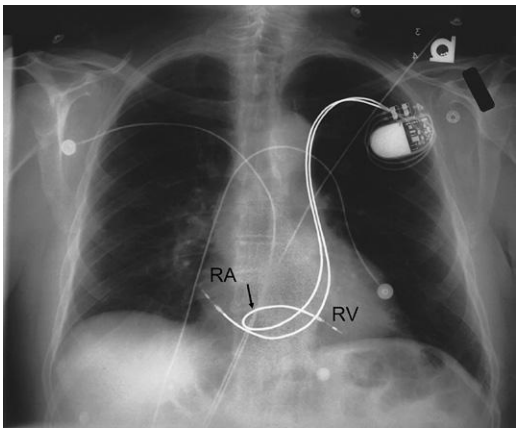


Figure 5.3 Anteroposterior chest radiograph of a patient with a dual chamber pacemaker placed through a congenital persistent left superior vena cava. Given the circuitous course of the ventricular lead (arrow), long lead lengths are sometimes needed to reach the right ventricle. RA, right atrial lead; RV, right ventricular lead.

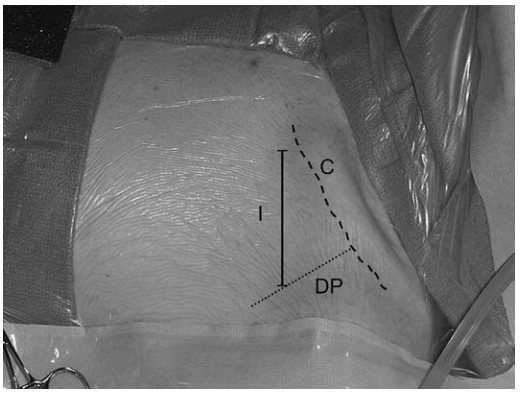


Figure 5.4 Surface landmarks in a patient about to undergo pacemaker implantation. The patient's head is to the right. The dashed line (C) indicates the inferior margin of the left clavicle. The solid line (I) 2 cm beneath indicates the site of incision, from which access to the subclavian, axillary, and cephalic veins is possible. The diagonal dotted line (DP) indicates the deltopectoral groove in which the cephalic vein is found. Incision at this site allows access to the cephalic and axillary veins.

echocardiography or venography will confirm the diagnosis.

Although both single chamber ventricular and dual chamber systems have been placed through a persistent left SVC via the CS,[16] it is preferable to approach implantation from the right side when this anomaly exists (Figure 5.3). Rarely, there is a co-existent absence of the right SVC with all brachiocephalic flow entering into the CS. Such a condition should be excluded before implantation is attempted from the right side in patients with a persistent left SVC. The increasing experience with pacing from the coronary venous system, coupled with the relative ease of entering these vessels in the case of persistent left SVC, suggests that this is a reasonable alternative in the latter patients. Other options for patients with anomalous venous drainage include an iliofemoral approach or an epicardial implantation, which now may be performed through a subxiphoid or thoracoscopic approach.

Venous access

Figure 5.4 illustrates the two major easily identifiable landmarks (clavicle and deltopectoral groove) for implantation in a left infraclavicular site. Venous access into either the axillary/subclavian or cephalic vein is usually achieved through an incision that will also serve as the portal for subcutaneous generator placement. Local anesthetic is injected through a small-gauge needle along a line 4–6 cm long and two fingerbreadths below and parallel to the clavicle. If the cephalic vein is used, the incision begins about 0.5 cm lateral to the deltopectoral groove and is extended medially; otherwise, the incision may be placed just medial to the groove. This method provides adequate exposure for access to either the subclavian or cephalic vein.

Some operators begin with a smaller incision specifically located to achieve venous access, after which the incision is extended or a new one is made for the pocket. This is necessary when a supraclavicular approach to the subclavian vein or a jugular venous access is contemplated. In the latter situations, the leads are tunneled over the clavicle to the generator, which is placed in the usual ipsilateral infraclavicular position.

Pacing leads may be introduced through a venotomy in an exposed vein (cephalic, jugular, iliofemoral), or venous access may be achieved using the Seldinger technique. The latter approach provides easy access to a relatively large central vein, obviating the need for surgical dissection. In addition, the use of the dilator-sheath technique

facilitates the introduction of multiple large leads and provides a means (via a retained guidewire) to re-enter the venous system should that be necessary. Nevertheless, the subclavian puncture poses the risk of injury to nearby structures, including the artery, lung, thoracic duct, and nerves, and it is sometimes the most hazardous part of the implantation procedure.

Axillary vein approach

The Seldinger approach to the subclavian vein has long been a popular method of gaining rapid access to the central venous circulation. However, the traditional percutaneous subclavian approach may result in access to the medial aspect of the vein, which may later cause entrapment of the lead between the subclavius muscle and the costoclavicular ligament. Forces exerted on leads in this position may predispose them to insulation failure and/or conductor fracture (Figure 5.5). This may be most problematic for some polyurethane leads (especially those made with Pellethane 80A), which appear to be particularly susceptible to failure when placed via the subclavian route. These observations have led to the development of techniques to access the axillary vein by direct needle stick. This method appears to be safe and effective and it is more likely to be successful than cephalic vein cutdown.[17]

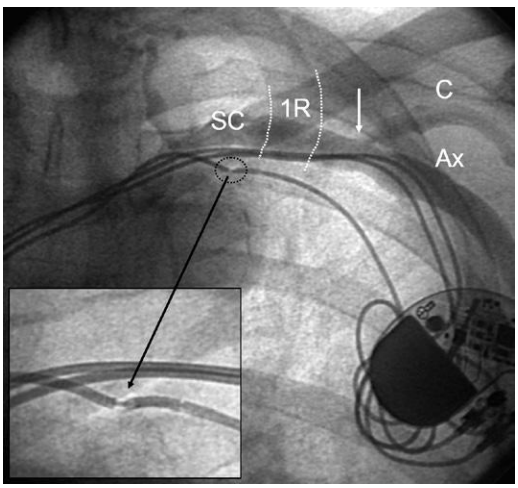


Figure 5.5 Lead fracture from "subclavian crush" seen on fluoroscopy during left arm venography. The fractured lead (dotted circle) was placed through a venous access point in the subclavian vein (SC) medial to the first rib (1R, outlined with dotted lines). The other two leads, placed more laterally in the left axillary vein (Ax), are intact. Note that the cephalic vein (C) joins the axillary vein lateral to the first rib (arrow); leads placed in the cephalic vein are generally immune from this risk. Inset shows complete disruption of the insulation and outer conductor coil, and stretching of the inner conductor coil of the fractured lead.

The introduction of the tear-away sheath has provided an effective means for the insertion of permanent pacemaker leads, and this method is now the most frequently used. The efficacy and safety of axillary and subclavian entry are increased by taking measures to distend the vein (proper hydration, leg elevation) and place it in the proper position (by placing a wedge under the patient's shoulders and by adduction of the ipsilateral upper extremity).

We find ipsilateral upper extremity contrast venography to be helpful in demonstrating patency of the vessel, ruling out any anomaly which would preclude access, and providing a "road map" for using the axillary access technique. Adequate opacification of the axillary/subclavian vein is achieved by the injection of a bolus of 10–20 mL of iodinated contrast through a large-bore cannula in an ipsilateral arm vein. This should be followed immediately by injection of a saline "chaser" to hasten the transit of the contrast solution. The amount of fluid and rate of injection are gauged by fluoroscopic observation of the course of dye into the central veins. It is important that enough contrast be used and that adequate time be given for the contrast to fill the subclavian vein or collateral vessels. If the vessel is patent, there is often enough lingering contrast to allow an exploring needle to be directed at it.

Our current practice is to use a smaller gauge micropuncture system for all percutaneous vascular access; this system is safer and usually less painful (Figure 5.6). The micropuncture needle, attached to a 10-mL syringe containing a few milliliters of local anesthetic or saline, is introduced through an incision that has been dissected to the underlying pre-pectoral fascia. The needle enters the pectoral muscle with the access needle just medial to the coracoid process on anteroposterior fluoroscopy. If a submuscular pocket is to be used, it is best to access the vein through the floor of the

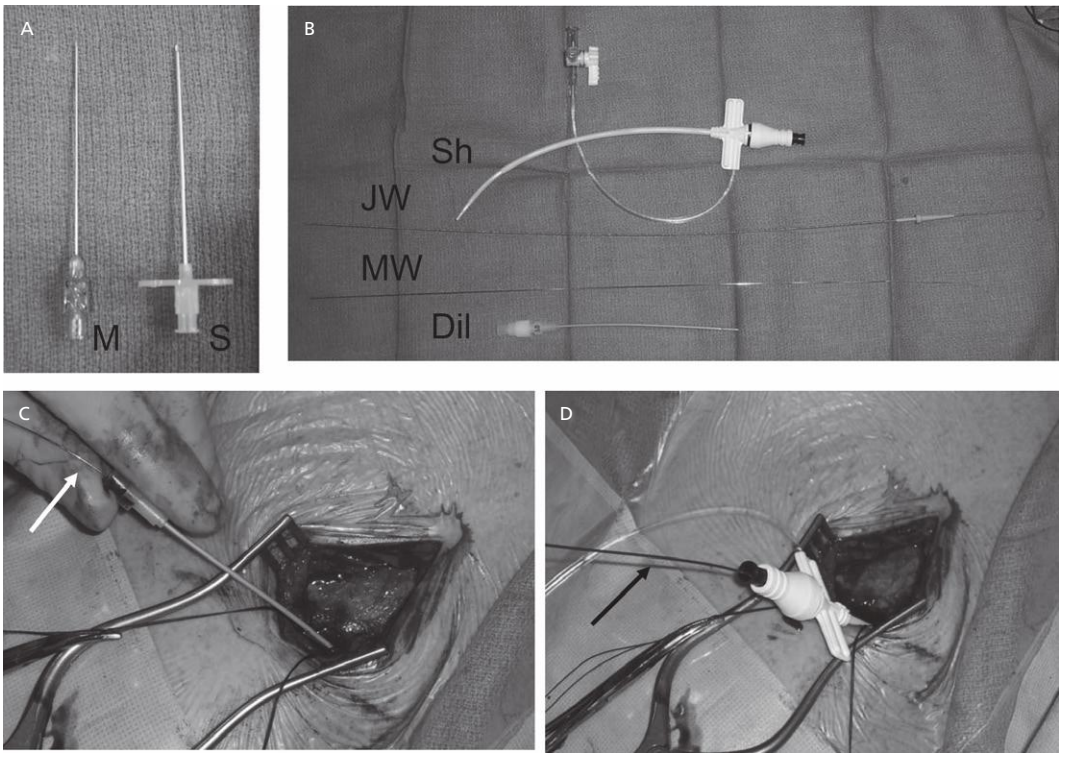


Figure 5.6 Micropuncture technique for vascular access. (A) 18-G micropuncture needle (M) is compared with a standard 21-G Seldinger needle (S). (B) Other components of the access equipment, including the valved peel-away sheath (Sh), standard 0.035 J-wire (JW), the 0.018 micropuncture wire (MW), and the 5.0-Fr micropuncture dilator (Dil). (C) After venous access is obtained, the micropuncture dilator is placed over the micropuncture wire (arrow), which is then removed and a standard J-wire or glidewire is then passed into the right atrium or inferior vena cava. (D) The valved peel-away sheath is placed over the standard wire (arrow).

pocket with the needle. This will prevent excessive angulation of the leads between the access site and the pocket. Through the floor of the submuscular pocket, the axillary vein may be extremely shallow, and care is needed to avoid entry into the thorax. The needle is then directed under fluoroscopy to the point at which the lateral border of the first rib appears to cross the inferior margin of the clavicle (Figure 5.7). The needle approach is angulated to a degree such that the first rib is struck with the needle if the vein is not entered. By walking the needle up and down the first rib on repeated passes, the axillary vein is eventually entered. Small amounts of anesthetic may be injected along this course. Negative pressure is exerted on the syringe as the needle is advanced so that blood is aspirated on entry into the vein.

After advancement, the needle should not be redirected; doing so may lacerate underlying structures. If venous entry is not obtained, the needle should be withdrawn, cleared of any obstructing tissue, and re-inserted in a slightly different direction. Inadvertent arterial entry is apparent with the appearance of pulsatile bright red blood. Prompt withdrawal of the needle and compression at its entry site is usually all that is necessary to obtain hemostasis. Repeated unsuccessful attempts to enter the vein suggest a deviation in anatomy or occlusion of the vessel. In either situation, the risk of complication is increased with additional blind needle insertions. At this point one should consider a repeat contrast injection to determine vessel patency and to provide an updated road map.

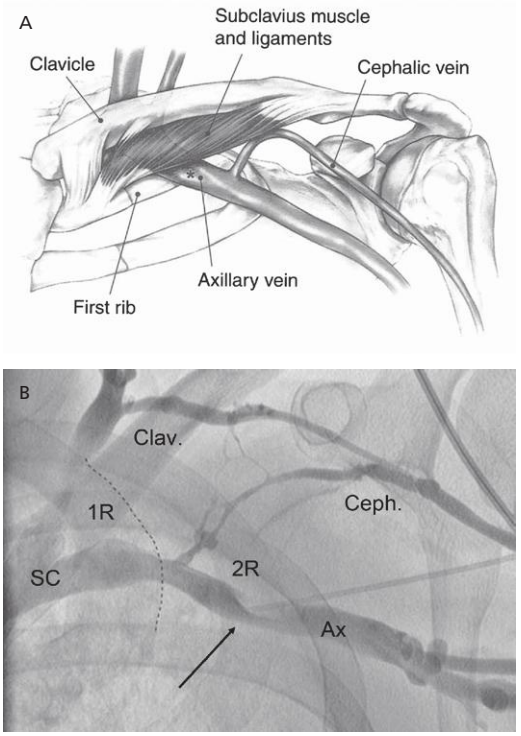


Figure 5.7 (A) Anatomy of the subclavian venous system and skeletal landmarks relevant to percutaneous access. The subclavius muscle and costoclavicular ligament complex are shown between the clavicle and first rib. Accessing the subclavian vein medially requires the lead to pass through these structures. This may be associated with a higher risk of lead fracture due to compressive forces on the lead. By accessing the cephalic vein or axillary vein (*) extrathoracically, the problems of lead entrapment are eliminated. (B) Fluoroscopic guidance for the introducer needle into the axillary vein. The peripheral venogram delineates the axillary vein (Ax) as it crosses the first rib (1R, dotted line) in anteroposterior projection. The introducer needle is seen indenting the axilllary vein (arrow) just before puncture over the second rib (2R) at a site that is far outside the thoracic cage. Ceph., cephalic vein; Clav., left clavicle; SC, subclavian vein.

On successful entry of the needle into a vessel, the character of the aspirated blood is examined. Dark non-pulsatile flow suggests a venous location; however, non-pulsatile flow does not exclude arterial entry, and pulsatile flow is sometimes noted from a vein (e.g. tricuspid regurgitation, right heart failure, cannon waves). Once vascular access is achieved, the syringe is detached (taking care to prevent air from entering the venous system) and a micropuncture wire is inserted through the needle and advanced under fluoroscopy to the inferior vena cava (IVC). If this is accomplished, inadvertent aortic entry is precluded; merely observing the guidewire coursing to the right of the sternum or even into a ventricular chamber does not exclude its presence in a tortuous ascending aorta or its passing retrograde into the left ventricle (LV). It is critically important that entry into the proper venous structure is confirmed prior to advancing a dilator or sheath over the wire.

If resistance to advancement of the guidewire is encountered, the guidewire should be withdrawn through the needle with great care to prevent shearing off the distal wire by the needle tip. If any difficulty is encountered with withdrawal, both the wire and needle should be withdrawn together or, if enough wire has been passed into the vein, the needle may be withdrawn and a small-lumen plastic catheter advanced over the wire and into the vein. In the latter situation, contrast may then be injected through the catheter to identify the problem and a more torqueable wire capable of being directed appropriately can be introduced.

After the micropuncture wire has been properly placed, a 4- or 5-Fr micro-puncture dilator is placed over the wire and the wire withdrawn, taking care to avoid entry of air into the vasculature. A standard J-wire or glidewire is then placed through the micropuncture dilator and passed into the IVC. The access procedure may be repeated for as many leads as will be implanted during the procedure. Some operators prefer to use a single access site and retain the guidewire throughout the case. Although this potentially reduces the risk of vascular injury or pneumothorax, this approach may create problems with lead–lead interaction during positioning within the heart.

Once the guidewire is positioned in the IVC, a commercially available peel-away sheath–dilator combination (7–9 Fr, depending on lead size) may be advanced over the wire into the SVC, which will provide access for the introduction of pacing leads. The relatively stiff, straight dilator should be molded into a gentle curve by the operator before insertion. Advancement of the device under the clavicle may be facilitated by torqueing it as if it were being screwed into place. Considerable

resistance may be encountered if the subclavian vein has been entered medially through a fibrous or calcified ligament. Entrance into such a location may be a marker for future lead entrapment; thus, one may consider seeking a more lateral entry site. If the site is retained, the use of a stiffer guidewire may be advantageous in such a situation, as may the passage of initially small, then progressively larger dilators. Excessive force should not be necessary once the sheath has entered the vein. Fluoroscopic confirmation of proper alignment of dilator and wire is necessary if resistance is encountered. On occasion, countertraction on the wire while advancing the dilator is helpful. The sheath should not be allowed to slide over the tapered tip of the dilator, nor should the dilator be unprotected by a guidewire at any time during advancement.

Once it is properly positioned in the SVC, the dilator is removed while the guidewire is retained within the sheath to allow for the introduction of a second sheath if necessary. A clamp should be applied to the end of the guidewire to prevent its accidental migration into the vein. Care should be taken to limit the possibility of the aspiration of air through the large-bore open sheath by pinching its orifice until the lead is inserted. If possible, the patient should not be heavily sedated and should be instructed to avoid deep inspiration during this process. Deep breathing, and particularly snoring, greatly increases the chance of significant air embolus through an unvalved sheath. The use of tear-away sheaths with hemostatic valves is helpful in limiting bleeding and preventing air embolism, and should be used whenever possible.

The pacing lead is introduced carefully to avoid kinking the tip and advanced into the right atrium or IVC, at which time the sheath is withdrawn and peeled apart proximal to the venous entry site to prevent injury to the vessel. Some operators prefer to retain the sheath until the lead is placed in its final position in the heart. If a dual chamber device is to be employed, the retained wire or a second access wire is used to introduce a second sheath. If only one lead is to be used, it may be helpful to retain one guidewire so that venous re-entry is facilitated should the lead prove inadequate.

Cephalic vein approach

The cephalic vein resides in the sulcus between the deltoid and pectoral muscles. This area is readily identified by palpation and is occupied by loose connective tissue and fat, which are easily separated to reveal the underlying vein that sometimes lies fairly deep in this groove. The consistent course of this vessel, its reasonable size, and the direct path it takes to the central venous system make it useful for transvenous lead placement. On occasion, however, this vessel is small, consists of a plexus of tiny veins rather than a larger single channel, or takes a circuitous route to the subclavian vein. These conditions may make lead insertion difficult or impossible. In addition, the occasional difficulty in inserting two leads into the cephalic vein may limit the opportunity of using this approach for dual lead systems in some patients.

The vein is isolated along a 1–2-cm length within the groove and ligated distally with a silk suture (Figure 5.8). A ligature is looped but not tightened around the proximal aspect of the vein for hemostasis. The vein is entered by venotomy using a straight blade or with iris scissors. Using a vein pick, the tip of a 4- or 5-Fr dilator is placed in the venotomy and used to guide a floppy or hydrophilic-coated wire to secure access. Use of an angled glidewire with a torquing tool can be particularly helpful in negotiating the junction between the cephalic and axillary veins, which may form an acute angle in some patients, taking the wire peripherally down the arm rather than centrally to the thorax. A dilator–introducer sheath combination may then be used as described previously for the retained wire method in the subclavian approach.

The greatest benefit of the cephalic approach is its margin of safety compared with that of the axillary/subclavian puncture—there is almost no risk of pneumothorax or hemothorax. Although the cephalic vein itself is often sacrificed by this hybrid procedure, there is rarely any clinical consequence. In either case, the guidewire provides virtually unlimited access to the central venous system. Tearing of the vein may result in significant bleeding from tributaries into the pocket, which may be controlled with a purse string suture around the venous access site.

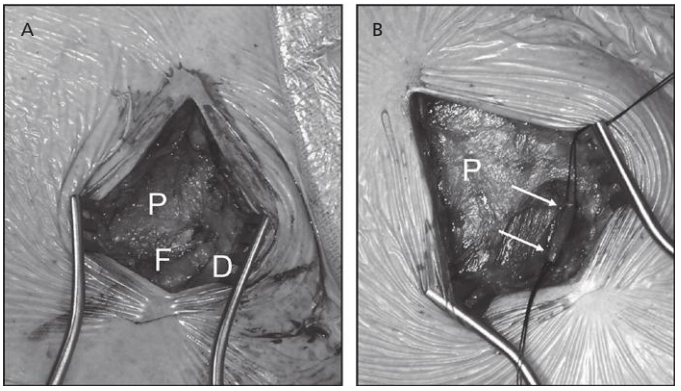


Figure 5.8 Surgical access to the left cephalic vein at pacemaker implant. (A) The incision has been carried down to the pectoralis fascia, exposing the left pectoralis major muscle (P), deltoid muscle (D), and fat stripe (F) which marks the deltopectoral groove. (B) The moderately large cephalic vein (arrows) lies in the dissected deltopectoral groove and has ligatures placed proximally and distally. This vein can be accessed directly with venotomy, a peripheral IV catheter, or a micropuncture dilator to introduce a guidewire and peel-away sheath.

Rarely, the cephalic vein takes an aberrant course or a pectoral vein is inadvertently accessed. In such cases the guidewire may easily enter the subclavian vein, but it may not be possible to manipulate a sheath over the wire successfully, which necessitates abandoning the technique and sacrificing the vein. In other cases, the vein may spasm or invaginate by passage of the sheath essentially grasping it and preventing its advancement or removal. Application of a vasodilator (e.g. nitroglycerin) or actually cutting the constricting vein, exposed by pulling back on the dilator, may be necessary to insert the sheath fully. Despite these potential limitations of the cephalic technique, an experienced operator can successfully implant leads by this approach in most cases when it is attempted.

Subclavian vein approach

Despite widespread use in the past, the subclavian vein approach should be used rarely in favor of the axillary and cephalic access methods described above. On occasion, when these two methods are unsuccessful, the traditional subclavian vein approach may be required and so it will be described further.

Preparation of the patient is similar to the axillary vein approach described above. Contrast venography through the ipsilateral arm may be helpful to assure patency of the vein and to define its anatomical course, which may vary in different patients. Temporarily raising the patient's legs on a wedge may help to distend the vein and make puncture easier. The patient's arm should be pul led caudally to flatten the clavicle and minimize "hunching" of the shoulders.

The access needle, attached to a 10-mL syringe containing a few milliliters of local anesthetic or saline, is introduced through an incision that has been bluntly dissected to the underlying prepectoral fascia. The tip of the needle is advanced, bevel down, along this tissue plane at the level of the junction of the medial and middle thirds of the clavicle, and directed toward a point just above the sternal notch. The appropriate point to meet the clavicle is at the angle evident on palpation or fluoroscopy. On reaching the clavicle, the needle's angle of entry with respect to the thorax is increased until the tip slips under the bone. Alternatively, the needle is marched anterior to posterior along the clavicle using the thumb of the nondominant hand to depress the needle or barrel of the syringe. Once under the clavicle, the needle and syringe should be maintained parallel to the floor; this prevents the needle from plunging ever more posteriorly as the needle is advanced. Negative pressure is exerted on the syringe as the needle is advanced so that blood is aspirated upon entry into

the vein. Once under the clavicle, the needle should not be redirected; doing so may lacerate underlying structures. If venous entry is not obtained, the needle should be withdrawn, cleared with saline, and re-inserted in a slightly different direction. The subclavian artery is cranial and posterior to the subclavian vein. Entry into the subclavian artery should lead to appropriate adjustments in the needle's trajectory. In addition, crossing under the clavicle from too lateral a position will often result in arterial access.

Once venous entry is assured, a J-wire or glidewire is passed and the procedure continued as described in "Axillary vein access."

Pacemaker pocket

The pacemaker is usually placed in a subcutaneous position near the site of venous entry. Generators have continued to decrease in size and can be placed easily in most patients, including those having a paucity of subcutaneous tissue. Most often, the device is placed in the infraclavicular area through the incision used to obtain venous access. Local anesthesia is applied to the subcutaneous tissue, which is then dissected down to the pre-pectoral fascia. The pocket should be created in the plane just above this fascial layer and below the subcutaneous fat. Placing the pocket too superficially in a subcuticular pocket may lead to erosion or to a pain syndrome requiring re-operation.

A pocket directed inferomedially over the pectoral fascia and large enough to accommodate both the generator and redundant lead is made in this tissue plane by a combination of electrocautery and blunt dissection. Too small a pocket may result in tension exerted on the overlying tissue by the implanted hardware; too large a pocket invites future migration or "flipping over" of the generator. Augmentation of anesthesia with a rapidly acting parenteral agent is recommended during the brief time it takes for pocket creation, because this is usually the most painful part of the procedure. Attention to hemostasis is necessary, but significant bleeding rarely accompanies blunt dissection and electrocautery in the proper tissue plane. Stripping away the pectoral fascia during the dissection often leads to excessive bleeding from the denuded muscle, especially in patients taking antiplatelet agents. On completion of its formation, the pocket may be flushed with antibacterial solution and temporarily packed with radio-opaque sponges. All sponges used in this fashion should be accounted for in order to avoid leaving one in the pocket. Even a radio-opaque sponge may be missed by fluoroscopy if it is under the generator and only casual observation is made. The use of oversized laparotomy sponges that cannot be concealed in the pocket may also avoid this problem.

In some circumstances (e.g. sparse subcutaneous tissue, large generator, impending erosion from a previous device, concerns about cosmetic appearance) the generator may be placed subpectorally or under the breast.[18] These procedures should be planned ahead of time with the assistance of appropriate personnel (e.g. a plastic surgeon) as needed. The subpectoral site is best accessed by dissecting the natural plane between the pectoralis major and minor muscles. This plane is identified by blunt dissection in the deltopectoral groove and carried inferiorly and medially. Alternatively, a muscle-splitting incision can be made in the body of the pectoralis major itself. When used, the subpectoral location should be noted in the operative report for reference for future revisions or generator changes.

A pocket located at a distance from the site of lead insertion requires that the leads (with or without extenders) be tunneled through subcutaneous tissue to its location.

Lead implantation

A variety of leads are available for endocardial placement. They differ in composition, shape, electrode configuration, and method of fixation. Passive fixation leads have tines that anchor them in the trabeculated RV or atrial appendage. Active fixation leads employ a helix as the mechanism for fixing them to the endocardium. The helix may be extendable and retractable, or may be permanently fixed at the tip. In some lead models, the fixed helix is covered with an absorbable agent to facilitate passage of the lead to its site of implantation, by which time absorption of the material exposes the helix and allows it to be fixed to the heart. In general, leads with extendable–retractable helices

Table 5.2 Lead characteristics

Active fixation lead	Easy passage
	Low acute dislodgement rate
	Unrestricted positioning
	Easier removal of chronic implant
	Higher capture thresholds
Passive fixation lead	Greater electrode variety
	Lower thresholds
	More difficult passage
	More difficult chronic removal
	Higher early dislodgement rate

are easier to implant and easier to remove if necessary.

Both active and passive fixation leads have advantages and disadvantages (Table 5.2) and may be used for either atrial or ventricular placement. Steroid-eluting passive fixation leads may offer some benefit in terms of lowered subacute and possibly chronic thresholds. Despite the progress in lead designs and their overall excellent performance, the failure over time of several models of these devices remains a cause for concern.[19,20]

Before their introduction, leads should be inspected for anomalies. Proper sheath selection should be made to allow passage of the lead and, if used, the retained guidewire. Active fixation leads should be tested on a clean surface to ensure that the helix extends and retracts appropriately. The connector pin of the lead should be appropriate for the selected pulse generator. For the past 20 years, the IS-1 pin connector system has been used almost exclusively for new atrial and RV pacing leads. The suture sleeve should be positioned at the proximal portion of the lead and prevented from migrating distally during lead placement.

Stylets of varying length and stiffness are used to manipulate and steer the lead in the body. Stylets should be kept clean and dry to facilitate insertion and withdrawal from the lead. Torque applied to a shaped stylet will help rotate the lead to its desired location. Steerable stylets are now available that allow for *in-situ* alteration of the degree of curve they provide to the lead tip, which may facilitate atrial placement or selective-site ventricular lead placement. One lead model has no central lumen for a stylet and uses a steerable sheath system for implantation.

Leads are usually inserted through a valved peel-away sheath. Care should be taken to avoid damaging the lead tip when pushing it through the valve. The central venous system is usually traversed easily and the lead advanced to the low right atrium or IVC. On occasion there may be difficulty in advancing the lead through a kink in the sheath or through tortuous central vasculature. Withdrawing the sheath slightly, advancing the retained guidewire along with the lead, and sometimes withdrawing the stylet to soften the lead tip may prove helpful in these situations. When tortuous or stenosed central vasculature is encountered, a long sheath may be required for passage of the lead into the heart.

Although the retained-guidewire approach facilitates the insertion of the two leads required for dual chamber pacing, manipulation of one lead may affect the position of the other, especially when silicone-coated leads are used. Some implanters consider that two independent sheaths should be used and not withdrawn until both leads have been positioned, or that separate venous sites (e.g. cephalic and axillary or two separate axillary entry sites) be accessed for each lead. If necessary, however, two leads may usually be inserted and positioned through the same access site by using the retained-guidewire technique. Good fluoroscopic imaging is a key to successful lead implantation, and care should be taken always to image the tip of any lead as it is advanced, and with any lead manipulation in the heart.

Ventricular lead positioning

In dual chamber systems, the RV lead is usually positioned first because it may supply back-up pacing, its position is usually more stable than that of the atrial lead, and it is usually the most important of the leads. LV lead placement is described in Chapter 9.

Once the RV lead has been advanced to the low right atrium or IVC, the straight stylet is withdrawn a few inches to allow the lead tip to catch in the right atrium; further advancement of the lead will cause its distal portion to form a J shape, which may then be rotated toward the tricuspid valve (Figure 5.9A–F). Slight retraction results in

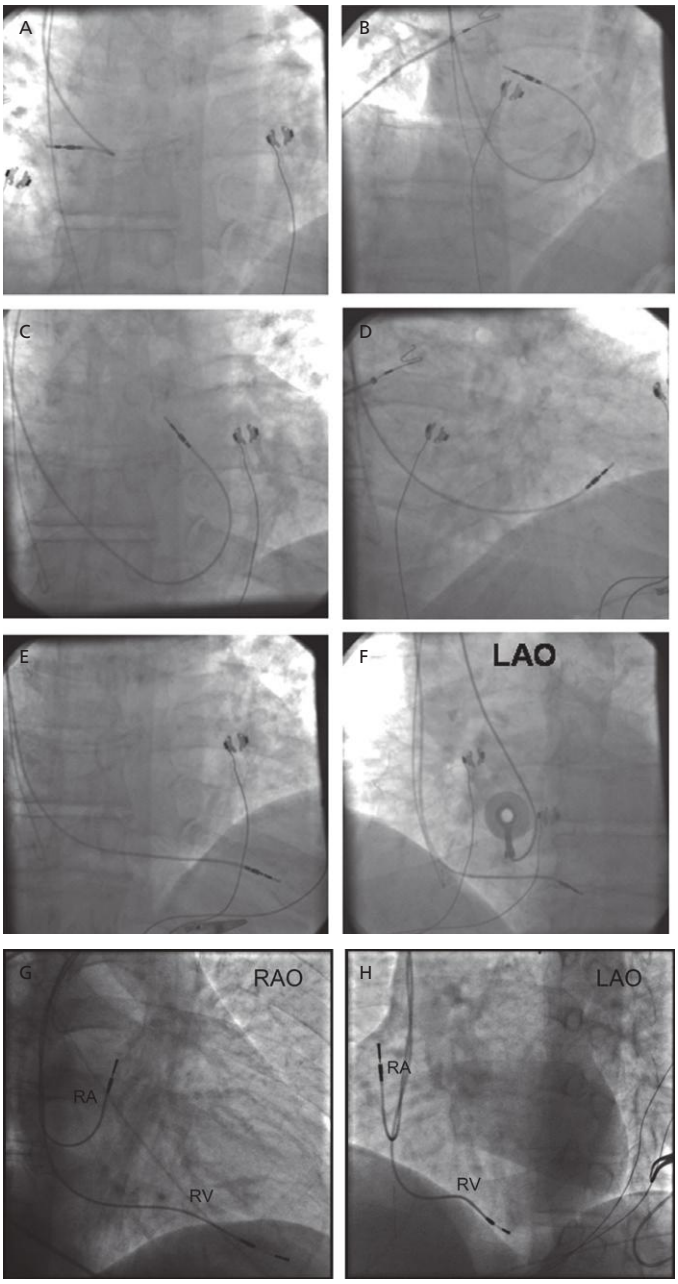


Figure 5.9 (A–F) Placement of the ventricular lead in right anterior oblique (RAO) views. (A) The lead forms a loop in the right atrium. (B) The lead is rotated and the loop advanced across the tricuspid valve. (C) The lead is advanced to pass the tip into the right ventricular outflow tract. (D) Changing from a curved to a straight stylet, the lead is withdrawn toward the apex. As the lead falls, it may be advanced slightly to engage positions suitable for septal pacing. (E), After the tip falls to the floor of the ventricle, the lead is advanced to its final position in the apex, as shown in RAO and left anterior oblique (LAO) views (F). (G) RAO and (H) LAO views of passive fixation right atrial (RA) and right ventricular (RV) apical lead positions at the time of implantation. The ventricular lead is positioned with the tip at the RV apex, well beyond the spine shadow, as shown here. The slight downward position of the tip is desirable. Some indentation of the ventricular lead at the level of the tricuspid valve is common. In LAO the lead lies against the ventricular septum. The atrial lead is positioned in the RA appendage.

prolapse into the RV, at which time the lead can be either advanced into the pulmonary artery or directed down toward the apex by advancing the stylet while the lead is slowly pulled back. Prolapsing the lead into the RV ensures that the lead is not in the CS and is not passing through the tricuspid valve apparatus. Entry into the pulmonary artery confirms that the lead has traversed the RV and is neither in the atrium nor in the CS. The lead may then be pulled back as the stylet is advanced. Tined leads may become readily entangled with the tricuspid apparatus when prolapsed across the valve. Directly steering these leads through the valve may be necessary.

Once the lead tip falls toward the apex, the patient is asked to inspire deeply and the lead is advanced into place. This maneuver is often accompanied by ventricular ectopy, the absence of which suggests that the lead is not in the ventricle. An alternative method of gaining entry to the RV is to form the stylet into a dog leg or a J shape and to use it to direct the lead across the tricuspid valve or to facilitate prolapsing the lead from the right atrium. Once it is in the RV, the shaped stylet may be replaced with a straight one to facilitate positioning at the apex. The proper fluoroscopic appearance of the RV apical lead is one in which the lead's tip is to the left of the spine and is pointing anteriorly and slightly caudal (Figure 5.9G,H). Visualization of the lead in multiple planes should be performed to confirm appropriate location of the lead.

For the patient with LBBB or AV block with a ventricular escape mechanism, special care needs to be taken when crossing the tricuspid valve to avoid bumping the right bundle branch if no temporary pacing wire is in place. The transient block in conduction may result in prolonged asystole and even death if temporary pacing cannot be quickly established. In these situations, less experienced operators may wish to place a temporary pacing wire at the outset of the procedure to avoid this complication.

In the anteroposterior projection it may not be possible to distinguish whether a lead is in a posterior coronary vein, the LV, or the RV apex. Left oblique views and the 12-lead ECG pattern of ventricular activation (QRS morphology) during pacing are helpful in avoiding such lead misplacement. If a lead is inadvertently placed in the LV, the paced QRS complex will usually show a right bundle branch block (RBBB) pattern, whereas positioning in the RV will usually show a LBBB pattern. In patients with LV prominence and/or counterclockwise rotation of the heart, the lead tip may not appear to extend far enough to the left border of the cardiac silhouette. Imaging in the right anterior oblique (RAO) position may be helpful in such circumstances; observing the position of the lead with respect to the tricuspid valve allows an estimation of how far the lead projects into the RV. Pacing at 10-V output is performed to exclude diaphragmatic stimulation by the lead, which may indicate microperforation and should usually lead to repositioning of the lead.

Once the proper position has been confirmed, the active fixation mechanism, if present, should be deployed while viewed under magnified fluoroscopy. The stylet is then partly withdrawn and pacing parameters (R wave size, pacing impedance, and capture threshold) are determined. High-output pacing is performed again. Once in place after stylet withdrawal and lead fixation, the tip should maintain a relatively stable position and not appear to bounce with cardiac contraction. A slight loop of lead (or "heel") should be retained in the right atrium to avoid tension at the tip during deep inspiration. Too large a loop may result in ectopy, lead dislodgement, or prolapse into the IVC, while too little slack in the lead creates a risk for dislodgement from mediastinal shift when the patient resumes upright posture and normal inspiration.

Although an apical RV lead position is usually preferred for reasons of stability, there are occasions when another location in the RV is required (e.g. a retained ventricular lead, which might result in contact potentials). Efforts to obtain a more physiological activation sequence and a more efficient mechanical contraction from RV stimulation have led some investigators to advocate positioning the lead in the RV outflow tract (Figure 5.10) or on the interventricular septum (Figure 5.11).[21] In these circumstances, the use of an active fixation lead is required. To place a lead in the outflow tract or septum, the lead is prolapsed into the pulmonary artery as described. By withdrawing the lead

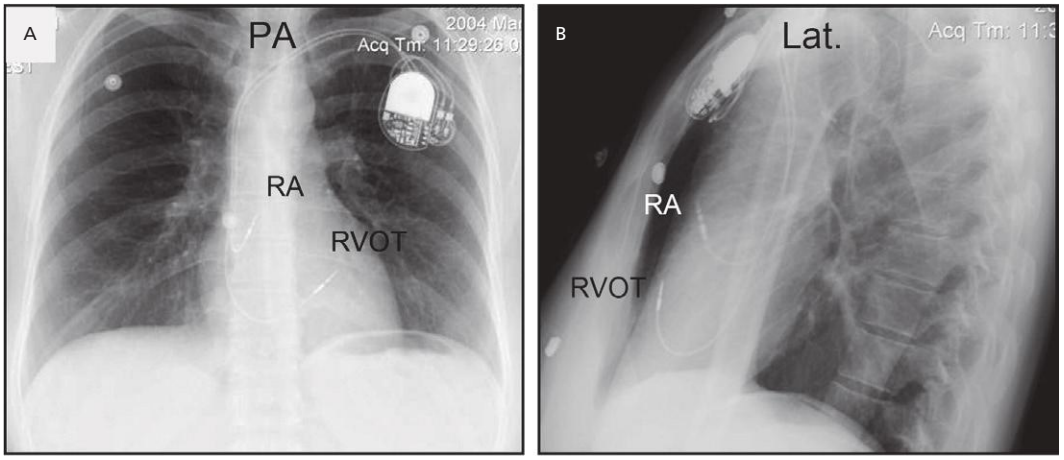


Figure 5.10 (A) Posteroanterior and (B) lateral chest radiographs of active fixation right atrial (RA) and right ventricular outflow tract (RVOT) lead positions after implantation. Stable ventricular lead placement in the RVOT usually requires an active fixation lead. The RA lead is in the right atrial appendage. PA, pulmonary artery.

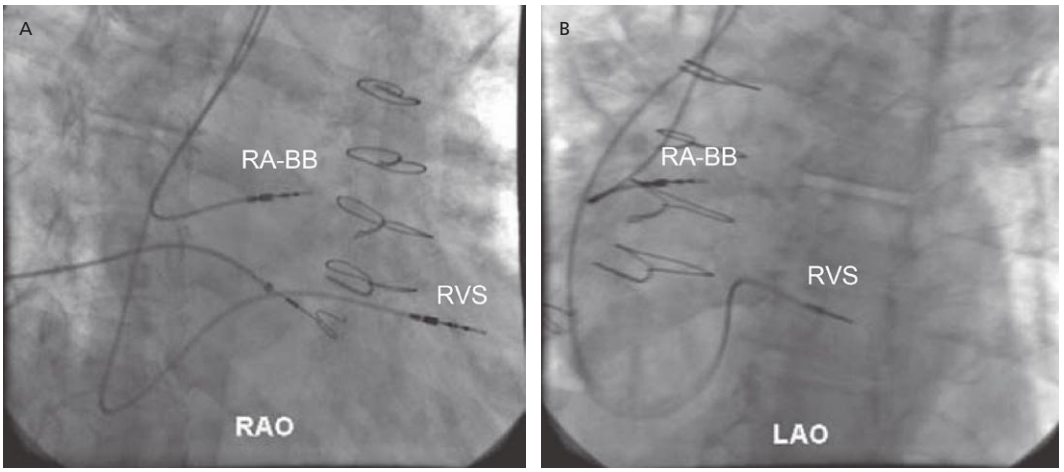


Figure 5.11 (A) Right anterior oblique (RAO) and (B) left anterior oblique (LAO) views of an atrial lead in the high right atrial septum (Bachmann's bundle) at the time of implant (RA-BB). Note that in the LAO view the lead tip is directed posteriorly as opposed to anteriorly for right atrial appendage positions (compare with Figure 5.8B). The unique position of the lead is difficult to appreciate in the RAO view. The ventricular lead (RVS) is fixed to the right ventricular septum.

with a curved stylet and torque to drive the tip into the septum, the septum can be mapped and the lead fixed. The hemodynamic benefits of routinely seeking such a position compared with the stability of the traditional apical location are unproven,[22] but this position may reduce the risk of free wall perforation and diaphragmatic stimulation when an active fixation lead is required.

When a reasonable position is obtained, preliminary measurements of the electrical parameters are made. This is usually accomplished with the stylet withdrawn about halfway so as not to interfere with the position of the lead tip and to facilitate movement of the lead body should that be necessary. When active fixation leads are used, such measurements may be taken before extensions of

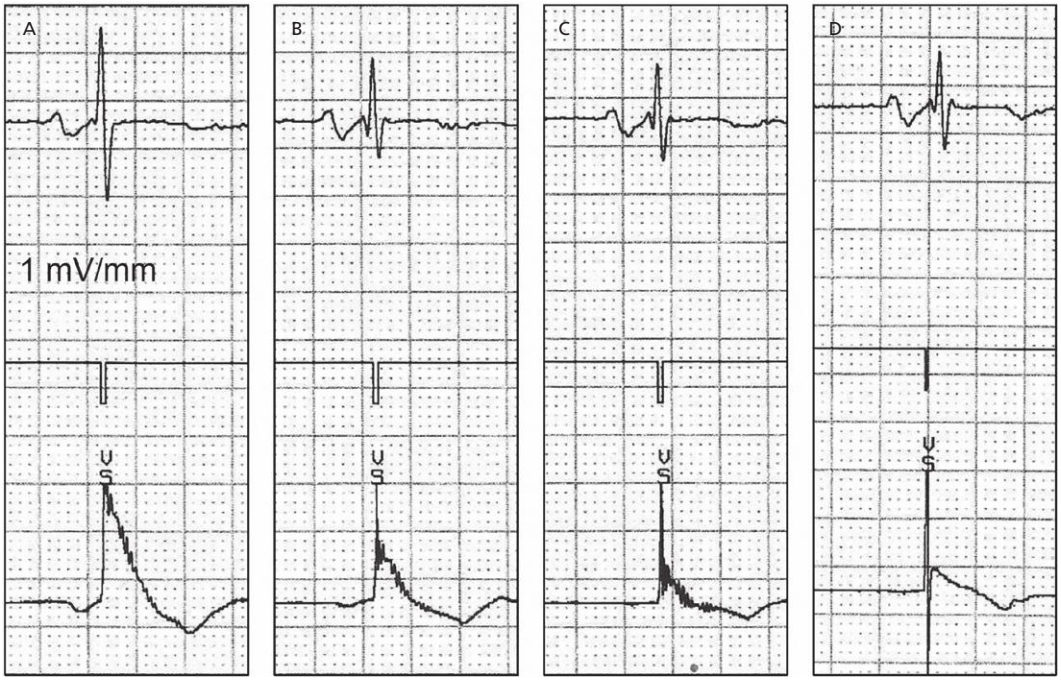


Figure 5.12 Current of injury recorded by a pacing system analyzer after extension of the helix of an active fixation ventricular lead. (A) Maximal injury current immediately after extension of the helix. (B,C) The current gradually decreasing over several minutes. (D) The final electrogram recorded through the pulse generator.

the helix, as a screen of the implant site prior to fixing the leads. If the parameters are not acceptable, an alternative position may be tried. Once a reasonable site is established, the helix is extended and the parameters re-measured. Failure to record a current of injury after deployment of active fixation leads suggests a potentially unstable lead position (Figure 5.12).[23]

Active fixation leads vary in the ways they interface with the heart; the helix may be electrically active, the distal ring electrode may be active, or both the helix and a distal ring electrode may be active. Adequate pacing characteristics may not be found immediately after extension of the helix: the screw may not have entered the myocardium, the site may be inadequate, or local tissue injury may have occurred due to entry of the helix. All lead positions should be confirmed by both left anterior oblique (LAO) and RAO views in the laboratory. It is common for capture thresholds to decrease significantly 15–30 min after active fixation.

Threshold parameters tested with a PSA define the electrical adequacy of lead position. This is accomplished using a set of connector cables, which can be configured for unipolar or bipolar leads. When testing unipolar leads, the anode is connected to tissue in the pacemaker pocket using a disk electrode or a clamp. Electrograms may be obtainable from the PSA or may be recorded using the chest (V) lead of a standard ECG machine. If satisfactory parameters (Table 5.3) are not obtained, alternative lead positions should be sought. It is

Table 5.3 Acceptable electrical parameters for new lead placement

Parameter	*Atrium*	*Ventricle*
Capture threshold*	<1.5 V	<1.0 V
Sensed P/R wave	>1.5 mV	>5.0 mV
Slew rate	>0.2 V/s	>0.5 V/s
Impedance	300–1000 Ω†	300–1000 Ω†

*At 0.5-ms pulse duration.

†High-impedance leads typically exceed these values; check with manufacturer for acceptable values.

important to confirm that diaphragmatic pacing does not occur by temporarily testing the lead at high output energy (10 V).

Capture threshold may be influenced by a number of factors, including myocardial site, presence of infarction or scar, electrolyte disturbance, medications, and lead type. On occasion, optimal parameters may not be achieved, and acceptance of the best available position is necessary. However, because the short- and long-term success of the pacing system is related to the initial lead position, effort should be made to obtain the best possible initial location in terms of both stability and electrical performance. Rarely, a CS vein may prove the only site from which one may sense and/or pace the ventricle reliably.[24]

Once acceptable lead parameters are obtained, the amount of lead slack should be adjusted, depending on the size of the patient. Taller and heavier patients will typically require greater lead redundancy to account for the mediastinal shift that will take place as the patient stands and inspires deeply. The lead stylet is then removed and the lead secured to the pectoral fascia with 2-0 or 0 nonabsorbable suture (silk or equivalent). These sutures should be placed around a suture sleeve, and never directly to the lead insulation, which may fracture under this chronic stress.

Atrial lead implantation

The right atrial appendage has become the preferred implant site for atrial leads because of its trabeculated nature. Studies have shown that good pacing parameters may be obtained and maintained from this location. A number of studies have suggested that dislodgement is not more common with atrial leads, but reliance on an atrial appendage location may mandate the acceptance of less than ideal pacing characteristics that become unacceptable over time. Active fixation leads appear to be beneficial in this regard by allowing further exploration of the right atrium in the search for an optimal position. There is no evidence that the atrial stimulation site influences hemodynamics *per se*, although atrial septal pacing near Bachmann's bundle may be of some importance when atrial tachycardia algorithms are applied (Figure 5.11). Trials of alternative or multisite right atrial pacing for prevention of atrial tachyarrhythmias have yielded mixed results.

A variety of leads (active, passive, J-shaped, straight) may be used for atrial pacing. When using active fixation leads, there are advantages and disadvantages to preformed devices. A straight active fixation lead may be easier to place in areas other than the appendage; however, dislodgement may result in the lead's falling into the RV and causing competitive pacing or ectopy (Figure 5.13). The J-shaped active fixation lead may also be positioned almost anywhere in the atrium, but in some sites (e.g. the low atrium) its shape may cause undue tension at the site of attachment to the endocardium, increasing the risk of dislodgement or cardiac perforation.

The atrial lead is inserted into the venous system with a straight stylet to facilitate negotiation of the central veins. Positioning in the atrial appendage is usually attempted first. The lead is directed toward the high anterior atrium and allowed to take its J shape either by withdrawing the straight stylet (in preformed leads) or by inserting a J stylet. Slow retraction of the preformed J-shaped lead results in the tip entering the appendage, where it will appear to catch and take on a characteristic to-and-fro motion with atrial activity (Figure 5.14). When it is well positioned, slight rotation of the lead should not dislodge the tip, and deep inspiration opens the curve to an L configuration but no further. In some patients the atrial appendage may be enlarged and trabeculae may be attenuated; in others, who have received cardiopulmonary bypass, the appendage may be oversewn. In these circumstances, placement of a passive fixation J lead may be difficult.

Although some implanters feel that previous cardiac surgery is a mandate for an active fixation atrial lead, others find passive fixation leads to be acceptable. We nearly always use active fixation atrial leads for patients with prior cardiac surgery. To place a lead on the atrial septum, allow the curve of the active fixation lead to form free in the body of the atrium and be directed anteriorly. Rotate the lead to the septum in the LAO view and pull the lead up until the roof of the atrium is encountered (Figure 5.11). Opening the stylet to a curve of less than 180° facilitates reaching the septum.

Acceptable electrical parameters for atrial pacing are listed in Table 5.3. As seen when active fixation

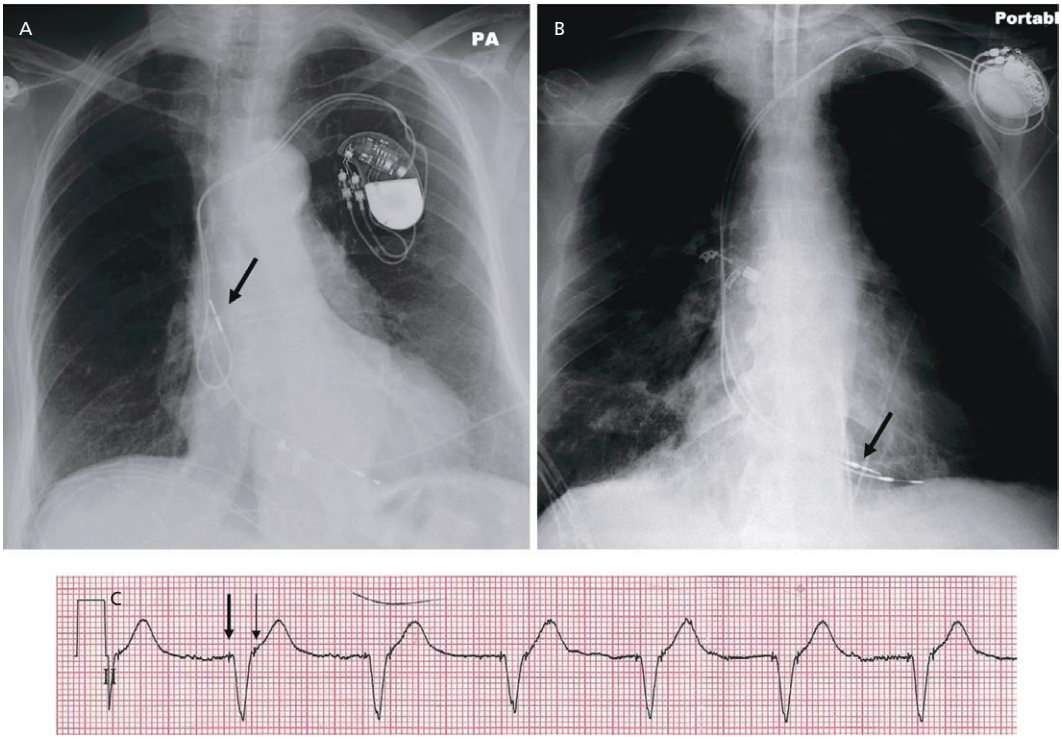


Figure 5.13 Posteroanterior radiographic views illustrating different patterns of atrial dislodgement. (A) This preformed atrial "J" lead was dislodged within 24 h of implant and retracted into the superior vena cava (arrow), producing loss of atrial sensing and right phrenic nerve stimulation. (B) This straight active fixation lead was dislodged shortly after implantation into the right ventricle (arrow), resulting in the ECG in C. (C) ECG showing ventricular capture from the dislodged atrial lead (wide arrow) followed by ventricular pacing at the paced atrioventricular delay (thin arrow) without capture.

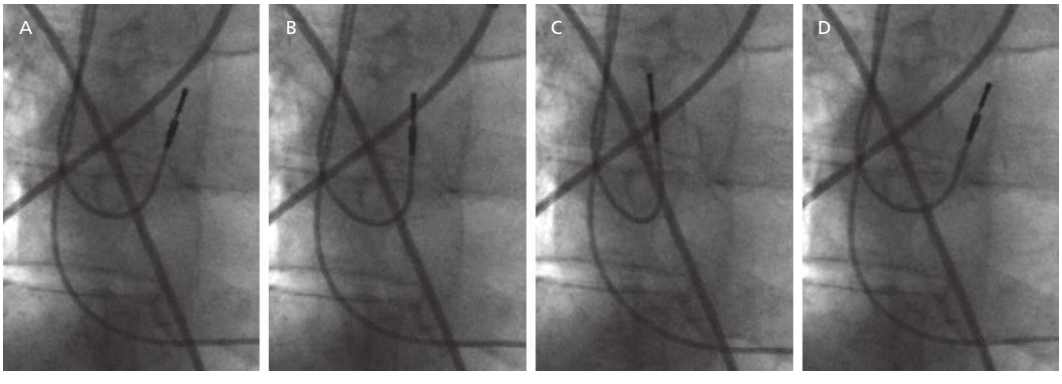


Figure 5.14 (A–D) Motion of an atrial lead placed in the right atrial appendage in a series of fluoroscopic views in the right anterior oblique projection. Typical lead motion through a single cardiac cycle is depicted.

leads are used in the ventricle, there may be a significant improvement of the parameters during the first 15–30 min. If borderline values are obtained initially, it may be worthwhile to perform serial measurements every 3–5 min. If poor values are obtained initially, however, it is best to search for a new position. The better the electrical characteristics, the more probable that long-term pacing will be successful. As with the ventricular lead, it is important to test for diaphragmatic pacing by temporarily stimulating the atrium at high output (10 V) and observing the right hemidiaphragm for phrenic nerve capture.

When acceptable parameters are obtained, the lead slack is adjusted, the stylet is removed, and the lead secured with non-absorbable suture. Final lead parameters are then obtained for both atrial and ventricular leads.

Epicardial lead placement

Permanent epicardial leads can be placed on the atria and ventricles at thoracotomy using a variety of surgical approaches. Newer steroid-eluting active fixation and atraumatic suture-on electrodes provide the best long-term thresholds.[25] Chronic epicardial atrial lead performance remains problematic, however. These leads must be passed between or beneath the ribs and then tunneled subcutaneously to the pocket, potentially raising risk of lead fracture (Figure 5.15). In general, available epicardial lead systems demonstrate decreased longevity and worse chronic lead performance compared with endocardial pacing. Surgical epicardial placement of LV pacing leads may be needed in a small percent of patients to achieve biventricular pacing when the CS approach is unsuitable due to unfavorable anatomy or refractory phrenic nerve

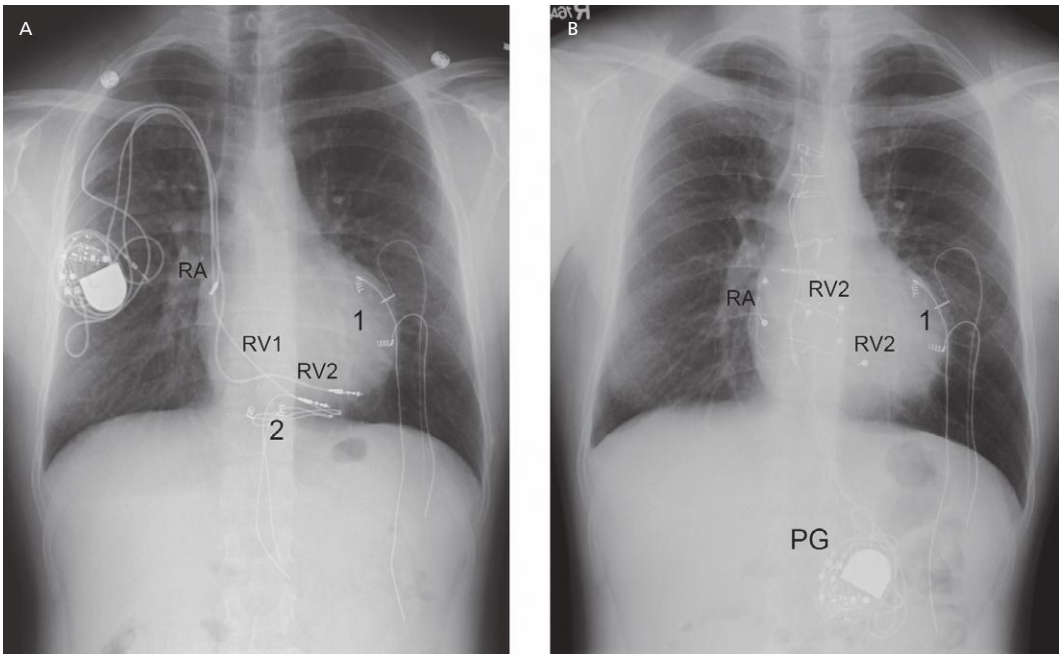


Figure 5.15 Series of epicardial pacing systems in a 34-year-old man who underwent his first pacemaker implantation at the age of 4 years due to acquired atrioventricular block. (A) Posteroanterior chest X-ray shows two sets of abandoned failed epicardial VVI systems (1 and 2). A right-sided dual chamber transvenous system was later placed (RA and RV1). Failure of the first endocardial right ventricular (RV) lead led to its replacement (RV2). (B) Infection of the transvenous pacing leads led to complete surgical extraction of that system, followed by implantation of a third dual chamber epicardial system, with bipolar right atrial (RA) and right ventricular (RV1 and RV2) leads tunneled to an epigastric pulse generator (PG). The second RV lead was capped for potential future use should the first lead fail. One of the old epicardial systems (2) was removed at the same operation.

stimulation. The minimally invasive thoracoscopic approach may often be employed.[26]

Single lead VDD pacing

The general principles of lead insertion are similar for the dual chamber VDD systems that use specially arrayed proximal atrial sensing electrodes as well as a tip electrode to sense and pace the ventricle on a single lead. These devices may be useful for selected patients with AV block who have a normal sinus mechanism, because they obviate the need for a separate atrial lead. When used, it is important to have the atrial electrodes at an optimal position in the right atrium; one may have to choose among leads with varying distances between the tip and atrial electrodes. Care is necessary to ensure that there is a chronotropically intact sinus mechanism before implantation and that atrial activity is consistently sensed by the lead at implantation. Testing for atrial sensing during extremes of respiration and during cough is necessary. Although it may be necessary to accept low-amplitude P waves and program the device to a high atrial sensitivity, reasonable results have been reported over a moderately long follow-up period.[27]

Inappropriate atrial sensing may become a problem for a significant proportion of patients implanted with single lead VDD systems. Because atrial capture is rarely possible with VDD leads, the device provides only single chamber VVI(R) function if the atrial rhythm slows below the lower rate limit and atrial undersensing occurs. Of course, the VDD system is at a disadvantage if there is sinus node dysfunction, unless one is willing to sacrifice atrial synchronization and revert to VVI(R).

Generator insertion

After the leads have been placed in acceptable positions, stability is confirmed with fluoroscopic observation during deep inspiration and cough. There should be enough intravascular lead to prevent undue tension at the tip with inspiration. The suture sleeve is carefully advanced distally, with care not to pull on the lead. Frequent fluoroscopic checks are important during this process. The lead is tied down to the underlying muscle with two or three non-absorbable sutures. Sutures should never be tied around the unprotected lead; even with the suture sleeve, too tight a suture may compromise lead integrity. The sutures should be tight enough, however, to avoid lead migration. Electrical parameters and fluoroscopic position should be rechecked after suturing; if they are not optimal, the sutures may be removed and the lead repositioned.

Once the leads have been secured, any sponges that had been placed in the subcutaneous pocket are removed and the area is irrigated and checked for hemostasis and foreign matter. Fluoroscopy of the pocket area will reveal any radio-opaque foreign body (such as sponges or needles) that was not removed before the generator insertion. The pacemaker should be pre-programmed to the desired initial settings while still in its sterile package, after which it is given to the operator for implantation. For dual chamber devices it is important that the atrial and ventricular leads be correctly identified and connected properly to the generator (Figure 5.16).

The lead pins should be cleaned and dried prior to insertion into the generator. The distal connector pin of the lead should be seen to pass the set-screw(s) of the generator and remain there after tightening. Care should be taken that the screws are not overtorqued when tightened. A slight tug on the lead will confirm a tight connection. For in-line bipolar leads, both screws (when present) must be set correctly. Some pacemakers (i.e. unipolar) may not function as programmed until the generator (functioning as the anode) is placed within the pocket.

The generator is carefully placed in the pocket, coiling redundant leads along the sides of the device or underneath it to avoid acute angulations. Extra leads should not be placed above the generator, as this will complicate generator replacement or lead revision in the future. We generally tie the generator down to the pectoralis fascia with a 0-silk suture through the tie-down hole in the header of the generator. This serves to limit migration of the generator and to defend against patient "twiddling" of the device (Figure 5.17). Once in place, evidence of proper pacemaker function should be observed, with placement of a sterile magnet or programming head if necessary. Fluoroscopic



Figure 5.16 Continuous rhythm strip of a patient with a dual chamber pacemaker in whom the leads were inadvertently reversed at the generator. There is atrioventricular sequential output from the generator (arrows) with the first stimulus capturing the ventricle and the second stimulus to the atrium occurring late in the QRS complex. This problem can be averted at implantation by double-checking appropriate lead placement in the header by serial number and documenting appropriate pacemaker activity prior to closing the pocket.

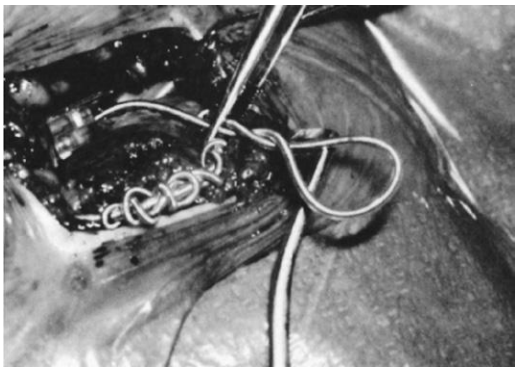


Figure 5.17 Photograph obtained at the time of operative intervention to reposition a lead dislodged due to Twiddler's syndrome. The lead can be seen to be tightly twisted upon itself. Although this tangle can be straightened, the stresses imparted to both the conductor and the insulation make it unsafe to reuse this lead. A new lead should be inserted. (Source: Courtesy of Dr Paul Levine MD.)

examination of the entire system should be performed before pocket closure.

The pocket is closed in layers using 2-0 to 4-0 resorbable suture. Care must be taken to avoid piercing a lead with the suture needle. The skin edges may be approximated with skin sutures, resorbable subcuticular sutures, or surgical staples. A sterile dressing is then applied.

Before the patient leaves the pacemaker laboratory, a final fluoroscopic check of the generator pocket and the course of the leads is made. The system is non-invasively interrogated to confirm adequacy of function and is programmed so that it temporarily overdrives the intrinsic heart rate. A 12-lead ECG is obtained to demonstrate the configuration of the paced rhythm, and then final programming of the pacemaker is performed.

In some centers, when the patient has reached the recovery room or the hospital floor, an overpenetrated anteroposterior chest radiograph is performed to document the lead position and the absence of a pneumothorax. In other centers, an immediate postoperative chest X-ray is not performed unless there is clinical suspicion of a complication. A sling may help discourage excessive movement of the ipsilateral upper extremity during the first 12–24 h. A thorough operative report should be generated immediately to include the manufacturer, model, and serial numbers of all hardware implanted, abandoned, or explanted, as well as any difficulties encountered during the case.

Revision of the implanted pacemaker system and pulse generator change

Revision of an implanted pacing system may involve replacement of the pulse generator, the pacing leads, or both (Figures 5.15 and 5.18). The uncomplicated generator change is usually a straightforward procedure; however, the preparation is in some ways more involved than for a new implant (Figure 5.19). The indication for generator change should be confirmed and documented, and the system evaluated non-invasively to identify any problems with the leads. In addition, pacemaker generator change provides an opportunity for the physician to evaluate the indications for pacing to ensure that the existing hardware is

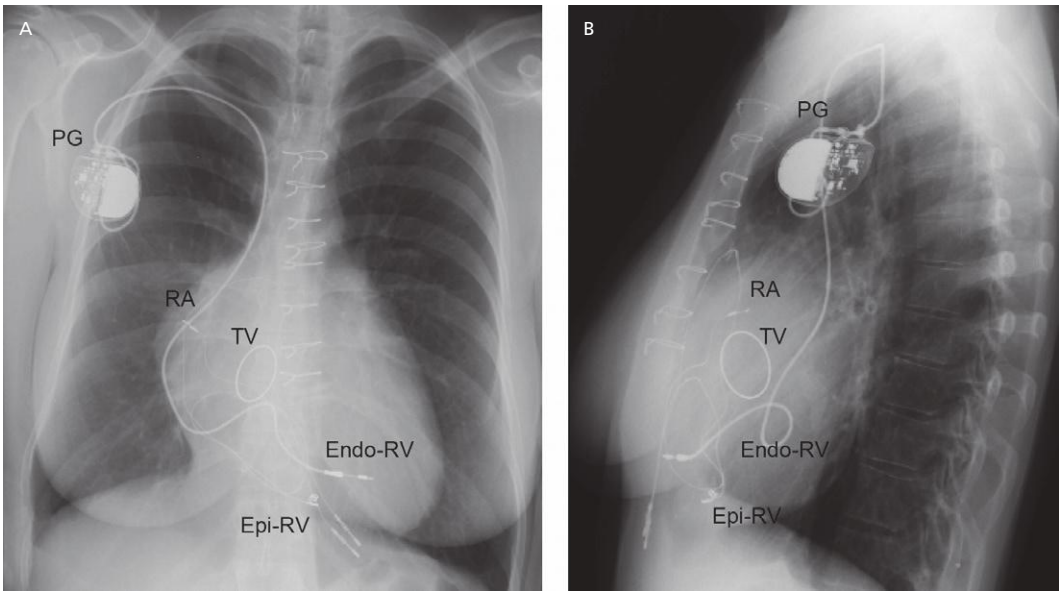


Figure 5.18 (A) Posteroanterior and (B) lateral chest X-ray of a 38-year-old woman with Ebstein's anomaly and complete atrioventricular block. In childhood, she had undergone implantation of a dual chamber unipolar epicardial system using a transmyocardial right atrial lead (RA) and epicardial ventricular lead (Epi-RV). She later had tricuspid valve replacement with a bioprosthesis. By age 21 she had developed ventricular lead failure and permanent atrial fibrillation, leading to placement of a single-chamber transvenous pacemaker (Endo-RV) with a subpectoral pulse generator (PG). At age 30, her tricuspid valve bioprosthesis had failed and was replaced with a mechanical prosthesis (TV). The transvenous right ventricular (RV) lead was placed outside the sewing ring of the prosthesis. This lead can now be extracted only by an open surgical route.

appropriate for the patient's needs. In some cases, addition of atrial or LV pacing leads may be appropriate. In other cases, the patient may have developed an indication for revision of the system to an ICD.

For lead failure or system revision, the procedure itself is often more complex than a new implant (usually due to issues of venous access) and again requires preoperative investigation into the cause of the lead failure to prevent its recurrence. If a lead replacement is anticipated, the patency of the ipsilateral upper extremity venous system should be confirmed by venography. The decision to extract malfunctioning or abandoned leads should be made beforehand so that appropriate preparations can be made (see "Lead extraction"). Even if the leads are known to function preoperatively, they may be damaged or found to be compromised on surgical exposure. Therefore, the patient and operator should be prepared for revision of any or all of the pacemaker leads at the time of generator replacement. One of the most critical aspects in preparing for a lead or generator change is ensuring mechanical and electrical compatibility between the new and retained components, as well as any new components that may be added to the system (Figure 5.19). Over the years, pacemaker systems have been manufactured with a variety of lead connector pins and generator header ports that may not be interchangeable. Currently, all new pacing systems conform to standard designs for these components (IS-1 standard, adopted in the early 1990s). Older systems may have pacemaker lead designs that are incompatible with new generators or have a serviceable generator that is not compatible with new leads.

One infrequent but potentially challenging situation which may be encountered during otherwise uncomplicated generator replacement or system

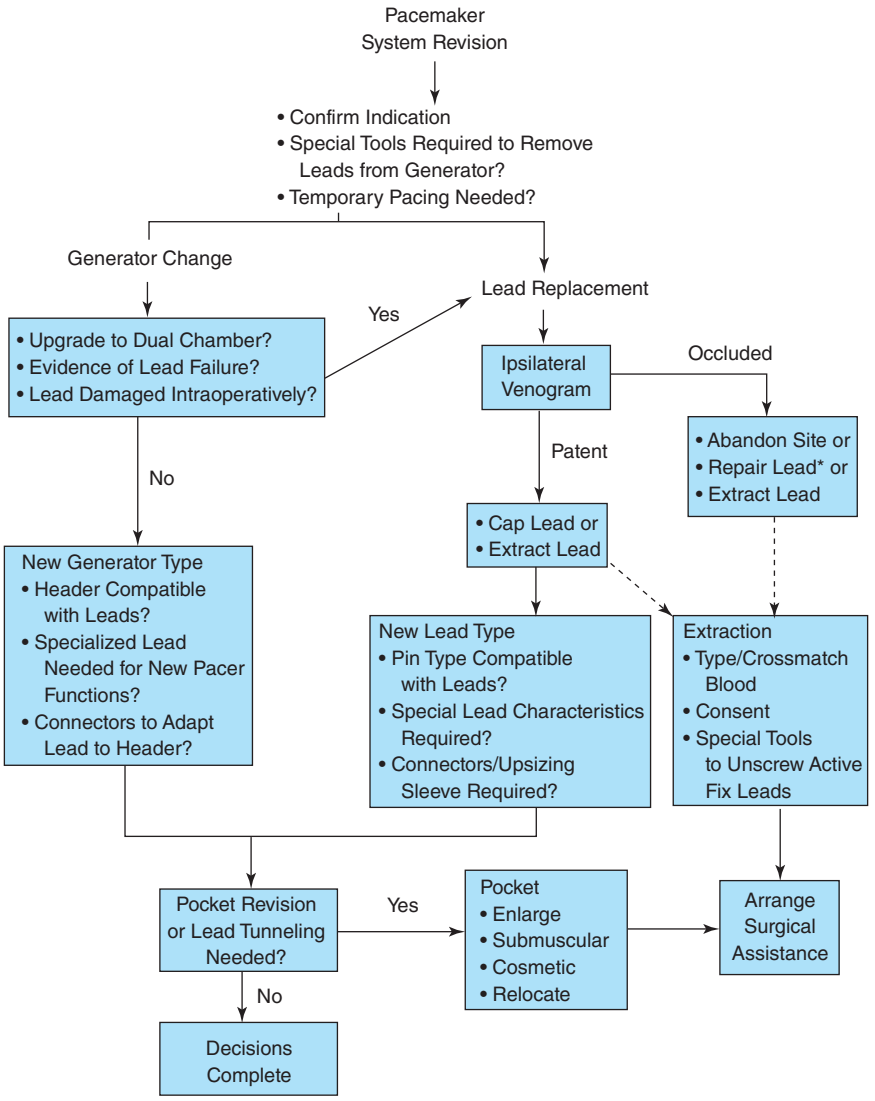


Figure 5.19 Flow chart for decisions surrounding revision of a previously implanted pacemaker system. All decisions should be thoroughly considered and the necessary equipment secured before the patient enters the operating room. (*Repair of an isolated outer insulation defect can be performed on an exposed section of some silicone insulation leads using a repair kit. The integrity of the lead conductors is not assured, however.)

revision is the "frozen lead," which will not easily disengage from the header. Estimated to occur in 1–2% of generator replacements, this situation may be caused by a stripped set-screw or when some component of the lead pin has melted or otherwise fused with the header or *vice versa*. When firm traction is applied to the point where lead integrity may be compromised, an alternative solution should be sought. Potential solutions include use of silicone lubricants, application of surgical or dental drills, or use of orthopedic bone cutters to reveal the distal end of the pin, allowing it to be pushed through the header.[28] Rarely, if no solution is available, the lead may have to be cut from the header, then capped and replaced. The problem of the frozen lead, though infrequent, points to the value

of having a temporary wire placed for generator replacements and system revisions in pacemaker-dependent patients.

For the lead to fit into the generator, the lead diameter, pin length, and presence or absence of sealing rings must be accommodated by the pulse generator. In addition, at least one manufacturer (Guidant/Boston Scientific) has introduced a proprietary LV-1 pin configuration for some of its CS leads. Certain leads can be made compatible with new generators by the use of adaptors. Most manufacturers continue to provide generator models to fit some of the discontinued lead styles. In addition, some pacemakers require unique leads to perform specialized functions or special tools to free the leads from the device. The importance of identifying the lead and pacemaker connector configuration before surgery cannot be overstated. Manufacturers can provide the needed information about compatibility between components.

During the operative procedure, electrocautery may cause failure of output in generators near their end of service. For this reason and because leads may be damaged during generator removal, temporary pacing should be established in pacemaker-dependent patients (see Chapter 4). Meticulous attention to surgical technique is mandatory to prevent damage to implanted hardware and to reduce the risk of infection. If lead replacement is required but the ipsilateral vein is occluded, abandoning the entire system for another site or recanalization of the vein by lead extraction (see "Lead extraction") will be necessary. Occasionally, isolated outer insulation defects in silicone leads can be repaired, but the integrity of the conductors remains questionable. If leads are capped and abandoned in the pocket, it is advisable to suture the lead to the floor of the pocket to prevent migration or erosion of the free end. Some operators prefer to cut the proximal portion of abandoned leads to reduce the hardware remaining in the pocket. This may be problematic for active fixation leads since retraction of the helix may not be possible, complicating extraction should that be needed in the future. Cutting a lead too short may predispose to retraction of the lead into the venous system and embolization of the proximal portion into the heart.

Finally, replacement of a lead or generator provides the opportunity also to revise the pocket, re-implant the generator submuscularly, or revise the surgical scar as indicated. All of these factors should be evaluated and plans made for any contingency before the surgical procedure begins.

Post-procedure management

Elective generator replacement is most often accomplished on an outpatient basis. While there has been some enthusiasm for performing same-day *de-novo* pacemaker implantation, most procedures involving lead placement or revision continue to involve in-hospital observation for at least one night. For such new implants, ECG telemetry is usually obtained for 12–24 h.[13] The following morning, an ECG is performed. Prior to discharge, posteroanterior and lateral chest radiographs are performed to document lead positions and exclude delayed pneumothorax.

Longer hospitalization may be required because of ancillary medical problems or as a result of complication. Analgesia may be necessary, but it is rarely needed after the first few days. The patient is advised to limit motion of the ipsilateral upper extremity for a time—specifically, to avoid raising it high above the shoulder level or subjecting it to marked abduction for approximately 2 weeks. Patients should not, however, excessively restrict motion of the arm, as this may cause a frozen shoulder and delay ultimate rehabilitation. The incision should be kept dry for 3–7 days.

Even the most skilfully implanted permanent pacemaker system will provide limited benefit if it is not programmed properly. Before discharge, the device should be programmed in accordance with the patient's specific needs and a complete noninvasive assessment of the pacing system performed. Programming of the pacemaker is guided by two principles: (1) optimization of the patient's hemodynamic state, and (2) maximal conservation of battery energy expenditure. When these two factors are in opposition, the first should take precedence; however, opportunities to achieve the second should not be overlooked. This might include programming a longer AV interval to avoid fusion beats, a lower resting minimal heart rate, and lower stimulation outputs (within an

acceptable safety margin). In general, higher outputs are programmed at initial implant to accommodate the possibility of acute threshold rise. Outputs are then lowered to maximize battery longevity 6–12 weeks after implantation.

A number of studies have indicated the importance of avoiding unnecessary RV pacing, especially in patients with heart failure and LV dysfunction.[29] Such patients with preserved AV conduction should be programmed with long AV delays and/or a non-tracking mode (such as DDI).

Rate-adaptive parameters may be set before the patient is discharged or during a follow-up visit. This is commonly done empirically and is tested by having the patient perform walking exercises, if necessary. The adequacy of pacing response may be judged by real-time telemetry or by using rate histograms stored in the pacer. Follow-up evaluation and possibly adjustment of programmed parameters, including rate adaptation, will be necessary.

Some of the newer pacemaker generators have a mechanism for automatic capture threshold detection. These devices may allow for the programming of a lower pacing output with the recognition that the algorithm will increase pacing output if it detects a rise in threshold. Care should be taken to ensure that these devices have acceptable evoked response amplitudes acutely and at follow-up assessments, especially in pacemaker-dependent patients, who may experience syncope with even a rare transient failure of the algorithm. A copy of the programmed parameters should be given to the patient to keep, in addition to the device registry card.

It is important that the physician or pacemaker field technician registers the generator and leads appropriately so that the patient may be tracked should a device advisory occur. Arrangements for follow-up care should be made by the implanting physician, and the patient should be counseled as to the importance of having the system checked at regular intervals. While there was previously some controversy as to the need for endocarditis prophylaxis, current guidelines do not recommend routine antibiotic prophylaxis for patients with endocardial leads.

Complications of implantation

Inherent to pacemaker therapy is the potential for the occurrence of an untoward event. Skill, experience, and technique are all mitigating factors, but every operator should anticipate that they will have to manage a complication eventually. Thus, the implanting physician must be concerned not only with measures to avoid complications, but also with their recognition and treatment. Such untoward events associated with the introduction and physical presence of the generator and leads may be classified according to their etiology (Table 5.4 and Table 5.5).

In the Pacemaker Selection in the Elderly (PASE) study, 6.1% of the 407 patients receiving dual chamber pacing systems had a complication of implantation.[30] There were nine lead dislodgements (2%), eight instances of pneumothorax (2%), and four cardiac perforations (1%). A repeat surgical procedure was required in 18 (4.4%) of the

Table 5.4 Acute complications of pacemaker implantation

Venous access	*Lead placement*	*Generator*
Secondary to Seldinger technique:	Brady- or tachy-arrhythmia	Improper or inadequate
Pneumothorax	Perforation of heart or vein	connection of lead
Hemothorax	Damage to heart valve	Pocket hematoma
Other (e.g. injury to thoracic duct, nerves, etc.)	Damage to lead	
Secondary to sheath insertion:		
Air or foreign body embolism		
Perforation of the heart or central vein		
Inadvertent entry into artery		

Table 5.5 Delayed complications of pacemaker therapy

Lead related	*Generator related*	*Patient related*
Intravascular thrombosis and/or embolization	Pain	Twiddler's syndrome
Intravascular stenosis (i.e. superior vena cava obstruction)	Erosion	
Macro- or micro-lead dislodgement	Infection of pocket	
Fibrosis at electrode–myocardial interface (exit block)	Migration	
Infection—endocarditis	Premature failure	
Lead failure:	Damage from extrinsic energy (e.g. radiation, electrical shock, etc.)	
Insulation failure (inner/outer)		
Conductor fracture		
Retention wire fracture		
Chronic perforation		
Pericarditis		

patients. In a single-center study of more than 1300 permanent pacemaker implants reported by Tobin *et al.*,[31] complications were noted in 4.2% of patients. Lead dislodgement occurred in 2.4%, significant pneumothorax in 1.5%, pericardial tamponade in 0.2%, and hemothorax leading to death in one patient (0.08%). The economic consequences of a complication were substantial, with the average incremental cost of $14 547 for a lead dislodgment, $10 052 for a pneumothorax and $32 472 for a tamponade. There was an inverse relationship between the incidence of acute complication and operator case volume and experience. Although the acute implant complications associated with DDD pacing are no different from those with single chamber pacing, the total complication rate associated with dual chamber pacing over time is higher than that with VVI or single lead VDD due to the presence of the additional lead.

Although neither elective generator replacement nor revision of a VVI system to a dual chamber device is usually considered to be a dangerous procedure, both are associated with potential complications. Harcombe *et al.* found that the rate of late complications (those occurring later than 6 weeks after the procedure) was higher for elective replacement (6.5%) than for initial system implantation (1.4%).[32] These were primarily erosion and infection related to the pacemaker pocket. Complications were more common with inexperienced operators, suggesting that technique as well as physiological substrate play important etiological roles. Revision of a VVI device to a dual chamber or biventricular system carries the potential for all the complications associated with venous access and lead placement (which may be confounded by the pre-existing lead and associated vascular abnormalities), as well as an increase in risk of late pocket infection and skin erosion. Revision procedures are often longer in duration than a *de-novo* dual chamber implantation. This may be related to difficulty isolating the generator and lead in the pocket due to adhesion formation, difficulty with venous access, interference with the existing lead, or a combination of these factors.

Venous access

By its very nature, the axillary/subclavian venous puncture has a potential for complication, the risk of which depends on both operator skill and the patient's anatomy. Inadvertent damage by the exploring needle to structures that lie in proximity to the vein (e.g. lung, subclavian artery, thoracic duct, and nerves) is the most frequent cause of significant complications encountered during the implantation process. Knowledge of subclavian venous anatomy by venography may

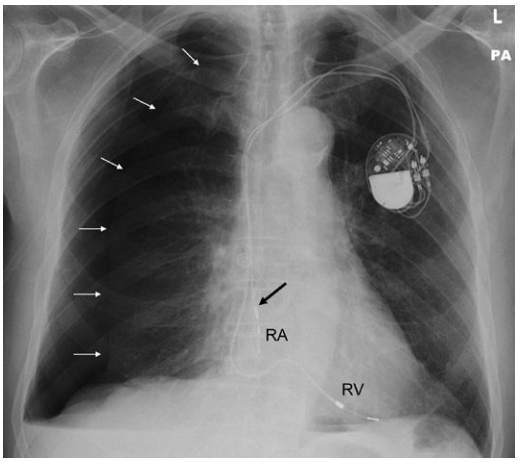


Figure 5.20 Right pneumothorax after left-sided pacemaker implantation in an elderly man with emphysema. The pleural line is indicated by the white arrows. This unusual complication probably results from microperforation of the active fixation right atrial lead (black arrow). Note the mediastinal shift to the left. RA, right atrial lead; RV, right ventricular lead.

be helpful in accessing the vessel and avoiding complication.

Pneumothorax is often asymptomatic and discovered on the routine post-procedure chest radiograph (Figure 5.20). Rarely, it may be the cause of severe respiratory distress intraprocedurally. Pleuritic pain, cough (especially if productive of blood-tinged sputum), and difficulty in breathing suggest the diagnosis. The aspiration of air into the syringe during attempted venous puncture may also raise concern about this possibility, but it is neither a sensitive nor specific sign. The presence of apical cystic lung disease, variations in the relationship between the clavicle and subclavian vein, and an uncooperative patient may increase the risk for this complication—and repeated unsuccessful attempts at venous puncture certainly do. Respiratory symptoms arising during the procedure should prompt assessment of pulse, blood pressure, oximetry, and perhaps blood gas analysis. Fluoroscopic examination of both lung fields should also be performed.

Treatment of pneumothorax depends on its severity and associated symptoms. Respiratory distress during the procedure may necessitate the urgent/emergency insertion of a chest tube. The completion of the implantation will depend on the patient's status and the progress already made. Although there may be some controversy as to the need for evacuation of an asymptomatic pneumothorax seen on chest radiograph, if its extent is greater than 10% a chest tube should be considered. If a small pneumothorax does not resolve or enlarges on serial radiographs, evacuation is indicated. Inspiration of 100% oxygen by facemask may help to resolve a small pneumothorax.

Hemothorax, a less common complication of the axillary/subclavian approach, results from injury to the subclavian artery, vein, or other intrathoracic vessel. Penetration of the subclavian artery by the exploring needle is usually harmless if the needle is withdrawn and pressure is applied at the site of entry under the clavicle. Significant complication may occur, however, if the artery is lacerated by the cutting edge of the needle or if a large-bore dilator or sheath is inadvertently introduced. If a large sheath is mistakenly inserted into the artery, it should probably be left in place, pending a prompt definitive management decision, since removal may result in significant bleeding. Options include surgical repair; endovascular treatment using a prolonged balloon inflation or a stent graft; or an attempt at sheath withdrawal with external compression. If the latter option is considered, there are several case reports of using vascular closure devices to assist with hemostasis. Use of both a collagen-based system (Angio-Seal; St. Jude Medical, St Paul, MN, USA) and a suture-based system (Perclose; Abbott Laboratories, Redwood City, CA, USA) has been described.

Opinions from an interventional radiologist and a vascular surgeon should be obtained if possible. A quick angiogram may determine whether an important branch vessel (e.g. internal mammary graft or vertebral artery) is involved or might be excluded by a covered stent. Because of the risk of thrombus formation around the sheath, it should be withdrawn to the subclavian artery itself to prevent embolization of clot to the cerebrovascular system. The likelihood of a bleeding complication is increased if the coagulation system is impaired either intrinsically by co-existing disease or by pharmacological therapy. Angiographic evaluation and possible repair should be considered for severe or persistent bleeding from an uncertain source.

Table 5.6 Avoidance of air embolism

1 Increase central venous pressure:
Hydrate well
Elevate legs (Trendelenburg position)
Have patient perform Valsalva maneuver when sheath is open
2 Awaken patient and caution against deep inspiration
3 Use smallest sheath compatible with task
4 Pinch or occlude neck of sheath when appropriate
5 Use of sheaths with hemostatic valves
6 Timing of critical parts of sheath manipulation with respiratory cycle in uncooperative patients

Table 5.7 Causes of arrhythmia during pacer implantation

Bradyarrhythmia	Patient's underlying electrophysiological disorder
	Vagal reaction
	Lead trauma to the conduction system
	Inadvertent disruption of a pacing system
	Suppression of escape rhythm by anesthetic
Tachyarrhythmia	Atrial/ventricular
	Underlying electrophysiology
	Irritation by lead/wire
	Ischemia, anesthesia, hypoxia

Air embolism can occur when a central vein is accessed by a sheath, regardless of the technique used to introduce it. This complication may be signaled by a hiss as air is sucked into the sheath by negative intrathoracic pressure and may occur suddenly when a heavily sedated, snoring patient deeply inspires at a time when control over the sheath's orifice is not adequate. Air may be fluoroscopically tracked into the RV and pulmonary outflow tract. In most instances, the amount of air introduced is small and well tolerated, but respiratory distress, chest pain, hypotension, and arterial oxygen desaturation may occur if there is significant blockage of pulmonary flow. Infrequently, introduced air may cross a patent foramen ovale or atrial septal defect and cause a stroke or coronary air embolus. Treatment of symptomatic air embolism includes supplemental oxygen, attempted catheter aspiration, and inotropic support if necessary. These supportive measures will usually suffice until the air embolism breaks up and absorption occurs. Preventive measures are listed in Table 5.6. The most important of these is routine use of valved sheaths.

Rare complications of venous access include laceration of the thoracic duct leading to chylothorax, and damage to the internal mammary artery, which may cause acute ischemia when this conduit has been used as a coronary arterial graft.

Lead placement

The introduction, manipulation, and positioning of the pacemaker leads in the heart may give rise to a number of complications.

Arrhythmia

Arrhythmia may be a manifestation of the patient's underlying disease, or it may be procedurally related (Table 5.7). In a pacemaker-dependent patient, accidental interference with a pre-existing pacing system—whether temporary or permanent—may cause asystole or symptomatic bradycardia. Other causes of a bradyarrhythmia include a vagal reaction, excessive local anesthetic, and injury to the conduction system during lead manipulation (e.g. trauma to the right bundle branch in a patient with LBBB). The use of transcutaneous pacing and/or the administration of atropine or isoproterenol may be helpful in these situations until a means of effective pacing can be established. For patients at risk of asystole during permanent pacemaker implantation, revision, or generator change, a preoperative temporary pacing wire should be considered.

Tachyarrhythmia may also occur during implantation; it is usually the result of stimulation of myocardium by a lead or guidewire. Supraventricular arrhythmias are most likely to occur in patients with atrial enlargement, heart failure, pulmonary disease, or other predisposing conditions such as sick sinus syndrome; they are usually transient. Atrial fibrillation occurring before or during atrial lead placement may be problematic, in that atrial parameters cannot be tested unless the rhythm terminates either spontaneously or by chemical or electrical cardioversion. An atrial lead may be placed in the presence of atrial fibrillation

occurring at the time of implantation using the criterion of intracardiac fibrillatory amplitude of 1.0 mV or greater. This reduces implantation time compared with the option of intraprocedural cardioversion, which may also lead to postoperative stroke.[33]

Ventricular arrhythmia is common as the lead is manipulated in this chamber, but it is rarely sustained. Predisposing factors to more malignant arrhythmia include hypoxia, ischemia, pharmacological therapy (e.g. sympathomimetics), and asynchronous pacing. Removal of the lead from an irritating position almost always terminates the ectopy. In a susceptible patient, however, wire- or lead-induced ventricular ectopy may induce sustained ventricular tachycardia or fibrillation, and the implanting team should be prepared for this possibility and ready to defibrillate the patient if needed. Because the attention of the implanter may be focused on the fluoroscopic image during lead placement, another individual, usually the nurse or anesthetist, should be assigned to monitor the ECG during this time. On occasion, a retained guidewire or a temporary ventricular pacing lead is displaced and serves as an occult source of ventricular irritation that is not resolved by retraction of the permanent pacing lead. Rarely, a permanent ventricular (or prolapsing atrial) pacing lead will be the cause of recurrent ventricular ectopy post implantation.

Perforation

The heart may be perforated internally (into another cardiac chamber) or externally (into the pericardial space) by the pacing lead; such perforations may be acute or delayed.[34] RV perforations are probably more common than reported because clinical sequelae may not occur. Poor sensing or capture thresholds may prompt withdrawal of the lead back into the ventricle with "self-sealing" of the perforation. On occasion, however, life-threatening tamponade may occur, and progressive hypotension during or after lead placement should be considered tamponade until proven otherwise. If access to an echocardiogram is not readily available or not feasible due to rapid deterioration in hemodynamic status, fluoroscopy in LAO projection to assess the cardiac silhouette excursion is helpful to evaluate pericardial fluid collection and allow expedited pericardiocentesis.[35] Older age, female gender, steroid therapy, recent RV infarction, and the use of stiff leads (or stylets) may be considered risk factors for perforation. Pericarditis, tamponade, and even pneumothorax have been reported as complications caused by active fixation atrial lead placement due to the helix protruding through the atrial myocardium.

Interference with normal coagulation predisposes the patient to pericardial tamponade. Thrombolytics should be considered contraindicated in the immediate post-implant period. If symptoms suggestive of tamponade occur, echocardiographic confirmation should be obtained unless the condition dictates emergency pericardiocentesis. Every effort should be made to obtain an echocardiogram in the latter situation as soon as possible. Pericardiocentesis with catheter drainage will rapidly reverse the pathophysiology of tamponade and may be the only therapy necessary, since the perforation is frequently self-sealing. In some cases tamponade may occur with the acute accumulation of only a small amount of pericardial fluid. In such cases it may be difficult to access the pericardial space with a needle, necessitating emergency surgical consultation. Less frequently, a more slowly accumulating effusion may develop over several days as a reaction to a relatively small amount of bleeding into the pericardial space or irritation from a subclinically perforated lead. This may follow signs and/or symptoms of pericarditis or present as *de-novo* tamponade. Drainage may be necessary if hemodynamic stability is threatened; otherwise, non-steroidal anti-inflammatory agents and observation may be used.

Suspicion of perforation without tamponade may be aroused by an extreme distal location of the lead tip at the cardiac apex (especially if it seems to curve around the apex, tenting up the cardiac silhouette), or by the presence of a pericardial friction rub, chest pain, an ECG pacing pattern of RBBB, or an upright unipolar electrogram recorded from the lead tip. Poor pacing and sensing thresholds may be seen. In such situations, fluoroscopy or computed tomography scanning may be helpful in localizing the lead tip (Figure 5.21).[36] If perforation is confirmed, the lead should be withdrawn under hemodynamic monitoring at

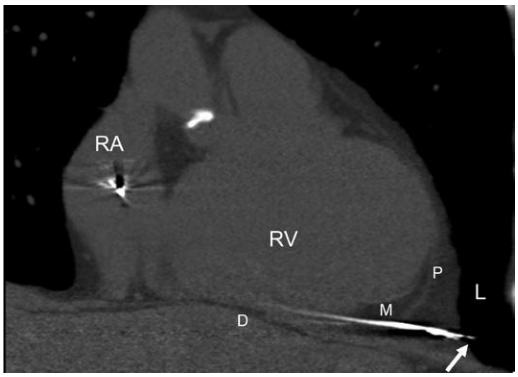


Figure 5.21 Reconstructed computed tomographic image in right anterior oblique view showing perforation of an active fixation ventricular lead through the right ventricular apex and pericardium into the lung parenchyma. This problem may present with loss of ventricular sensing and capture, pneumothorax, pericardial effusion, and/or stimulation of the diaphragm or chest wall. The lead was later withdrawn uneventfully in the operating room. D, diaphragm; L, left lung; M, right ventricular myocardium; P, pericardium; RA, right atrium; RV, right ventricle.

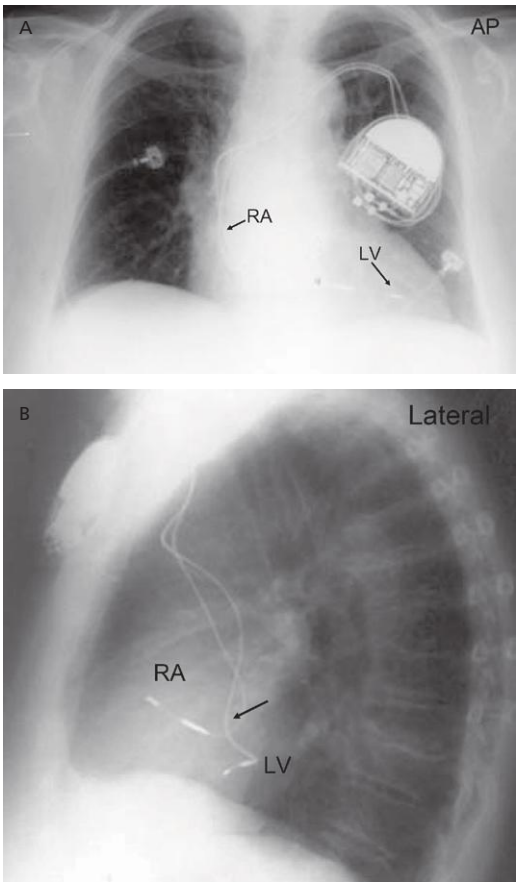


Figure 5.22 Chest radiographs of a patient after implantation of a dual chamber pacemaker with inadvertent left-sided ventricular lead placement. The paced QRS complex on 12-lead ECG showed a right bundle branch block pattern. (A) On anteroposterior view, the ventricular lead appears to be positioned near the right ventricular apex. (B) Lateral chest radiograph shows a posterior diversion of the ventricular lead at the atrial level (arrow). Passage of the lead across a patent foramen ovale, across the mitral valve, and into the left ventricle was later confirmed. Treatment options include removal of the lead or chronic anticoagulation to prevent thromboembolus. This problem can be avoided by careful fluoroscopy of the leads in multiple views and observation of an appropriate 12-lead paced QRS complex at the time of implantation. LV, ventricular lead in the left ventricle; RA, right atrial lead.

a time and facility capable of emergency surgical drainage if necessary.

A transvenous pacing lead may enter the left heart through a communication between the atria, through the membranous septum separating the right atrium from the LV, or through the muscular intraventricular septum. The permanent pacing lead may also be inadvertently introduced into an artery and passed retrograde across the aortic valve into the LV. The anteroposterior radiographic image of a lead positioned in the LV may not be distinguishable from an image of one placed in the RV apical position. Oblique or lateral views, however, will demonstrate the posterior location of an LV lead (Figure 5.22). In addition, pacing from the LV will result in a RBBB QRS pattern on ECG. This combination of techniques should always be performed during lead implantation to exclude this important and preventable complication.

Early recognition of a lead in a systemic chamber should prompt its immediate repositioning because of the danger of thrombus formation and systemic embolization. A review of the literature has found that 10 of 27 patients with systemic pacing leads had thromboembolic complications, including three patients on antiplatelet drugs.[37] Options for management of patients with chronically implanted left heart endocardial leads include long-term anticoagulation, lead removal at thoracotomy, or

percutaneous lead removal. The latter has been thought to be associated with excessive risk of systemic embolization, but a number of successful procedures have been reported.

Other lead complications

The presence of a pacing lead across the tricuspid valve orifice ordinarily results in little or no valvular dysfunction. On occasion, however, this structure may be compromised or damaged, resulting in tricuspid regurgitation.[38] During insertion, the tines of a passive fixation lead may become entangled with the chordae tendineae, and rupture of the latter may result if vigorous lead withdrawal is attempted. Occasionally, extrication of the lead from the tricuspid apparatus may require use of a locking stylet (with or without an extraction sheath) to transmit the force of traction to the lead tip rather than merely stretching the lead. The valve may be chronically injured by the lead's passage across it and by the resultant fibrosis. Thrombus and adhesions may form between the two and serve as a nidus for infection. Recurrent endocarditis on an RV lead has been associated with the development of tricuspid stenosis and insufficiency.

The pacing lead itself may be damaged by the physical forces exerted upon it during the process of implantation, by entrapment in the musculoskeletal system, by retention ligatures, and by the stresses placed on it by the beating heart. Loss of integrity of the insulation (either inner or outer) is usually manifested by a low pacing impedance that causes a high current drain; conductor fracture is associated with a high pacing impedance. Lead fracture may be recognized radiographically (Figure 5.5). A defect in the insulation between the conductor wires of a bipolar lead may produce contact potentials resulting in oversensing and transient inhibition of pacemaker output. Detection of such intermittent dysfunction may require the performance of provocative maneuvers such as raising, abducting, or adducting the ipsilateral upper extremity. Prolonged contact between the conductors can result in a short circuit, preventing current from reaching the electrodes and depleting the battery. Both lead fracture and loss of insulation integrity may lead to clinical symptoms and adverse events in pacemaker-dependent patients.

The most common complication of lead placement is its subsequent dislodgement (Figure 5.12). This may be obvious on fluoroscopy or radiography (macro-) or accompanied by no obvious change in position (micro-) and usually occurs early after implantation, before adhesion and fibrosis act to anchor the device further. Dislodgement rates are inversely related to the experience of the implanter, which suggests that inadequate initial positioning, allowance of lead slack, and/or anchoring are significant risk factors. Patient-related factors may include variant anatomy, right atrial/ventricular enlargement, and tricuspid regurgitation, especially when passive fixation leads are utilized.

An additional clinical scenario, termed "sagging heart syndrome," may be seen in patients with marked caudal mediastinal shift with upright posture, resulting in loss of what appeared to be adequate lead slack in the supine posture during lead implantation. This problem has been described in obese patients and in patients who have undergone significant weight loss.

A unique cause of lead dislodgement is known as Twiddler's syndrome. In these cases, the patient twists the pacemaker generator in the pocket (usually subconsciously), turning it in such a way that the leads are wound around it and are gradually withdrawn from the heart (Figure 5.17). A similar problem may occur when the generator is not sutured to the underlying pectoralis fascia. In this scenario, a generator lying in the subcutaneous tissue (or in a submuscular space) may gradually descend through this space and exert traction on the lead.

The incidence of lead dislodgement has been reduced with refinement of both active and passive fixation devices; it is now less than 2–3%. The risk of this complication is lessened by ensuring a stable position at implant, leaving a proper amount of intravascular lead slack so that tension is not exerted at the tip by respiration or arm motion, adequately anchoring the suture sleeve to underlying tissue, and limiting abduction and elevation of the ipsilateral upper extremity for a short time after implantation.

Early recognition of lead dislodgement (often by deterioration in pacing parameters or the occurrence of ectopy) should result in attempts at repositioning as soon as possible. This is usually accomplished with minimal effort when the lead has not fibrosed to endocardium or venous endothelium. Deterioration of the performance of one or more chronic leads may present a more difficult problem and it is often necessary to implant a new lead.

Venous thrombosis

The presence of one or more intravascular leads may incite deep venous thrombosis (DVT) of the subclavian vein. Although asymptomatic thrombosis appears to be common, its relationship with the number and type of leads remains controversial. Clinically significant pulmonary embolization is rare. Symptomatic thrombosis of the subclavian, axillary, or cephalic veins occurs on occasion and presents as a swollen, painful upper extremity, usually within a few weeks of implantation. Extension of the thrombus to involve the innominate vein, SVC, contralateral structures, or the cerebral venous sinus may occasionally occur. Venography will reveal the extent of thrombus and the state of development of collateral pathways (Figure 5.23). Symptomatic thrombosis that is limited to the subclavian or axillary veins may be treated conservatively, with heparin acutely, upper extremity elevation, and then warfarin anticoagulation for 3–6 months. In selected patients with highly symptomatic acute DVT with proximal extension, thrombolytic therapy may be considered.

Silent DVT is common. Routine venography at the time of elective generator replacement has shown an approximately 25% incidence of severe stenosis or occlusion of the ipsilateral subclavian vein.[39] No risk factors for thrombotic or fibrotic venous occlusion have been unequivocally identified, although some studies have suggested

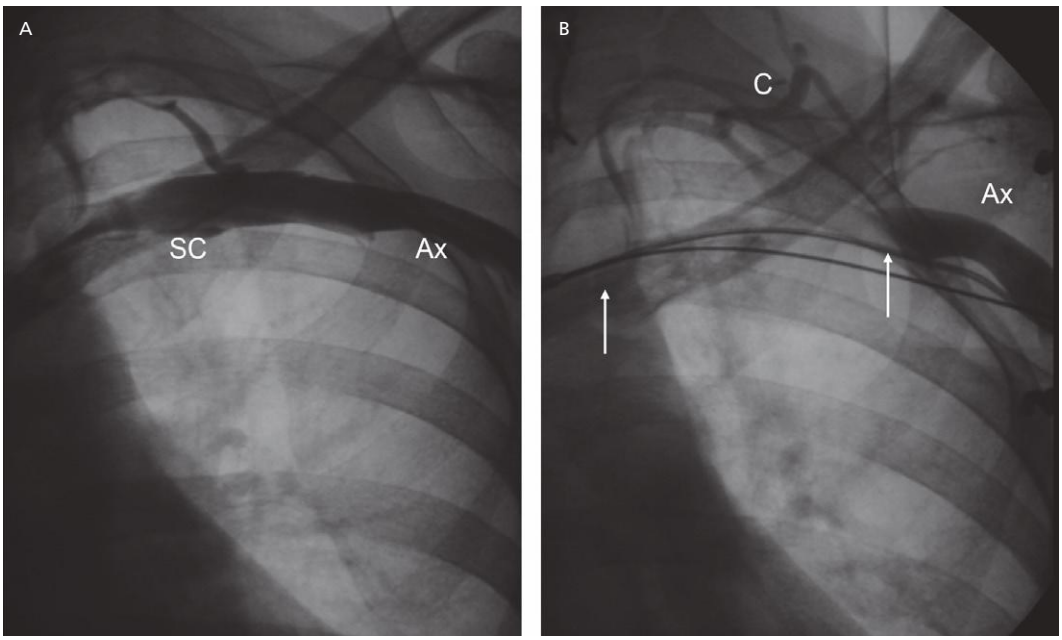


Figure 5.23 Deep venous thrombosis (DVT) during pacemaker implantation. (A) Pre-procedure left upper extremity venogram shows patent axillary (Ax) and subclavian (SC) veins. (B) A second intraprocedural venogram was performed due to an inability to access the vein for a third left ventricular lead after placement of the right ventricular and atrial leads. Acute occlusion of the subclavian vein between the two arrows is demonstrated, along with the appearance of collateral venous circulation (C).

that an increased number of leads and systemic infection predispose to venous occlusion. In most patients, asymptomatic venous occlusion becomes a problem only when attempts are made to re-enter the vessel for lead revision or placement of additional leads. It is not necessary to treat asymptomatic chronic occlusions. Pacemaker leads inserted by the transfemoral route may be associated with femoral and iliac thrombosis, and significant pulmonary embolization, necessitating lead extraction, anticoagulation, and possibly insertion of an IVC filter.

Complete or partial occlusion of the SVC has been reported as a complication of pacemakers. This has been attributed to both thrombosis and fibrosis, and may be treated with balloon dilation or surgical reconstruction if it becomes symptomatic. Acute or subacute occlusion may be treated with anticoagulants and/or thrombolytic agents. Chronic occlusion is more problematic and is, in general, resistant to pharmacotherapy. In some situations of total occlusion of the SVC, endovascular reconstruction may be complicated by an inability to pass a guidewire through the obstruction. In such cases it may be possible to remove the existing leads and use the extraction sheath as a means of gaining entrance through the occluded venous system. Dilation and stenting may then be considered. Stenting should not be performed over indwelling pacemaker leads. In cases in which endovascular repair is not possible, a surgical approach that enlarges the venous channel with a patch graft has been used with some success.

The true incidence of lead-associated thrombus is uncertain, since transesophageal echocardiography (TEE) is usually performed only if there is a clinical indication. Such thrombus in the presence of infection would be termed a "vegetation." In general, the chance finding of a thrombus on a lead does not, in itself, mandate therapy; however, if it is very large, consideration should be given to anticoagulation. Anticoagulation therapy would be indicated if there is evidence of thromboembolism. A pedunculated thrombus on a pacing lead may occlude the tricuspid orifice and cause symptoms similar to those of a myxoma. Treatment of lead-associated atrial thrombus with thrombolytic therapy has been reported.

Generator

The function of a pacing system depends on a proper connection between the leads and the generator. The terminal lead pins are inserted into the connector block of the generator and are fixed into position by some mechanism, usually set-screws. If this procedure is not performed properly, the pin may either lose contact altogether (i.e. have no electrical continuity, an "open circuit") or intermittently contact the pacemaker terminal and produce spurious potentials that may be sensed by the pacemaker as intrinsic electrical activity, which will cause inhibition of pulse generator output. When dual chamber systems are used, it is essential that the atrial and ventricular leads be connected correctly to their corresponding terminals (Figure 5.16).

Care should be exercised when using electrocautery, since its application in the vicinity of the generator may lead to inhibition of pacing or to abnormal tracking. Reprogramming of the device to a reversion mode may also result. Exposure to other sources of energy—such as direct-current defibrillation, magnetic resonance imaging, and high-dose radiation therapy—may also affect pacemaker function. In some cases, pacemaker function can be restored by use of a special engineering programmer; in other situations, the device may be permanently damaged and require replacement.

The generator is usually well tolerated in its subcutaneous pocket, but on occasion its presence may be associated with pain. Most often this occurs because the pocket is small and tension is exerted on the overlying tissue. A chronic indolent infection may also be a source of pain. Pain attributed to neuralgia has been treated successfully with steroid injections and with pocket revision. Movement of the pacemaker may occur if the pocket is large, the surrounding tissue lax, and the device not secured. Swelling of the pocket may be caused by infection, seroma, or hematoma. Aspiration of the effusion should be discouraged because of the possibility of introducing infection. A strong suspicion of infection should prompt surgical exploration.

Migration of the pacemaker under the breast or into the axilla may place tension on the leads or result in the assumption of a position that is uncomfortable or is predisposed to erosion.

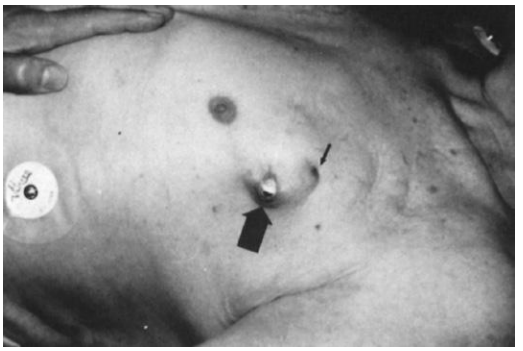


Figure 5.24 Patient with a permanent pacemaker in whom areas of pre-erosion (small arrow) and erosion (large arrow) are present. This problem is almost always due to indolent infection and requires complete extraction of the system.

Erosion of pacing hardware is caused by pressure necrosis of overlying tissue or infection. This event is usually signaled by a preceding period of "pre-erosion," during which there is discomfort and discoloration of thinning tissue tensely stretched over a protrusion of the pacing apparatus (Figure 5.24). The risk factors for erosion include a paucity of subcutaneous tissue, the mass and configuration of the pacemaker, need for extra hardware (e.g. lead adaptor) in the pocket, the pocket's construction, and irritation caused by activity or physical manipulation or by articles of clothing. Identification of pre-erosion allows the possibility of salvage of the pacing system, as the hardware may be repositioned under the pectoralis muscle or in an abdominal location.

If erosion occurs, the system is considered contaminated and current practice is removal of the generator and leads. Some operators have proposed that extensive debridement of the pocket and prolonged irrigation and antibiotic therapy may provide an alternative option to removal in cases of both erosion and frank infection, but this approach is not generally accepted, and should be considered only in exceptional clinical circumstances.

Bleeding into the pocket may occur when hemostasis is inadequate, when there is a co-existent coagulopathy, or when anticoagulant or thrombolytic therapy is begun soon after implantation. On occasion, this may compromise the pocket's integrity and may be a risk factor for infection. Hematoma progression, excessive pain, and stress on the suture line may require hematoma evacuation and search for a bleeding site.

Although not a complication of implantation *per se*, a generator may prematurely and without warning fail or may revert to an unsafe pacing mode. The former may relate to a defect in the power supply and the latter is a function of unrecognized problems with circuit design. The incidence of pacemaker failure has steadily declined over the years with improvement in design, and in 2006 the risk was estimated to be approximately 1.4 per 1000 devices.[40] Despite the decrease in absolute risk over the years, public concern over this issue has increased in the wake of several highly publicized device advisories.

Infection

Even a non-eroded pacemaker implantation site may become infected. Diabetes mellitus and post-operative hematoma appear to be predisposing factors. Acute infections (usually with *Staphylococcus aureus*) become manifest within the first few weeks of implantation and are often associated with the accumulation of pus. A more indolent infection caused by a less virulent agent such as *S. epidermidis* may present months or years after implantation. A fungal infection may also occur in the pocket and present as an indolent process with relatively scant growth of the organism. Infections with less virulent organisms may present as a small area of erythema, a pimple-like lesion, or a draining sinus. Some cases of indolent infection appear as cellulitis or pre-erosions. One-third to one-half of acute infections complicate new implants; the remainder are associated with re-operation for generator replacement or lead repositioning. Pocket infections are generally considered to result from organisms introduced from the skin's surface.[15] Superficial infections of the suture line that do not extend to the pocket itself may be treated conservatively.

Staphylococci, and presumably other pathogens, adhere to the plastic insulation of pacing hardware and form colonies that become covered with a secreted substance protecting the organism from host defense and antimicrobial drugs. Antibiotic therapy alone is rarely sufficient to eradicate these

infections, and removal of the pacing system is usually indicated. In patients with erosions or localized pocket infections who have been on antimicrobial therapy and have negative blood cultures, it may be possible to place a new pacing system at a different site at the time of removal of the suspect hardware. Most of the time, however, it is prudent to use a two-step approach with temporary pacing (if the patient is pacer dependent) used to bridge the time between explantation and new device implantation a few days later. After device removal, the infected pocket may be partially closed and a drain inserted, or packed with wet-to-dry dressings and left open to heal by secondary intention.

Vacuum-assisted wound closure is a technique introduced in 1997 to assist in wound healing through the application of continuous negative pressure, resulting in removal of toxic products, devitalized tissue, and secretions, and increased lymphatic and blood flow. This technique accelerates healing and may allow for delayed surgical closure. Applied successfully to cases of orthopedic, diabetic, and sternal wound infections, it has been used to promote wound healing after pacemaker and ICD explantation in which the wound must be left open. Small case series have been published in which the technique has been used to salvage an infected pocket site without lead extraction in patients deemed to be at prohibitive risk or who refuse extraction.[41] However, there are currently no controlled trials showing that vacuum-assisted wound closure is superior to standard therapy for either indication.

Less frequently, a pacemaker patient may develop bacteremia without localizing signs, in which case endocarditis associated with a pacing lead should be considered. Lead endocarditis generally occurs later than pocket infection. It may be related to an organism introduced at implantation, but is more often thought to be secondary to a transient bacteremia, often from an undefined source. The diagnosis of lead endocarditis can be made when a vegetation is detected by echocardiography in the presence of other signs of infection (Figure 5.25). TEE may be helpful if transthoracic examination is non-diagnostic. One report has suggested that pacemaker-associated endocarditis

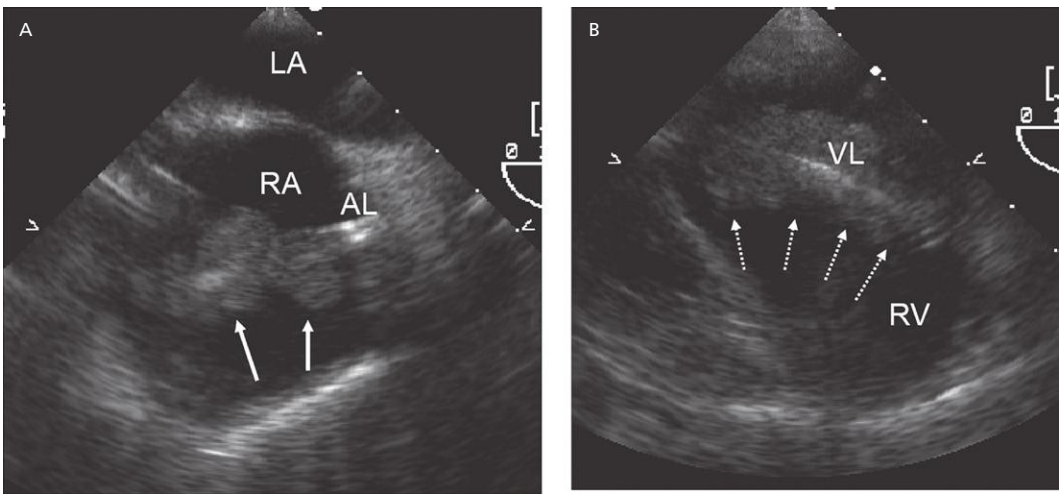


Figure 5.25 Pacemaker lead infection in transesophageal echocardiographic (TEE) images from a patient presenting with signs and symptoms of subacute endocarditis. Blood cultures grew *Staphylococcus epidermidis*. (A) The right atrium (RA) showing two large vegetations (arrows) attached to the right atrial lead (AL). LA, left atrium. (B) The right ventricle (RV) showing the ventricular lead (VL) encased in fibrinous infectious material (arrows). The pacemaker system was extracted with an open surgical procedure and an epicardial pacing system was placed.

constitutes 4.6% of the entire population with infective endocarditis and occurs with an incidence of about 0.6% in patients with pacemakers. Staphylococcal species predominate, with about two-thirds being coagulase negative.[42] Occult Gram-positive bacteremia is a class I indication and occult Gram-negative bacteremia is a class IIa indication for extraction of endocardial leads.

Diagnosis of pacemaker lead infection necessitates the removal of all pacing hardware after antibiotics have been started.[43] In these situations, adequate time between explantation and implantation of a new permanent system is necessary for antibiotic therapy to sterilize the blood. Generally, this interval is related to the duration of previous antibiotic treatment and the confirmation of negative blood cultures, usually for 3–10 days.[5] The antibiotic therapy is selected on the basis of the organism cultured from the blood or hardware, and treatment duration should be similar to that of non–pacemaker-associated infective endocarditis with the same organism.

Complications of biventricular pacing

Implantation of a coronary venous lead is the major procedural difference between biventricular and simple dual chamber pacemakers. It is subject to all the complications associated with dual chamber systems plus those unique to LV pacing.[44] The LV lead must be placed in a lateral wall coronary sinus tributary vein. The technical challenge of this procedure has decreased with improvement in lead design and delivery equipment. Inability to achieve an LV lead placement by a transvenous approach ranges from 2% to 10%.

Unique complications include coronary sinus dissection (2–4%) and coronary venous perforation (2%), complications mainly related to coronary sinus venography. Coronary sinus perforation may lead to pericardial tamponade requiring urgent drainage. With better leads and delivery equipment, and greater operator experience, lead placement has been facilitated and the procedure times as well as the significant complication rate reduced. Extracardiac stimulation from the LV lead (diaphragm and phrenic nerve) may also be problematic and should be sought at the time of implantation. Its occurrence should prompt the search for another lead implant site. This problem may also first appear after implantation and can sometimes be corrected with reprogramming, although lead revision may be required. Newer lead design, such as the quadripolar lead configuration, may reduce the risk of this problem and allow for more options for "electronic repositioning."

Lead extraction

General principles

Removal of existing "permanent" endocardial leads is being considered with increasing frequency because: the rate of CIED infection has increased; there are large numbers of defibrillator leads exhibiting premature failure; and the tools and techniques for lead removal have matured and are associated with an increased success rate and, in experienced hands, a decreased complication rate (Table 5.8). The ease of accomplishing lead removal and the associated risks are related to the time the lead has been implanted. Thus, a lead that has been in place for 3 months or less is usually easily removed, whereas one in place for more than 1 year may well present difficulties due to fibrosis, which may occur at a number of sites in the heart and central veins with which the lead has contact (Figure 5.26). Non-isodiametric leads, those with anchoring appendages (tines or fins), and dual coil ICD leads may present additional problems. The concept of "lead management" has come into vogue; it implies limiting the number of intravascular leads to those actively providing a service to the patient and removing non-functional or potentially problematic leads at an earlier time such that the process is easier, and perhaps, complications such as venous occlusion and device system infection are reduced.

When we speak of lead extraction, we are generally concerned with the special challenges presented by a chronically implanted lead. This definition may also be used in situations in which specialized tools (e.g. sheaths, locking stylets, snares, etc.) are needed and/or when the lead is removed from a site other than that of original venous access. The

Table 5.8 HRS consensus indications for transvenous lead extraction (Source: Wilkoff 2009.[45] Reproduced with permission of Elsevier.)

Recommendations for lead extraction apply only to those patients in whom the benefits of lead removal outweigh the risks when assessed based on individualized patient factors and operator-specific experience and outcomes.

Infection

Class I

1 Complete device and lead removal is recommended in all patients with definite cardiovascular implantable electronic device (CIED) system infection, as evidenced by valvular endocarditis, lead endocarditis or sepsis

2 Complete device and lead removal is recommended in all patients with CIED pocket infection as evidenced by pocket abscess, device erosion, skin adherence, or chronic draining sinus without clinically evident involvement of the transvenous portion of the lead system

3 Complete device and lead removal is recommended in all patients with valvular endocarditis without definite involvement of the lead(s) and/or device

4 Complete device and lead removal is recommended in patients with occult Gram-positive bacteremia (not contaminant)

Class IIa

1 Complete device and lead removal is reasonable in patients with persistent occult Gram-negative bacteremia

Class III

1 CIED removal is not indicated for a superficial or incisional infection without involvement of the device and/or leads

2 CIED removal is not indicated to treat chronic bacteremia due to a source other than the CIED, when long-term suppressive antibiotics are required

Chronic pain

Class IIa

1 Device and/or lead removal is reasonable in patients with severe chronic pain, at the device or lead insertion site, that causes significant discomfort for the patient, is not manageable by medical or surgical techniques, and for which there is no acceptable alternative

Thrombosis or venous stenosis

Class I

1 Lead removal is recommended in patients with clinically significant thromboembolic events associated with thrombus on a lead or a lead fragment

2 Lead removal is recommended in patients with bilateral subclavian vein or superior vena cava occlusion precluding implantation of a needed transvenous lead

3 Lead removal is recommended in patients with planned stent deployment in a vein already containing a transvenous lead, to avoid entrapment of the lead

4 Lead removal is recommended in patients with superior vena cava stenosis or occlusion with limiting symptoms

5 Lead removal is recommended in patients with ipsilateral venous occlusion preventing access to the venous circulation for required placement of an additional lead when there is a contraindication for using the contralateral side (e.g. contralateral atrioventricular fistula, shunt or vascular access port, mastectomy)

Class IIa

1 Lead removal is reasonable in patients with ipsilateral venous occlusion preventing access to the venous circulation for required placement of an additional lead, when there is no contraindication for using the contralateral side

Table 5.8 (*Continued*)

Functional leads

Class I

1 Lead removal is recommended in patients with life-threatening arrhythmias secondary to retained leads

2 Lead removal is recommended in patients with leads that, due to their design or their failure, may pose an immediate threat to the patients if left in place (e.g. Telectronics Accufix J-wire fracture with protrusion)

3 Lead removal is recommended in patients with leads that interfere with the operation of implanted cardiac devices

4 Lead removal is recommended in patients with leads that interfere with the treatment of a malignancy (radiation/reconstructive surgery)

Class IIb

1 Lead removal may be considered in patients with an abandoned functional lead that poses a risk of interference with the operation of the active CIED system

2 Lead removal may be considered in patients with functioning leads that, due to their design or their failure, pose a potential future threat to the patient if left in place (e.g. Telectronics Accufix without protrusion)

3 Lead removal may be considered in patients with leads that are functional but not being used (i.e. right ventricular pacing lead after upgrade to ICD)

4 Lead removal may be considered in patients who require specific imaging techniques (e.g. MRI) that cannot be imaged due to the presence of the CIED system for which there is no other available imaging alternative for the diagnosis

5 Lead removal may be considered in patients in order to permit the implantation of an MRI-conditional CIED system

Class III

1 Lead removal is not indicated in patients with functional but redundant leads if patients have a life expectancy of less than 1 year

2 Lead removal is not indicated in patients with known anomalous placement of leads through structures other than normal venous and cardiac structures (e.g. subclavian artery, aorta, pleura, atrial or ventricular wall or mediastinum) or through a systemic venous atrium or systemic ventricle. Additional techniques including surgical back-up may be used if the clinical scenario is compelling

Non-functional leads

Class I

1 Lead removal is recommended in patients with life-threatening arrhythmias secondary to retained leads or lead fragments

2 Lead removal is recommended in patients with leads that, due to their design or their failure, may pose an immediate threat to the patients if left in place (e.g. Telectronics Accufix J-wire fracture with protrusion)

3 Lead removal is recommended in patients with leads that interfere with the operation of implanted cardiac devices

4 Lead removal is recommended in patients with leads that interfere with the treatment of a malignancy (radiation/reconstructive surgery)

Class IIa

1 Lead removal is reasonable in patients with leads that due to their design or their failure pose a threat to the patient, that is not immediate or imminent if left in place (e.g. Telectronics Accufix without protrusion)

2 Lead removal is reasonable in patients if a CIED implantation would require more than four leads on one side or more than five leads through the superior vena cava

3 Lead removal is reasonable in patients who require specific imaging techniques (e.g. MRI) and cannot be imaged due to the presence of the CIED system for which there is no other available imaging alternative for the diagnosis

(*Continued*)

Table 5.8 (*Continued*)

Class IIb

1 Lead removal may be considered at the time of an indicated CIED procedure, in patients with non-functional leads, if contraindications are absent

2 Lead removal may be considered in order to permit the implantation of an MRI conditional CIED system

Class III

1 Lead removal is not indicated in patients with non-functional leads if patients have a life expectancy of less than 1 year

2 Lead removal is not indicated in patients with known anomalous placement of leads through structures other than normal venous and cardiac structures (e.g. subclavian artery, aorta, pleura, atrial or ventricular wall or mediastinum) or through a systemic venous atrium or systemic ventricle. Additional techniques including surgical back-up may be used if the clinical scenario is compelling

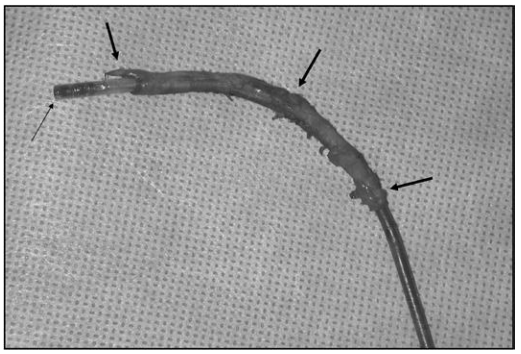


Figure 5.26 A newly extracted active fixation ventricular lead with numerous adherent fibrous vascular attachments (thick arrows). The active fixation helix has been retracted into the tip of the lead (thin arrow). It is these fibrous vascular adhesions, which may form anywhere along the length of the lead, that can make lead extraction physically challenging and potentially hazardous due to the risk of vascular or cardiac injury.

term "lead explant" is used for the removal of leads having an implant duration of less than 1 year with only the tools used in a typical implantation and manual traction. These definitions have some importance in terms of the requisite qualifications of physicians performing the respective procedures (see "Techniques").[45] Although most of this discussion is directed at lead "extraction," it is relevant to physicians performing lead "explantation" also.

There are two general approaches for the removal of pacing leads: percutaneous and transthoracic. Most pacing physicians and surgeons believe that if extraction is to be performed it should be done percutaneously. Certainly, simple traction on the lead is easy, straightforward, and logistically undemanding. If all leads would yield to this treatment there would be little debate as to the threshold for lead extraction and even less support for the more invasive surgical option. Unfortunately, chronic leads are not so readily removed and, even with the variety of tools available to assist in the percutaneous technique, the procedures may be long, difficult, and associated with a finite mortality and significant morbidity.

The risks of lead removal correctly influence the aggressiveness with which one should pursue this approach. Post-mortem pathological studies of the hearts of patients with permanent pacemakers have revealed intense fibrosis and encapsulation, especially involving the ventricular portion of the lead, and including the tricuspid valve and its supporting apparatus. Attempts to remove these leads *ex vivo* are associated with myocardial avulsion, valve damage, and disruption of the lead. Implants of longer duration tend to have more extensive fibrosis, but significant encapsulation of an atrial lead has been observed at post-mortem examination 6 weeks after implantation.

Contemporary leads are of low profile and primarily co-axial bipolar in configuration; they do not, in general, tolerate the physical forces that may be necessary to extract them by simple traction in the presence of significant fibrosis. A variety of tools have been developed to facilitate the extraction of these devices via the process of

"traction–countertraction."[46] These include a stylet that "locks" in the distal lead, and sheaths that are passed over the lead body, stripping it of fibrous attachments. Over the last decade powered sheaths (laser, electro-dissection, and mechanical/rotational) have been shown to facilitate lead extraction and increase the overall success rate.

The specific events that might complicate lead extraction pertain to the physical forces used to strip away fibrous adhesions to the lead body, and those used to extricate the tip of the lead from the heart. Catastrophic events, when they occur, usually result from either a laceration of a central vein by an extraction tool or perforation of the heart at the site of tip fixation. Embolization of a very large vegetation or thrombus to the pulmonary artery may also cause death. Damage to the tricuspid valve, or embolization of a lead fragment or thrombus to the lung, or through a patent foramen ovale to the systemic circulation, may also occur. Although most complications become evident during or shortly after the extraction procedure, some, such as a hemothorax, pulmonary embolism, or pericardial tamponade, may be delayed in presentation. Because of the risks involved it is essential that adequate informed consent be obtained from the patient and that the reasons for performing lead extraction, the potential risks and benefits, and alternatives are thoroughly discussed with the patient and family by the operator.

Indications

Lead extraction has inherent risks; thus the decision to undertake the procedure must be weighed against the risk of not extracting the lead. Consensus indications for lead removal have been developed by the Heart Rhythm Society (HRS) (formerly known as NASPE), first published in 2000 and subsequently revised and updated in 2009.[45] Consensus indications are classified in the ACC/AHA guideline format as: class I, general agreement for removal; class II, situations in which leads are often removed but with some divergence of opinion; and class III, general agreement that removal is unnecessary (Table 5.8). This classification primarily addresses the nature of the risk to the patient of not removing a lead, but it does not approach the risk of extracting a chronically implanted lead in a specific patient. Thus, an infected lead is often surprisingly easy to remove, whereas elective removal of a non-functioning passive fixation lead that has been in place for a number of years may be extremely difficult and result in complications.

A number of modifying factors based on clinical parameters thought to influence the risk of lead extraction have been included in the indication guidelines for the extracting physician to consider.[47] These parameters relate to the patient (age, gender, overall health); anatomy (presence of calcification and vegetations associated with the lead); lead (number, construction, and condition); operator (physician training, experience, and case volume); and the wishes of the patient. These factors are not absolutes, but rather provide a context in which to assess the risks for each specific situation and weigh these against the perceived benefit of extraction. Their consideration may be especially important for class II indications, for which the clinical necessity of removal may be debated.

An infected lead provides the strongest indication for lead removal, since complete removal of all prosthetic material has been shown to be necessary for eradication of the infection in most cases. In a large case series, 123 patients underwent pacemaker or ICD system extraction due to documented infection.[48] About one-third of patients had bacteremia, whereas most of the remainder had pocket infections. Staphylococci were the dominant infectious agents. One hundred and seventeen patients (95%) had complete system removal. Of the remaining six patents, three (50%) had relapse of infection, whereas only one of the 117 successfully extracted patients had relapse, and this single relapse resulted from reuse of an infected pocket. Delay in extracting an infected CIED in a bacteremic patient will increase the risk of death despite an uncomplicated lead extraction.

The microbiology of pacemaker and ICD infections in a published series of 412 patients is presented in Table 5.9.[42] As in previous reports, infections with staphylococci predominate, representing over 80% of infections. In addition, 10% of cases were polymicrobial and in 12% no organism could be identified. Of note, in this recent series, 50% of *Staphylococcus* species isolated

Table 5.9 Microbiology of pacemaker/ICD infections (Data from [48])

Staphylococcus epidermidis	44%
Staphylococcus aureus	36%
Enteroccoci	5%
Streptococcus viridans	2%
Other Gram-positive aerobes	1%
Gram-negative bacilli	9%
Anaerobic organism	1%
Fungi/mycobacteria	1%
Polymicrobial infections	10%
No organism identified	12%

Table 5.10 Risks of lead extraction (Data from [52])

Major	
Death	0.8%
Pericardial tamponade	1.4%
Hemothorax	0.4%
Pulmonary embolus	0.1%
Lead fragment migration	0.1%
Total major complications	1.9%
Minor	
Perforation	0.4%
Myocardial avulsion	0.1%
Venous avulsion	0.1%
Other	0.9%
Total minor complications	1.4%
Any complication	3.3%

were resistant to methicillin. The overall rate of relapsed infection was 1.9%, and was slightly higher in patients re-implanted during the same hospitalization.

Retained non-infected but non-functioning hardware generally poses little immediate risk to the patient, but may complicate the placement of additional pacing leads either by adding to the venous obstruction (and the risk of thrombosis/embolization) or by generation of spurious electrical potentials between leads. In addition, in young patients with a long life expectancy, the late risks of retained abandoned leads, especially ICD leads, are not well described. Since complications of extraction increase with time elapsed since lead implantation, some argue for routine extraction, rather than abandonment, of unused leads in these patients.[49] In the absence of clear data supporting one point of view, clinicians will need to balance risks and benefits of this approach on a case-by-case basis.[50] In the 2009 HRS Consensus Statement, extraction of abandoned functional or non-functional leads, in the absence of another specific indication, is a class IIb indication.[45]

Lead failure is usually defined in terms of electrical performance, i.e. the ability to pace and sense appropriately. Isolated pacing impedance changes may suggest insulation or conductor failure. There are leads, however, that may exhibit normal electrical function but offer a physical risk to the patient. The Accufix J lead presents a unique risk to the patient in that a small metal wire placed within the lead for the purpose of maintaining the J shape is subject to fracture under the stress and strain of repetitive cardiac motion. The fractured wire may wear through the insulation and perforate the heart, causing cardiac tamponade or mediastinal hemorrhage. Complete mitigation of this risk when the lead was recalled in 1994 would have required lead extraction in the approximately 45 000 implanted patients. However, a registry established to study this issue concluded that the risk of death from elective lead extraction of non-fractured leads is higher than the risk of injury from the lead itself.[51] This information has resulted in the recommendation of conservative management of these patients with periodic cinéfluoroscopy to screen for retention wire fracture. If fracture with protrusion occurs, the lead should generally be extracted.

Risks

In a multicenter study of 1684 patients at 89 US centers, lead extraction of pacing and ICD leads using modern tools was associated with a 0.8% risk of death and a 1.9% risk of major complications, such as pericardial tamponade, hemothorax, and pulmonary embolus (Table 5.10).[52] Ten percent of patients had incomplete (3%) or failed (7%) transvenous extraction. Of the 13 patients who died in this registry, five died from pericardial tamponade, three from hemothorax, one from pulmonary embolus, and one from innominate arteriovenous fistula.

More recently, the LExICon study reported on outcomes of 1449 consecutive patients at 13 centers

Table 5.11 Pre-explant information

Device	*Patient*	*Laboratory*
Site(s) of venous access Number and types of leads Method used for retention of leads Difficulties encountered in prior procedures Information on previously abandoned leads	Degree of pacemaker dependency and need for temporary pacing Risk for sedation/anesthesia Co-morbidities/medications Special considerations (e.g. vascular anomaly or occlusion; IVC filter, bleeding diathesis)	Complete blood cell count, INR, aPTT, platelet count, sample to blood bank Blood chemistries ECG Chest radiograph (PA and lateral) and/or lead fluoroscopy

aPTT, activated partial thromboplastin time; ECG, electrocardiogram; INR, International Normalized Ratio; IVC, inferior vena cava; PA, posteroanterior.

who underwent laser-assisted extraction of 2405 leads.[53] Leads were completely removed in 96.5% of cases. Procedural failure was more likely with leads implanted for more than 10 years. Major adverse events occurred in 1.4% of cases, and the procedural mortality rate was 0.28% (four patients—three vascular tears and one RV tear). In centers with higher procedure volumes, clinical success rates were higher and major adverse event rates were lower.

Increasing operator experience appears to reduce the risk of complications, and some highly experienced operators have reported complication rates lower than those reported in multicenter series. Risk of a major complication was associated with female gender, number of leads in place, and implant duration, whereas risk of any complication was related to less experienced operators (<50 procedures). Extraction of any chronically implanted lead should be undertaken only after careful consideration of the risk-to-benefit ratio, including patient age, overall health, presence of calcification or vegetations involving the leads, duration of implant, and patient preference to assume additional risk.

In addition to the acute risks of lead extraction, physicians should be aware of the potential for late mortality after the procedure; between 15% and 25% at 1 year in some series in which extraction was performed for infection.[42,54] These late deaths probably relate to underlying co-morbidities as well as infectious complications in this chronically ill population.

Technique

Extraction of chronically implanted endocardial leads should be undertaken only by experienced physicians and surgeons skilled in the required techniques. Unfortunately, this procedure is not frequently performed and there are few opportunities even in fellowship programs to receive adequate formal training. Acknowledging the well-documented association between complications and inexperienced operators, guidelines for the qualification of physicians have been proposed.[1,45] Extraction of a minimum of 40 leads under the supervision of an experienced (>75 leads) operator is recommended before independent practice of these techniques. To maintain skills, "extractionists" should extract at least 20 leads per year.

The extraction process begins with the gathering and collating of knowledge about the patient and implanted system from the patient's history and medical records (Table 5.11). A chest radiograph should be performed to exclude the presence of undocumented hardware. Recent laboratory data, such as complete blood cell count, platelet count, INR and aPTT, electrolytes, BUN, creatinine, and basic chemistries, should be confirmed as acceptable. Blood should be typed and cross-matched. It is necessary to know if complete removal of all leads is essential and whether a new device will be implanted as part of the same procedure. Based on these data, a plan of action is devised. Availability of all the tools and equipment that may be needed

Table 5.12 Recommended personnel for lead extraction procedures

Primary operator: A physician performing the lead extraction who is properly trained and experienced in device implantation, lead extraction, and the management of complications
Cardiothoracic surgeon well versed in the potential complications of lead extraction and techniques for their treatment, on site and immediately available
Anesthesia support
Personnel capable of operating fluoroscopic equipment
"Scrubbed" assistant (nurse/technician/physician)
Non-"scrubbed" assistant
Echocardiographer

should be confirmed before the patient is taken to the procedure room.

Lead extraction may be performed in either a specialized electrophysiology laboratory or in a cardiac surgical operating room.[55] At high-volume centers, hybrid cardiac catheterization–operating rooms specially designed for high-risk percutaneous cardiac procedures are increasingly utilized. Regardless of the venue, equipment, and personnel needed to perform emergency thoracotomy and cardiopulmonary bypass should be immediately available. The room should have adequate fluoroscopy. Anesthesia personnel should be available to provide deep sedation or general anesthesia. We almost always use an assistant for these procedures (either a fellow or second attending physician) due to the amount of equipment that must be controlled during the case, as well as to increase exposure to these procedures. Recommended personnel for lead extraction from the 2009 HRS Consensus Statement are listed in Table 5.12.

The routine preparation for lead extractions involves one or both groin areas for the placement of a venous line (6-Fr sheath) in the right femoral vein and a small arterial line in a femoral or radial artery for continuous monitoring of the arterial blood pressure. The femoral sheath provides for rapid fluid administration, emergent passage of a temporary pacing wire, and ability to upgrade to a femoral approach to extraction should such be needed. The chest, abdomen, and femoral regions are prepared with chlorhexidine- or iodine-based antiseptic solutions such that emergent thoracotomy could be performed. Drapes are liberally placed so that a sterile field is maintained from the neck to the thighs. If the patient is pacemaker dependent, a temporary pacing wire is inserted through either a femoral or an internal jugular vein. If prolonged temporary pacing will be needed, we employ a "permanent" active fixation lead as the temporary device via the contralateral internal jugular vein for added security against lead dislodgement during the interim period. All of our extractions are performed with a transesophageal echo probe available and after interrogation of the heart, valves, pericardial space, and leads has been performed.

A commercially available lead-extraction kit supplemented by a variety of other tools (such as snares, wires, locking stylets, biopsy forceps, guidewires, and laser extraction sheaths) should be available. The operator should have on hand all of the tools that may be needed in a complex case, whether their use is anticipated or not. All the equipment necessary for emergent heart surgery (including cardiopulmonary bypass) should be available. The extraction procedure cannot start unless a designated surgeon is confirmed to be available for emergent assistance if such is needed. The operator should have in mind a step-by-step approach to the specific problems presented by the case, and be ready to respond to emergencies as they arise.

The pocket is usually entered through the previous incision line, although this may be altered to include a site of erosion or skin necrosis. With a combination of sharp and blunt dissection, the generator and leads are freed. Electrocautery is essential in freeing leads that are often extensively fibrosed to themselves and subcutaneous tissue. The lead is traced to the venous entry point, the suture sleeve is identified, and all retention sutures are cut and removed. The lead is disconnected from the generator and its internal integrity is accessed by passing a standard stylet to the tip. In most cases, an initial attempt at gentle traction is worthwhile, but care must be taken not to damage the lead during this process. Observation during gentle traction also gives an idea about possible sites of lead attachment to the surrounding tissue.

Passive leads are usually more difficult to extract than active leads, presumably because the tines

incorporated on the former devices provide a greater surface area for fibrous adhesion. For active fixation leads, the helix should be retracted in order to facilitate removal and reduce the risk of cardiac perforation. If the retraction mechanism is not effective (or if this is a non-retractable helix), an attempt should be made to rotate the entire lead counter-clockwise to unscrew the tip from the heart. This may be impossible in situations where the body of the lead is extensively fibrosed to the heart and veins. While extraction of an active fixation ventricular lead with the helix extended is not likely to be a problem, an atrial lead may come free with a small full thickness piece of the wall, resulting in pericardial bleeding and potential tamponade.

Tools for extraction

A variety of tools are available to assist with lead extraction. A partial list of equipment which should be available to the operator is given in Table 5.13. Techniques for lead extraction can be broadly categorized into the superior approach (utilizing a locking stylet and telescoping sheaths placed over the lead to provide traction and countertraction) and the femoral approach (using different types of grasping snares and wires to remove leads).

Table 5.13 Tools and equipment for lead extraction

General equipment	Standard lead stylets
	Fluoroscopy
	Pacemaker tray
	Pericardiocentesis tray
	Chest tube insertion kit
	Emergency thoracotomy tray
Superior approach	Locking stylets
	Lead extraction kit (Cook Vascular)
	Selected manual extraction sheaths
	Laser generator lead extraction sheaths (Spectranetics)
	Radiofrequency extraction sheath
	Rotating mechanical extraction sheath (Evolution)
Femoral approach	Byrd femoral workstation
	Needle's Eye Snare (Cook Vascular)
	Selection of intravascular snares
	Biopsy forceps

Superior approach

If a lead is not easily removable by gentle traction, the stylet should be withdrawn and the lead cut close to the terminal pin with a lead cutter. The central lumen of the lead is identified and carefully dilated with a coil-expander tool. The diameter of the lumen is then determined by the insertion of a series of gauge pins. A locking stylet of a size corresponding to the largest gauge pin accepted by the lead is then advanced through the lumen to the lead tip. This device is essential to focus the force of traction as close to the lead tip as possible, and to distribute traction along the length of the lead.

There are several types of locking stylets available (Figure 5.27), which vary in the way they grip the inner core of the lead. Because current generations of these devices have a greater flexibility in adapting to a range of inner core diameters, fewer different types and sizes need to be stocked. The operator needs to be familiar with the specific directions for each of the locking stylets he/she uses. It may be difficult or impossible to reverse the locking mechanism and remove these devices once they are inserted into the lead. Some manufacturers incorporate "cables" into the insulation of the defibrillator leads to provide additional traction during lead extraction. By tying 0-silk sutures to these cables and to the body of the lead, the tension on the lead is distributed over a larger area (Figure 5.28). The use of a lead extender (Bulldog™, Cook Medical, Bloomington, IN, USA) may also be helpful in these cases and may facilitate difficult extractions, in which the inner conductor breaks free or when locking stylets cannot be passed. In patients with inner conductor failure, the inner lumen of the lead may be interrupted, making it impossible to pass a locking stylet. In this case the femoral approach may be required.

A variety of plastic or metal dilating sheaths, either "powered"(laser, electrocautery, or mechanically rotating cutting edge) or unpowered, are available to advance over the lead body and free it from fibrous adhesions (Figure 5.29). Most of these sheaths are provided with a shorter "outer" sheath that can be advanced co-axially in a telescoping fashion to aid in the extraction process. In many cases, applying considerable countertraction and torque to the sheath is necessary to separate the lead from fibrous adhesions. To minimize the risk

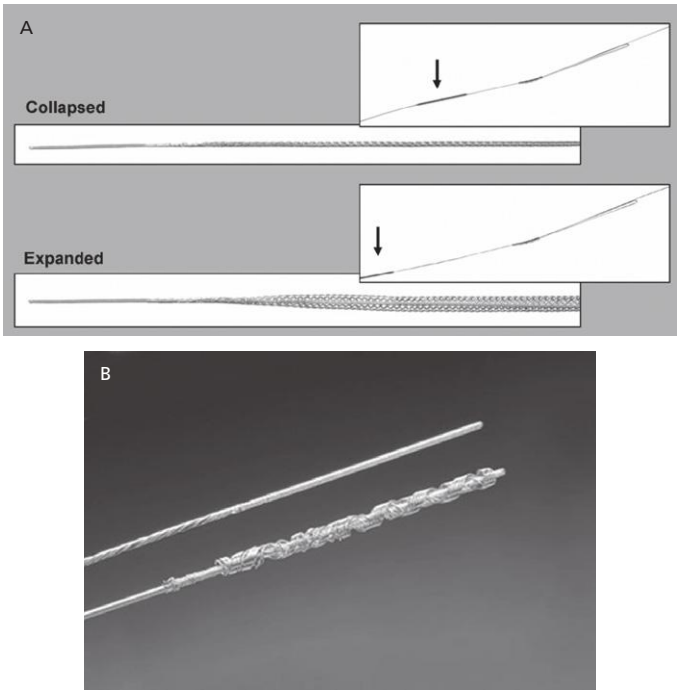


Figure 5.27 Locking stylets for lead extraction. (A) The Spectranetics LLD locking stylet (Spectranetics, Colorado Springs, CO, USA) has an expandable mesh over the stylet body that binds the lumen of the lead along its length. Top: With the mesh retracted, the entire length of the stylet is isodiametric with the stylet tip for insertion into the lead. Bottom: Once inside the lead to be extracted, the operator slides the locking mechanism (arrow) forward, expanding the mesh, which provides a broad distribution of force along the lead when traction is applied. (B) The Cook stylet (Cook Vascular) has a small wire mesh wound at the tip that unravels and binds at the distal end of the lead lumen.

of perforation by the stiff sheaths, fluoroscopic monitoring must be used to ensure that the proper co-axial alignment of the dilator sheath and the lead is maintained. Traction upon the lead via the locking stylet (usually maintained by the assistant) facilitates the processes. Correct positioning of the sheath provides a mechanism for countertraction to be applied to the lead tip to facilitate extraction. By advancing the outer sheath to the lead tip at the endocardial surface, the sheath applies countertraction to pin the myocardium in place and allows traction on the lead without invaginating or tearing the myocardium (Figure 5.30).

If the leads are removed successfully, a new pacing system may be implanted at the same site (if circumstances permit and infection is absent) by using a guidewire inserted through the extraction sheath to facilitate venous entry. Care should be taken to avoid air embolus as the wire is passed through the large empty extraction sheath. This technique allows access through even chronically occluded veins.

The process of lead extraction with the use of early-generation unpowered tools is labor intensive and time consuming: complete removal of a lead was achieved in 81–87% of cases and inability to remove the lead was encountered in 6–7% of cases. The evolution of technology and introduction of the excimer laser sheath have greatly facilitated lead extraction by the superior approach (Figure 5.30). The latter device has optical fibers arrayed circumferentially in the lining of the sheath, which is attached to the excimer laser generator (Spectranetics, Colorado Springs, CO, USA). Laser energy ablates the fibrous adhesions as the sheath

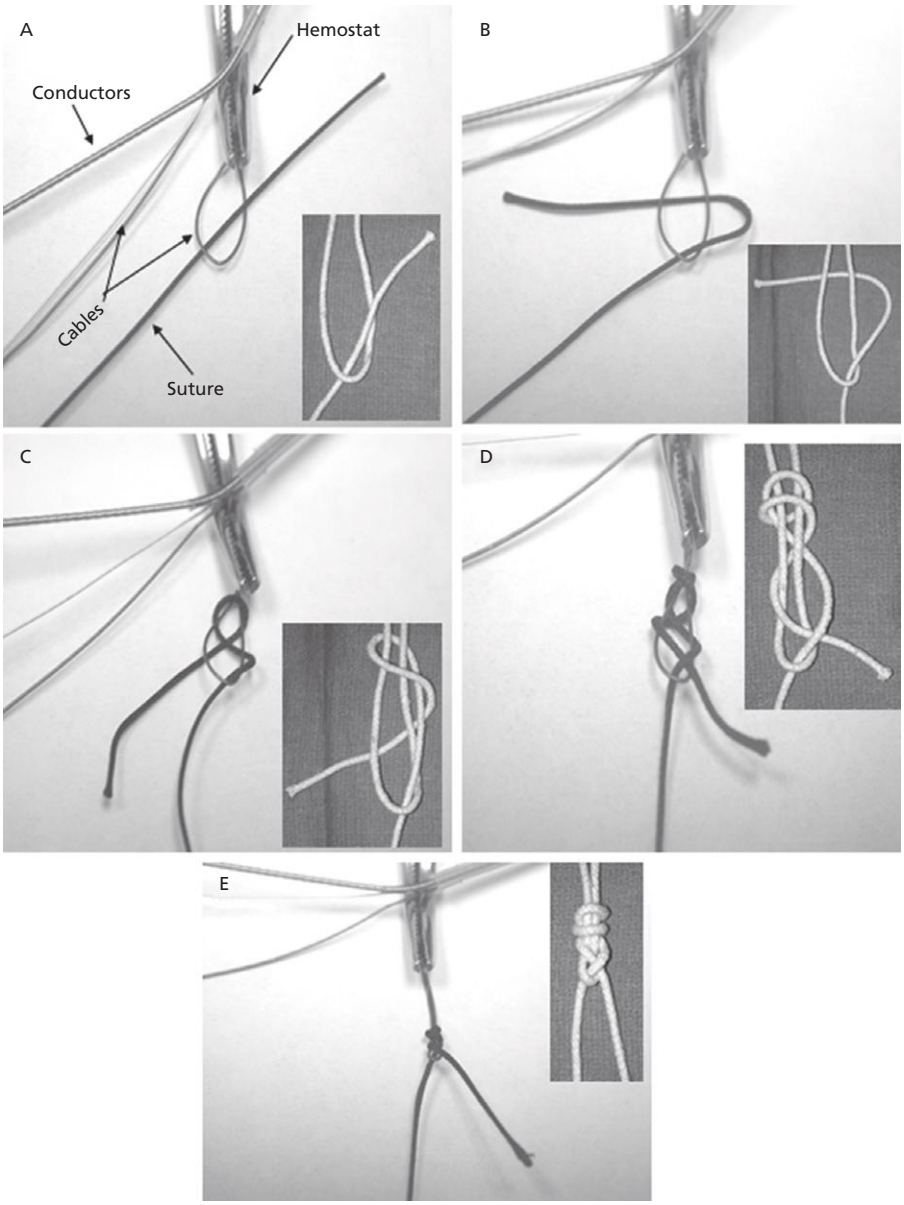


Figure 5.28 Tying to the "cables" of defibrillator leads. A modified sheet bend is used. (A) A loop is formed with the exposed end of the cable and held in place with a small hemostat. A 0-silk suture is passed through the loop from below. (B) The silk tie is passed behind the loop of cable. (C) The silk is passed in front of the loop of cable and then behind again 2–3 times, wrapping around the neck of the loop. (D) The end of the silk is passed under itself but over the loop of cable. (E) The ends of the silk are pulled to complete the knot. The long end of the silk tie is tied to the end of the locking stylet to provide traction on the cable.

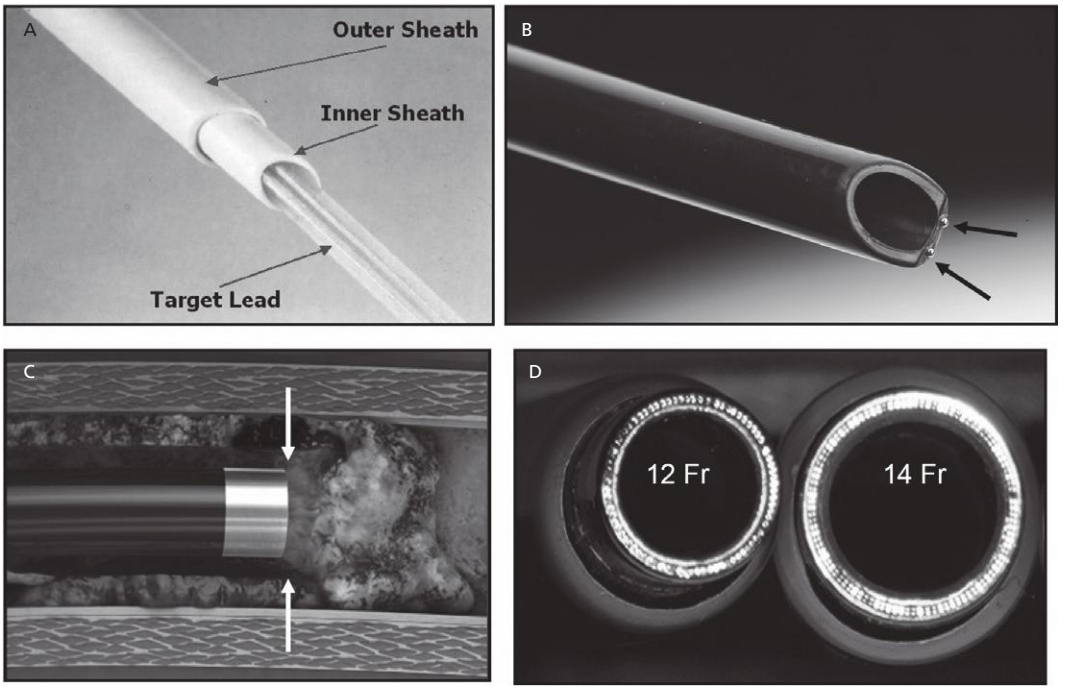


Figure 5.29 Different types of sheath used in lead extraction. (A) Simple telescoping sheaths over a lead. The outer sheath provides support as the inner sheath (with beveled edge) is gradually advanced over the lead to separate it from fibrous vascular adhesions by blunt dissection. (B) The Electrosurgical Dissection System (EDS, Cook Medical) utilizes an inner sheath with bipolar electrocautery/radiofrequency energy delivered between two poles on the tip of the sheath. Ablative energy is limited to approximately one-quarter of the circumference of the sheath. (C) The laser-assisted sheath (Spectranetics) consists of a series of parallel fiberoptic cables wound around a flexible inner sheath and terminating at the tip of the sheath (arrows). (D) When activated, the tip of the sheath emits pulses of high-energy ultraviolet light along the entire circumference of the sheath, vaporizing fibrous adhesions in direct contact with the tip.

is advanced (Figure 5.29). Complete removal of leads using this approach may be anticipated in over 90% of patients and partial removal in another 3%.[52,53] An electrosurgical cutting sheath is also available for lead extraction. This device is less expensive, but may not be as effective in the more difficult cases, as is the laser, although there are no adequate comparison trials.[56] Although they have improved efficacy, neither of these adjunct energy devices has demonstrably increased the safety of lead extraction.

An additional extraction tool that has recently been introduced is a mechanical dilator sheath which uses a rotational mechanism with a steel-bladed tip designed to cut through fibrotic adhesions (Evolution, Cook Medical). This system was successful in lead removal in 86% of 25 patients in a small early series.[57] While randomized trials comparing this device with other extraction tools are not available, it appears to have particular utility in separating the lead from highly calcified vascular adhesions and for gaining vascular access when there is extensive calcification under the clavicle.

Femoral approach

On occasion, a lead cannot be removed from its original venous access site using the techniques described above due to an inadequate lead remnant in the pocket or inability to pass a locking stylet. In these cases the femoral venous approach is often successful.[58] With this method, a large (16 Fr) sheath with a hemostatic valve is used as a "work-station" through which any of a number of devices

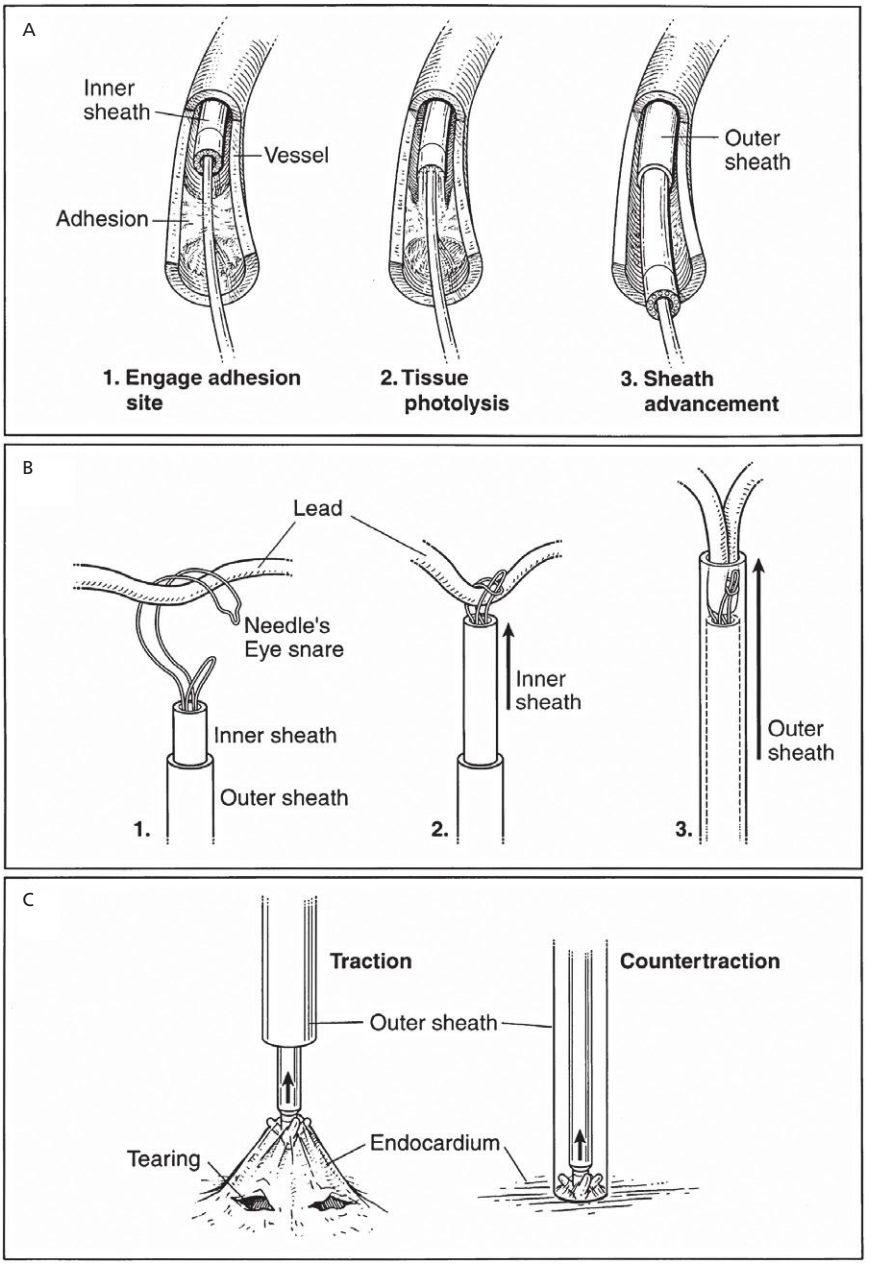


Figure 5.30 Basic techniques of lead extraction. (A) Lead extraction from the superior approach using the Spectranetics laser sheath apparatus. As the telescoping sheath apparatus encounters fibrous adhesions, the inner end-firing laser sheath is used to lyse the fibrosis. The larger outer sheath may then be advanced to apply countertraction at the lead tip. (B) Lead extraction from the femoral approach using the Cook Intravascular Needle's Eye Snare apparatus. The snare is deployed from telescoping sheaths in the femoral vein. The lead is entrapped in the snare and then secured against the inner sheath. The larger outer sheath may then be advanced to apply countertraction at the lead tip. (C) The concept of countertraction is illustrated. When unmodified traction is applied to the lead, the heart wall may invaginate and tear the myocardium around the lead tip. Using countertraction, the outer sheath holds the myocardium in place, thus minimizing deformity and tearing of the myocardium.

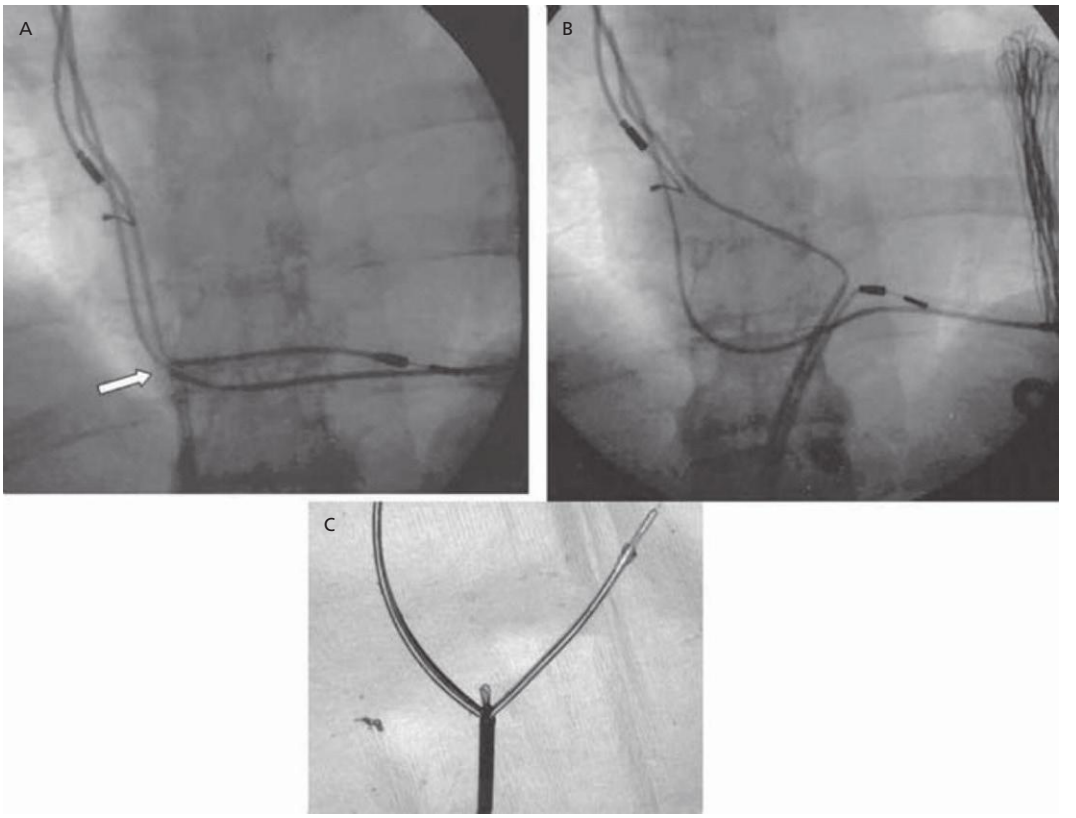


Figure 5.31 Fluoroscopic images of ventricular lead extraction by the femoral approach. (A) The ventricular lead has been captured with the Needle's Eye Snare apparatus at the point of the arrow and the redundancy of the lead retracted into the low atrium. (B) With traction, the lead tip is dislodged from the ventricle and the folded lead body is withdrawn into the large outer sheath. (C) The completely extracted lead.

designed to grasp the lead body may be introduced. These devices may include smaller sheaths, a Dotter retrieval basket, a tip-deflecting guidewire, a "needle's eye" device (Cook Vascular, Leechburg, PA, USA), or a variety of other catheters, snares, and bioptomes (Figure 5.31). With the femoral technique, one must grasp the lead body, which can be done with a single device (the Needle's Eye Snare) or with two devices such as a tip-deflecting wire and an Amplatz gooseneck snare. The needle's eye device is contained in a 12-Fr sheath. There are two independently moving mechanisms that can be advanced from the sheath: a hook-shaped wire loop (needle's eye) and a narrower "threader," which is designed to pass within the hook of the needle's eye. The goal is to place the device so that the lead body is trapped between the needle's eye and threader. This is usually accomplished by first placing the sheath in the low right atrium with the devices retained inside. The needle's eye is advanced out of the sheath and rotated so that it "hooks" around the lead body. The threader is then advanced so that it passes through the distal portion of the needle's eye so that the lead is between the devices (Figure 5.31).

The sheath is then advanced over the ensemble, fixing the captured lead. Once this is accomplished the proximal lead is cut near its original insertion site and traction applied by the sheath pulling the proximal lead into the heart. The captured lead may be prolapsed into the workstation, which can be used as a countertraction device as it is advanced over the distal lead; however, this may not be feasible with many larger leads. In the latter instance,

just withdrawing the proximal free end of the lead into the heart or IVC and then disengaging the needle's eye will allow it to be captured by a gooseneck snare and more easily removed through the workstation. The workstation may be advanced over the lead into the ventricle to supply countertraction if necessary.

The needle's eye technique has been found to be safe and effective, with a complete extraction success rate of 87% in a population that included patients who had failed prior extraction with the superior approach.[59] A similar procedure may be performed with a deflecting wire and snare. In this situation both the wire and snare are situated in the right atrium through the workstation. A "J" curve is placed on the deflector wire, which is used to "catch" the lead body. The snare is then advanced to tightly grasp the tip of the deflecting wire. This effectively forms a loop around the lead body, which can act to retract the lead after the proximal portion is cut from the original access site. Once captured, the lead can be removed as described previously for the needle's eye device.

Although it is always best to withdraw the lead through the workstation, there are times when this cannot be done and the workstation has to be removed with the lead inside. If multiple leads must be removed, we sometimes leave a second long wire in the femoral vein at the time of original access. This allows us to re-enter the same entry site with a second workstation if it is necessary to remove the first. Once all of the leads are out, it is safe to remove the workstation and apply manual pressure to the femoral access site for hemostasis.

The femoral workstation technique appears to be safe and quite successful. It avoids having to free up adhesions in the central veins because the proximal lead is usually more easily pulled through fibrous vascular attachments from below. On occasion, the proximal lead appears trapped within the subclavian vein and will not yield to femoral traction. In these cases the laser sheath can be very helpful in freeing up the proximal lead, allowing it to be extracted through the femoral workstation. The workstation has a large lumen and blood coagulates easily within it. A large thrombus may form and be pushed into the circulation during the manipulation of devices through the sheath. We routinely attach a pressurized continuous flush to the sidearm of the device to help prevent such thrombus formation.

Variations on the femoral approach include a hybrid procedure, in which the femoral workstation is used as described above to pull the proximal lead into the heart. At this point a snare introduced from the internal jugular vein is used to catch the free end of the lead and pull it out using countertraction from a long sheath placed in the internal jugular. The entire procedure might be performed using an internal jugular vein approach, which has been favored by some since the direction of force exerted during countertraction is parallel to the course of the lead.

The utility, safety, and efficacy of the femoral approach versus the superior approach using a laser sheath were compared in a multicenter study involving 459 patients.[60] In this study, rates of successful extraction and complications were similar between the two groups, while the femoral approach was associated with longer procedure and fluoroscopy times. Unless the lead to be removed has already retracted into the venous system, we start all lead removal cases from the original site of insertion and resort to the femoral approach if the situation demands.

Accufix wire fragment retrieval

As noted previously, fracture of the "J" retention wire in the Accufix family of atrial leads may produce protrusion of a wire fragment (Figure 5.32), which has the potential to lacerate the heart and other mediastinal structures. It may be possible to selectively retrieve the protruding fragment if it is the distal portion of the proximal part of the wire. This is achieved using an Amplatz gooseneck snare passed through an 8-Fr coronary guide catheter of a shape matching the specifics of the case. Since the proximal portion of the retention wire lies free under the outer insulation of the lead, traction on its protruding end results in the fragment's removal from the lead into the guide catheter without disrupting the lead itself. Detection of a protruding fragment (a so-called class III fracture) by screening fluoroscopy should prompt consideration of this form of therapy as an alternative to lead extraction. If the fragment cannot be selectively removed, complete extraction of the lead with the protruding fragment should be performed

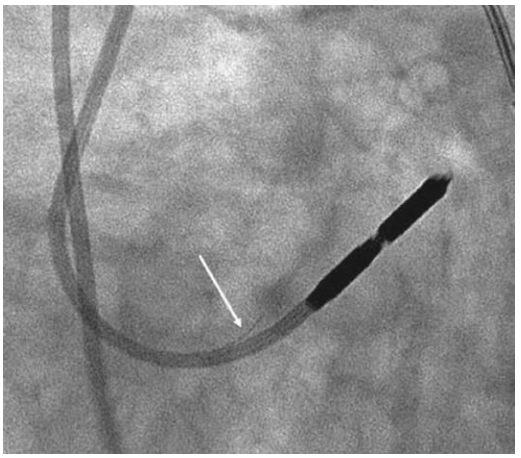


Figure 5.32 Ciné-fluoroscopy of the Telectronics Pacing Systems model 330–801 Accufix atrial J lead. This right anterior oblique projection shows the protruding segment of the retention wire fragment (arrow).

carefully, since the protruding fragment might lacerate the vasculature during extraction. When possible, one should try to protect the fragment by easing a larger sheath over the lead to encompass it.

Extraction of coronary venous leads

With the increased use of biventricular pacing, there has been some concern that removal of chronically implanted leads from the coronary venous system will be associated with high complication rates because of the risk of disruption of the thin-walled coronary veins. Although there is limited experience thus far, removal of these devices has not been associated with complications. These series, however, include only a small number of leads with long implant duration.[61,62] With chronic CS leads, the excimer laser sheath may be used with the countertraction technique to free the lead from adhesions up to the os of the CS. Safe use of extraction sheaths within the CS has not been well-demonstrated. Fortunately, in series reported to date, fibrous adhesions of these leads have generally been seen outside of the CS.

The largest series of CS lead extractions reported to date included 125 CS lead removals in 115 patients with a mean implant duration of 1.5 years and a range of 8 days to 8.2 years.[62] Ninety-one percent of leads were removed with simple traction, including 97% of leads implanted within 1 year. Three patients (2.4%) required use of a snare, two (1.6%) required a locking stylet alone, and six (4.8%) required a locking stylet and laser sheath. One of these six cases required laser application within the body of the CS, which was performed without complication. Ninety-nine percent of leads (124 of 125) were successfully removed. Eleven patients (8.8%) had a CS stenosis or dissection from the extraction or re-implantation procedure, while non-CS complications were low and similar to those in other reported series. One patient died due to RV perforation during extraction of an ICD lead. Removal of the Starfix® active fixation coronary venous lead may be difficult if the fixation lobes cannot be retracted. In these cases, extreme care must be used since there is considerable risk of tearing a coronary vein.

Thoracotomy for lead extraction

There has been a natural reticence even among surgeons to remove leads at thoracotomy. While there are no randomized data comparing the two percutaneous techniques, the Accufix experience suggests no clinically significant difference in the incidence of death or major complications. This is not surprising considering the advanced age and co-morbidity of many pacemaker patients. Surgery may be the only alternative in situations in which percutaneous techniques have failed and there is an absolute indication for lead removal, or if infected epicardial leads are a component of the system. Since most transvenous extraction series demonstrate a 5–10% rate of failure to remove all lead material completely, a significant role for surgical lead extraction remains. Primary thoracotomy should also be considered when there is a large lead vegetation ($>$2.5 cm) and perhaps when there is a vegetation and a right-to-left intracardiac shunt. Close collaboration between physicians who perform extractions and cardiothoracic surgeons who can perform surgical extraction and assist with management of complications of transvenous extraction is a vital component of a lead extraction program.

Lead abandonment

The alternative to extraction is lead abandonment and (usually) insertion of a new lead. This is not an

option in cases of infection, where failure to remove all hardware results in an unacceptable risk of re-infection despite vigorous treatment with antibiotics. One may abandon the lead by detaching it from the generator and applying an insulating cap to the connector pin. The lead may then be placed under the generator or elsewhere in the pocket, reserving the option for future use in some situations as well as lead extraction should that prove necessary (e.g. the occurrence of infection). Some operators prefer to cut some silicone pacing leads and electrically isolate them by pulling the silicone insulation over the exposed end and tying a ligature tightly around the insulation cuff. The lead is then sutured to the underlying tissue to prevent its retraction into the vascular space. Enough lead is left in the pocket to allow for future extraction if that proves necessary. Active fixation leads should generally not be cut, because this precludes retraction of the helix of the lead if extraction should ever be needed.

Medicolegal aspects of implantation

As with many invasive procedures, the patient's expectations for pacemaker therapy may exceed the results obtained. As noted above, there is ample opportunity for even the most skilled and experienced operator to encounter a misadventure. The risk of litigation is real and may focus on any of several areas of physician responsibility (Table 5.14). Avoiding litigation requires not only that the highest of standards be maintained, but also that a rapport be established with the patient and the patient's family.

The best defense against successful litigation is full documentation in the patient's medical record of every aspect of the implantation (or extraction) process. This should include the indication for the procedure, the informed consent, a complete procedure note to include the pacing parameters achieved and any difficulties encountered, evidence of post-procedure evaluation, and arrangements for follow-up care. The removal of pre-existing hardware and its disposition (e.g. returned to manufacturer for evaluation) should also be documented.

Pacemaker implantation implies a great deal of physician responsibility. As with any implantable device, there is continued risk to the patient as long as he/she has the device. Somewhat unique to implantable antiarrhythmic devices is the knowledge that the power source has limited life and will eventually need to be replaced. The HRS, ACC, and AHA have provided a service to physicians and the public by creating guidelines to assist in patient treatment.[1–5,45]

Table 5.14 Responsibilities of an implanting physician

1	Establish and document accepted indications
2	Obtain fully informed consent
3	Implant an indicated system
4	Avoid undue delay
5	Conform to accepted technique and standards
6	Obtain expert consultation when appropriate
7	Provide for follow-up care

References

1 Naccarelli GV, Conti JB, DiMarco JP, Tracy CM. Task Force 6. Training in specialized electrophysiology, cardiac pacing, and arrhythmia management: Endorsed by the Heart Rhythm Society. *J Am Coll Cardiol* 2008; 51: 374–380.

2 Epstein AE, DiMarco JP, Ellenbogen KA, *et al.* ACC/AHA/HRS 2008 guidelines for device-based therapy of cardiac rhythm abnormalities. A report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Writing Committee to revise the ACC/AHA/NASPE 2002 guideline update for implantation of cardiac pacemakers and antiarrhythmic devices. Developed in collaboration with the American Association for Thoracic Surgery and Society of Thoracic Surgeons. *J Am Coll Cardiol* 2008; 51: e1–62.

3 Gillis AM, Russo AM, Ellenbogen KA, *et al.* HRS/ACCF expert consensus statement on pacemaker device and mode selection. *Heart Rhythm* 2012; 9: 1344–1365.

4 Tracy CM, Epstein AE, Darbar D, *et al.* 2012 ACCF/AHA/HRS focused update of the 2008 guidelines for device-based therapy of cardiac rhythm abnormalities: A report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines. *J Am Coll Cardiol* 2012; 60: 1297–1313.

5 Baddour LM, Epstein AE, Erickson CC, *et al.* Update on cardiovascular implantable electronic device infections

and their management: A scientific statement from the American Heart Association. *Circulation* 2010; 121: 458–477.

6 Goldfarb S, McCullough PA, McDermott J, Gay SB. Contrast-induced acute kidney injury: Specialty-specific protocols for interventional radiology, diagnostic computed tomography radiology, and interventional cardiology. *Mayo Clin Proc* 2009; 84: 170–179.

7 Giudici MC, Barold SS, Paul DL, Bontu P. Pacemaker and implantable cardioverter defibrillator implantation without reversal of warfarin therapy. *Pacing Clin Electrophysiol* 2004; 27: 358–360.

8 Cheng A, Nazarian S, Brinker JA, *et al*. Continuation of warfarin during pacemaker or implantable cardioverter–defibrillator implantation: a randomized clinical trial. *Heart Rhythm* 2011; 8: 536–540.

9 Ghanbari H, Phard WS, Al-Ameri H, *et al*. Meta-analysis of safety and efficacy of uninterrupted warfarin compared to heparin-based bridging therapy during implantation of cardiac rhythm devices. *Am J Cardiol* 2012; 110: 1482–1488.

10 Tompkins C, Cheng A, Dalal D, *et al*. Dual antiplatelet therapy and heparin "bridging" significantly increase the risk of bleeding complications after pacemaker or implantable cardioverter-defibrillator device implantation. *J Am Coll Cardiol* 2010; 55: 2376–2382.

11 McCotter CJ, Angle JF, Prudente LA, *et al*. Placement of transvenous pacemaker and ICD leads across total chronic occlusions. *Pacing Clin Electrophysiol* 2005; 28: 921–925.

12 Eleid MF, Blauwet LA, Cha Y-M, *et al*. Bioprosthetic tricuspid valve regurgitation associated with pacemaker or defibrillator lead implantation. *J Am Coll Cardiol* 2012; 59: 813–818.

13 Osman F, Krishnamoorthy S, Nadir A, *et al*. Safety and cost-effectiveness of same day permanent pacemaker implantation. *Am J Cardiol* 2010; 106: 383–385.

14 DaCosta A, Kirkorian G, Cucherat M, *et al*. Antibiotic prophylaxis for permanent pacemaker implantation: a meta-analysis. *Circulation* 1998; 97: 1796–1801.

15 De Oliveira JC, Martinelli M, Nishioka SA, *et al*. Efficacy of antibiotic prophylaxis before the implantation of pacemakers and cardioverter-defibrillators: Results of a large, prospective, randomized, double-blind, placebo-controlled trial. *Circ Arrhythm Electrophysiol* 2009; 2: 29–34.

16 Biffi F, Bertini M, Ziacchi M, *et al*. Clinical implications of left superior vena cava persistence in candidates for pacemaker or cardioverter-defibrillator implantation. *Heart Vessels* 2009; 24: 142–146.

17 Calkins H, Ramza BM, Brinker J, *et al*. Prospective randomized comparison of the safety and effectiveness of placement of endocardial pacemaker and defibrillator leads using the extrathoracic subclavian vein guided by contrast venography versus the cephalic approach. *Pacing Clin Electrophysiol* 2001; 24: 456–464.

18 Kistler PM, Eizenberg N, Fynn SP, Mond HG. The subpectoral pacemaker implant: it isn't what it seems! *Pacing Clin Electrophysiol* 2004; 27: 361–364.

19 Brinker JA. Endocardial pacing leads: the good, the bad, and the ugly. *Pacing Clin Electrophysiol* 1995; 18: 953–954.

20 Hauser RG, Hayes DL, Kallinen LM, *et al*. Clinical experience with pacemaker pulse generators and transvenous leads: an 8-year prospective multicenter study. *Heart Rhythm* 2007; 4: 154–160.

21 Giudici MC, Thornburg GA, Buck DL, *et al*. Comparison of right ventricular outflow tract and apical lead permanent pacing on cardiac output. *Am J Cardiol* 1997; 79: 209–212.

22 Stambler BS, Ellenbogen K, Zhang X, *et al*. Right ventricular outflow versus apical pacing in pacemaker patients with congestive heart failure and atrial fibrillation. *J Cardiovasc Electrophysiol* 2003; 14: 1180–1186.

23 Saxenhouse SJ, Conti JB, Curtis AB. Current of injury predicts adequate active fixation in permanent pacemaker/defibrillation leads. *J Am Coll Cardiol* 2005; 45: 412–417.

24 Bilchick KC, Judge DP, Calkins H, Marine JE. Use of a coronary sinus lead and biventricular ICD to correct a sensing abnormality in a patient with arrhythmogenic right ventricular dysplasia/cardiomyopathy. *J Cardiovasc Electrophysiol* 2006; 17: 317–320.

25 Ector B, Willems R, Heidbuchel H, *et al*. Epicardial pacing: a single-centre study on 321 leads in 138 patients. *Acta Cardiol* 2006; 61: 343–351.

26 Jutley RS, Waller DA, Loke I, *et al*. Video-assisted thoracoscopic implantation of the left ventricular pacing lead for cardiac resynchronization therapy. *Pacing Clin Electrophysiol* 2008; 31: 812–818.

27 Huang M, Krahn AD, Yee R, *et al*. Optimal pacing for symptomatic AV block: a comparison of VDD and DDD pacing. *Pacing Clin Electrophysiol* 2004; 27: 19–23.

28 Fisher JD, Lapman P, Kim SG, *et al*. Lead stuck (frozen) in header: Salvage by bone cutter versus other techniques. *Pacing Clin Electrophysiol* 2004; 27: 1136–1143.

29 Wilkoff BL, Cook JR, Epstein AE, *et al*. Dual-chamber pacing or ventricular backup pacing in patients with an implantable defibrillator: the Dual Chamber and VVI Implantable Defibrillator (DAVID) trial. *JAMA* 2002; 288: 3115–3123.

30 Link MS, Estes NA 3rd, Griffin JJ, *et al*. Complications of dual chamber pacemaker implantation in the elderly. Pacemaker Selection in the Elderly (PASE) Investigators. *J Interv Card Electrophysiol* 1998; 2: 175–179.

31 Tobin K, Stewart J, Westveer D, Frumin H. Acute complications of permanent pacemaker implantation: their financial implications and relation to volume and operator experience. *Am J Cardiol* 2000; 85: 774–777.

32 Harcombe AA, Newell SA, Ludman PF, *et al*. Late complications following permanent pacemaker implantation or elective unit replacement. *Heart* 1998; 80: 240–244.

33 Wiegand UK, Bode F, Bonnemeier H, *et al*. Atrial lead placement during atrial fibrillation. Is restitution of sinus rhythm required for proper lead function? Feasibility and 12-month functional analysis. *Pacing Clin Electrophysiol* 2000; 23: 1144–1149.

34 Ellenbogen KA, Wood MA, Shepard RK. Delayed complications following pacemaker implantation. *Pacing Clin Electrophysiol* 2002; 25: 1155–1158.

35 Nanthakumar K, Kay GN, Plumb VJ, *et al*. Decrease in fluoroscopic cardiac silhouette excursion precedes hemodynamic compromise in intraprocedureal tamponade. *Heart Rhythm* 2005; 2: 1224–1230.

36 Henrikson CA, Leng CT, Yuh DD, Brinker JA. Computed tomography to assess possible cardiac lead perforation. *Pacing Clin Electrophysiol* 2006; 29: 509–511.

37 Van Gelder BM, Bracke FA, Oto A, *et al*. Diagnosis and management of inadvertently placed pacing and ICD leads in the left ventricle: a multicenter experience and review of the literature. *Pacing Clin Electrophysiol* 2000; 23: 877–883.

38 Lin G, Nishimura RA, Connolly HM, *et al*. Severe symptomatic tricuspid valve regurgitation due to permanent pacemaker or implantable cardioverter-defibrillator leads. *J Am Coll Cardiol* 2005; 45: 1672–1675.

39 Rozmus G, Daubert JP, Huang DT, Rosero S, Hall B, Francis C. Venous thrombosis and stenosis after implantation of pacemakers and defibrillators. *J Interv Card Electrophysiol* 2005; 13: 9–19.

40 Maisel WH, Moynahan M, Zuckerman BD, *et al*. Pacemaker and ICD generator malfunctions: analysis of Food and Drug Administration annual reports. *JAMA* 2006; 295: 1901–1906.

41 Poller WC, Schwerg M, Melzer C. Therapy of cardiac device pocket infections with vacuum-assisted wound closure—Long-term follow-up. *Pacing Clin Electrophysiol* 2012; 35: 1217–1221.

42 Tarakji KG, Chan EJ, Cantillon DJ, *et al*. Cardiac implantable electronic device infections: presentation, management, and patient outcomes. *Heart Rhythm* 2010; 7: 1043–1047.

43 Henrikson CA, Brinker JA. How to prevent, recognize, and manage complications of lead extraction. Part III: Procedural factors. *Heart Rhythm* 2008; 5: 1352–1354.

44 van Rees JB, de Bie MK, Thijssen J, *et al*. Implantation-related complications of implantable cardioverter-defibrillators and cardiac resynchronization therapy devices: a systematic review of randomized clinical trials. *J Am Coll Cardiol* 2011; 58: 995–1000.

45 Wilkoff BL, Love CJ, Byrd CL, *et al*. Transvenous lead extraction: Heart Rhythm Society expert consensus on facilities, training, indications, and patient management. *Heart Rhythm* 2009; 6: 1085–1104.

46 Smith MC, Love CJ. Extraction of transvenous pacing and ICD leads. *Pacing Clin Electrophysiol* 2008; 31: 736–752.

47 Roux J-F, Page P, Dubuc M, *et al*. Laser lead extraction: predictors of success and complications. *Pacing Clin Electrophysiol* 2007; 30: 214–220.

48 Chua JD, Wilkoff BL, Lee I, *et al*. Diagnosis and management of infections involving implantable electrophysiologic cardiac devices. *Ann Intern Med* 2000; 133: 604–608.

49 Maytin M, Epstein LM. Lead extraction is preferred for lead revisions and system upgrades: When less is more. *Circ Arrhythm Electrophysiol* 2010; 3: 413–424.

50 Henrikson CA. Think before you pull—not every lead has to come out. *Circ Arrhythm Electrophysiol* 2010; 3: 409–412.

51 Kay GN, Brinker JA, Kawanishi DT, *et al*. Risks of spontaneous injury and extraction of an active fixation pacemaker lead: report of the Accufix multicenter clinical study and worldwide registry. *Circulation* 1999; 100: 2344–2352.

52 Byrd CL, Willkoff BL, Love CJ, Sellers TD, Reiser C. Clinical study of the laser sheath for lead extraction: the total experience in the United States. *Pacing Clin Electrophysiol* 2002; 25: 804–808.

53 Lead extraction in the contemporary setting: The LExICon study: An observational retrospective study of consecutive laser lead extractions. *J Am Coll Cardiol* 2010; 55: 579–586.

54 Henrikson CA, Zhang K, Brinker JA. High mid-term mortality following successful lead extraction for infection. *Pacing Clin Electrophysiol* 2011; 34: 32–36.

55 Wood M, Ellenbogen K. Defining the appropriate venue for lead extraction: A place for everything. *Heart Rhythm* 2011; 8: 1006–1007.

56 Verma A, Wilkoff BL. Intravascular pacemaker and defibrillator lead extraction: a state-of-the-art review. *Heart Rhythm* 2004; 1: 739–745.

57 Hussein AA, Wilkoff BL, Martin DO, *et al*. Initial experience with the Evolution mechanical dilator sheath for lead extraction: Safety and efficacy. *Heart Rhythm* 2010; 7: 870–873.

58 Bellott PH. Lead extraction using the femoral vein. *Heart Rhythm* 2007; 4: 1102–1107.

59 Klug D, Jarwe M, Messaoudene SA, *et al*. Pacemaker lead extraction with the needle's eye snare for countertraction

via the femoral approach. *Pacing Clin Electrophysiol* 2002; 25: 1023–1028.

60 Bordachar P, Defaye P, Peyrouse E, *et al*. Extraction of old pacemaker or cardioverter-defibrillator leads by laser sheath versus femoral approach. *Circ Arrhythm Electrophysiol* 2010; 3: 319–323.

61 Williams SE, Arujuna A, Whitaker J, *et al*. Percutaneous lead and system extraction in patients with cardiac resynchronization therapy (CRT) devices and coronary sinus leads. *Pacing Clin Electrophysiol* 2011; 34: 12091216.

62 Sheldon S, Friedman PA, Hayes DL, *et al*. Outcomes and predictors of difficulty with coronary sinus lead removal. *J Interv Card Electrophysiol* 2012; 35: 93–100.

6

CHAPTER 6

Pacemaker timing cycles and special features

Jose F. Huizar
Medical College of Virginia/VCU School of Medicine, Richmond, VA, USA

Introduction

Since the development of implantable cardiac pacemakers in 1960, the features and functions built into these devices has continued to change as the cardiac field evolves. Pacemakers have become highly complex due to the addition of multiple specialized features in an attempt to treat different cardiac conditions, such as sick sinus syndrome with or without chronotropic incompetence, cardioinhibitory vasovagal syndrome, and paroxysmal atrial arrhythmias, and avoid some adverse effects of chronic pacing, such as heart failure, induction of atrial and supraventricular arrhythmias, etc. Thus, a deep understanding of the different pacing modes, pacemaker timing cycles, and special features is paramount to identify normal versus abnormal pacemaker function.

Timing cycles are based on cardiac events such as atrial- and ventricular-sensed and -paced events. Thus, appropriate pacemaker function depends on the ability of these devices to properly recognize atrial- and ventricular-sensed events. Timing cycles include different blanking periods, refractory periods, and intervals. The number and complexity of these timing cycles depend and vary based on the number of leads, pacing mode, and/or rate sensor. Accurate examination of timing cycles and pacemaker behavior requires device interrogation and analysis of *"event markers"* as they provide the actual pacemaker interpretation and response to different cardiac signals. For the rest of the chapter, the following abbreviations will be used to describe common pacemaker marker events: "P" native atrial depolarization, "A" an atrial-paced event, "R" a native ventricular depolarization, and "V" a ventricular-paced event.

Pacing nomenclature

A three-letter code describing the basic function of the various pacing systems was first proposed in 1974 by a combined task force from the American Heart Association and the American College of Cardiology. As pacemakers have become more complex with multiple features, the basic function of pacemakers is now denoted as a generic five-letter code (Table 6.1).[1] However, this five-letter code does not describe the specific or unique functional characteristics of each device.

The *first position* reflects the chamber or chambers in which stimulation occurs. "A" refers to the atrium, "V" indicates the ventricle, and "D" denotes dual chamber (or both atrium and ventricle).

The *second position* refers to the chamber or chambers in which sensing occurs. The letter

Cardiac Pacing and ICDs, Sixth Edition. Edited by Kenneth A. Ellenbogen and Karoly Kaszala.
© 2014 John Wiley & Sons, Ltd. Published 2014 by John Wiley & Sons, Ltd.

Table 6.1 Revised NASPE/BPEG generic code for bradycardia, adaptive-rate, and multisite pacing (Source: Modified from Bernstein 2002.[1] Reproduced with permission of John Wiley & Sons Ltd.)

Position				
I *Chamber(s) paced*	*II* *Chamber(s) sensed*	*III* *Response to sensing*	*IV* *Rate modulation*	*V* *Multisite pacing*
O = None A = Atrium V = Ventricle D = Dual (A + V)	O = None A = Atrium V = Ventricle D = Dual (A + V)	O = None T = Triggered I = Inhibited D = Dual (T + I)	O = None R = Rate modulation	O = None A = Atrium V = Ventricle D = Dual (A+V)

BPEG, British Pacing and Electrophysiology Group; NASPE, North American Society of Pacing and Electrophysiology.

designators are the same as those for the first position. Some manufacturers also use "S" in both the first and the second positions to indicate that the device is capable of pacing only a single cardiac chamber.

The *third position* refers to the mode of sensing, or how the pacemaker responds to a sensed event. An "I" indicates that a sensed event inhibits the pacing stimulus and causes the pacemaker to reset or re-initiate one or more timing cycles. A "T" means that an output pulse is triggered in response to a sensed event. Similar to the first two positions, a "D", means that there are dual modes of response. This designation is restricted to dual chamber systems. An event sensed in the atrium inhibits atrial output but triggers ventricular output, also referred to as P-synchronous pacing. Unlike the single chamber triggered mode, in which a pacing output is triggered immediately on sensing, a delay occurs between the sensed atrial event and the triggered ventricular pacing output to mimic the normal PR interval. Finally, if a native ventricular signal or R wave is sensed, it inhibits ventricular output and possibly even atrial output, depending on where sensing occurs.

The *fourth position* of the code reflects sensor rate modulation. An "R" indicates that the pacemaker incorporates a sensor to control the rate independently of intrinsic electrical activity of the heart, so-called rate-modulated pacing.

The *fifth position* indicates whether multisite pacing is not present (O) or present in the atrium (A), ventricle (V), or both (D). Multisite pacing is defined for this purpose as stimulation sites in both atria, both ventricles, more than one stimulation site in any single chamber, or any combination of these. The letter designators are the same as those for the first position. This fifth position has become relevant with the introduction of biventricular devices.

Pacing modes

Pacing modes have evolved with technology and each pacing mode has specific and general indications, as well as unique advantages and disadvantages (Table 6.2). The timing cycles of each of these pacing modes are discussed in the following section.

Single or dual chamber asynchronous pacing (AOO, VOO, DOO)

Ventricular asynchronous (VOO) pacing is the simplest of all pacing modes because there is neither sensing nor mode of response, and lower rate limit (LRL) is the only timing cycle available (Figure 6.1A). Atrial asynchronous (AOO) pacing behaves exactly like VOO, but pacing occurs in the atrial chamber. Dual chamber or sequential atrioventricular (AV) asynchronous pacing (DOO) occurs at the LRL in the atrium, followed by the ventricle after completion of the atrioventricular interval (AVI), irrespective of any cardiac events. This pacing mode may be transiently used in pacemaker-dependent patients to avoid inappropriate pacing inhibition during interventions or surgeries associated with noise (Table 6.2).

Table 6.2 Indications, advantages, and disadvantages of commonly used pacing modes (Source: Modified from Huizar JF, Kaszala K, Ellenbogen KA. Cardiac pacing modes and terminology. In: Sakena S, Camm AJ, eds. *Electrophysiological Disorders of the Heart*, 2nd Ed. Philadelphia, PA: Elsevier Saunders, 2012: 441–456. Reproduced with permission of Elsevier.)

Pacing mode	*Indication/advantages*	*Disadvantages*
Asynchronous pacing (AOO, VOO, DOO)	Pacemaker-dependent patients exposed to noise (e.g. electrocautery during surgery) Avoids oversensing and asystole	Pacing regardless of intrinsic events Potential risk for arrhythmia induction
Single chamber inhibited pacing (AAI, VVI)	AAI—sick sinus syndrome with intact AV node; preserves AV synchrony VVI—atrial fibrillation with slow VR and single-lead ICDs AAI/VVI require a single lead and increase battery longevity	AAI lacks ventricular pacing in the event of intermittent AV block VVI is associated with AV dyssynchrony (manifests as pacemaker syndrome). VVI has a higher incidence of atrial arrhythmias[30]
Single chamber triggered without inhibited pacing (AAT, VVT)	Historically used in pacemaker-dependent patients to assure pacing with lower probability of arrhythmia induction	Shortens battery life due to chronic pacing
DDD, DDDRV (CRT)	Preserves AV synchrony (less pacemaker syndrome) Low incidence of atrial arrhythmias and improved hemodynamics	Requires at least a two chamber lead system and has a shorter battery longevity
DDI	Functions as two different pacemakers (AAI and VVI) Used as mode switch to avoid tracking atrial tachyarrhythmias	Same as DDD Possible AV dyssynchrony and pacemaker syndrome (does not track atrial sensed events)
VDI	Used for mode switch purposes as it functions as a VVI (non-tracking pacing mode) with additional atrial sensing	Similar to VVI, as it is associated with AV dyssynchrony and potential atrial arrhythmias
VDD	Appropriate sinus node function with AV node disease, e.g. MDT RV lead model 5038; dual chamber with high atrial pacing threshold to minimize battery depletion	Lack of atrial pacing Potential AV dyssynchrony at lower rate limit
DVI	Severe sinus bradycardia/standstill and atrial lead malfunction (oversensing)	Asynchronous atrial pacing Potential AV dyssynchrony For both atrial and ventricular stimuli to be inhibited, the sensed R wave must occur during the VAI

For acronyms, see Table 6.3.

Single chamber (atrial or ventricular) inhibited pacing (AAI, VVI)

Pacemakers with an atrial lead can be programmed AAI, whereas devices with a ventricular lead can be programmed VVI (Figure 6.1B,C). AAI pacing mode denotes atrial pacing (A), atrial sensing (A), and inhibition (I) of pacing output in response to an atrial-sensed event (P wave), whereas VVI pacing mode indicates ventricular pacing (V), ventricular sensing (V), and inhibition (I) of pacing output in response to a ventricular sensed event (R wave). Atrial (AAI) and ventricular inhibited (VVI) pacing modes incorporate sensing on the atrial or ventricular channel, whereas pacemaker stimuli are inhibited by a sensed atrial or ventricular event, respectively.

Single chamber triggered mode (without inhibition) pacing (AAT, VVT)

Single chamber triggered mode pacing (AAT, VVT) will deliver pacing output every time a native event is sensed or the LRL interval is reached. As

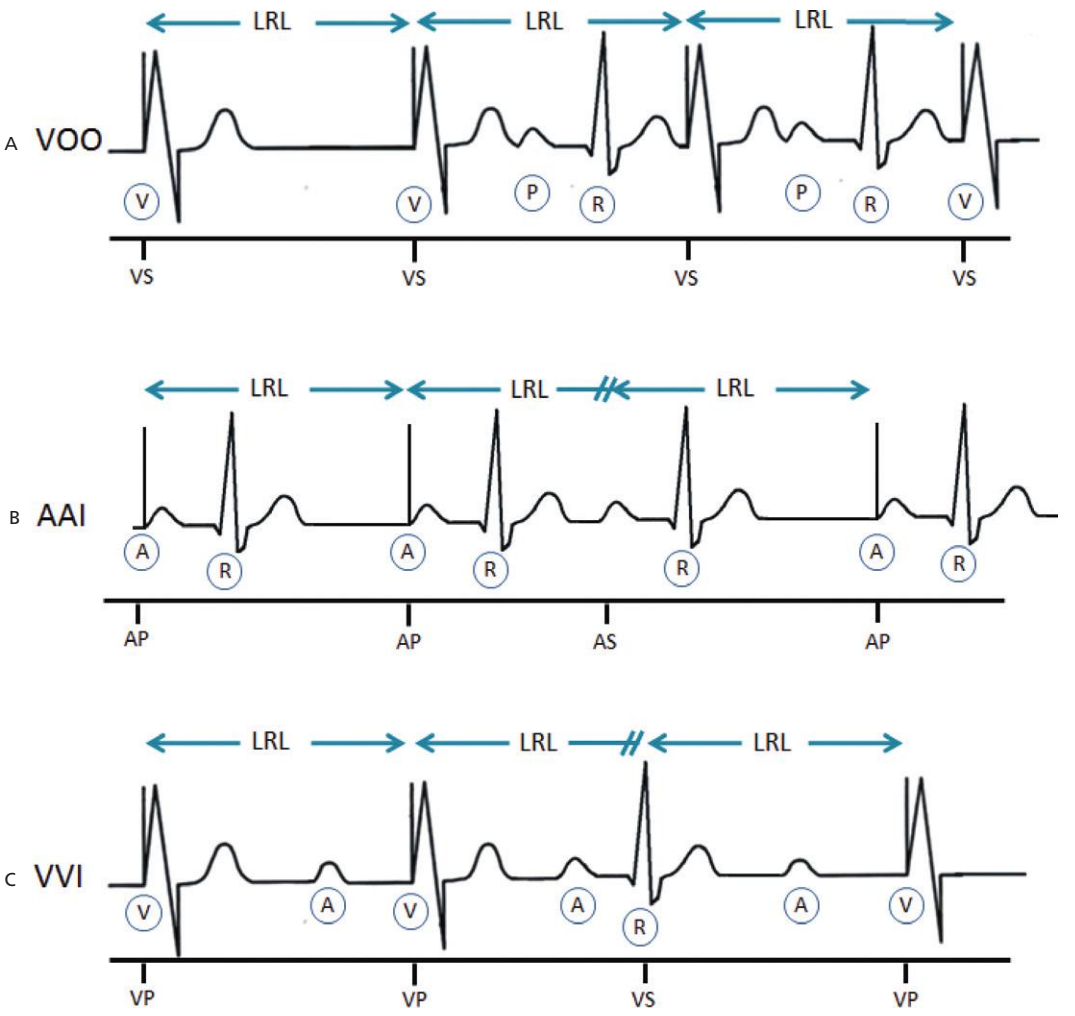


Figure 6.1 (A) VOO, (B) AAI, and (C) VVI pacing modes. "Event markers" represent the pacemaker's interpretation of different cardiac events. See text for details. A, atrial-paced event (AP); LRL, lower rate limit; P, intrinsic P wave (AS); R, intrinsic R wave (VS); V, ventricular-paced event (VP). (Source: Modified from Huizar JF, Kaszala K, Ellenbogen KA. Cardiac pacing modes and terminology. In: Sakena S, Camm AJ, eds. *Electrophysiological Disorders of the Heart*, 2nd Ed. Philadelphia, PA: Elsevier Saunders, 2012: 441–456. Reproduced with permission of Elsevier.)

it deforms the native signal, it may compromise electrocardiogram (ECG) interpretation. This pacing mode can serve as an excellent marker for the site and time of sensing within a complex in an ECG tracing. Historically, this pacing mode was used to prevent inappropriate inhibition from oversensing in a patient without a stable native escape rhythm. In contrast to asynchronous pacing (AOO or VOO), this pacing mode is less likely to induce arrhythmias as it will pace within refractoriness of myocardial tissue when the intrinsic cardiac event is sensed. However, arrhythmias could be initiated if non-cardiac signals are inappropriately sensed.

Dual chamber pacing and sensing with inhibition and tracking (DDD)

This can also be referred to as AV sequential (D) pacing, dual chamber sensing (D) with inhibition, and P-synchronous pacing (D). DDD mode refers to atrial and ventricular pacing and sensing with dual response (inhibited and triggered pacing) to

an intrinsic atrial-sensed event or a ventricular-sensed event (Figure 6.2A). In this pacing mode, the pacemaker will pace both the atrium and the ventricle (AV sequential pacing), with programmed AV delay if the intrinsic atrial and ventricular rates are below the LRL. If the atrial rate is slower than the LRL, the device will pace the atrium while *inhibiting* ventricular pacing if an intrinsic ventricular event is sensed within a pre-determined AV delay. If an atrial-sensed event is faster than the LRL without an intrinsic ventricular event, the pacemaker *inhibits* atrial pacing but *triggers* ventricular pacing (P-synchronous pacing) after a pre-determined AV delay (Figure 6.2A). However, tracking an atrial-sensed event will only occur up to a programmable maximum tracking rate (MTR), which will prevent the pacemaker from tracking atrial dysrhythmias beyond a certain rate (see "Upper rate behavior"). Finally, pacing will be completely *inhibited* if the intrinsic atrial and ventricular rates are above the LRL (unless a short AV delay is programmed). This pacing mode is the most commonly used in dual chamber devices (DDD or DDDR) and biventricular pacemakers (DDDOV or DDDRV).

Dual chamber pacing and sensing with inhibition but without tracking (DDI)

This can also be referred to as AV sequential pacing (D) with dual chamber sensing (D) and inhibition (I) *without* P-synchronous pacing. This pacing mode is similar to DDD without tracking atrial-sensed events or P-synchronous pacing. Because P wave tracking does not occur with the DDI mode, the ventricular paced rate is never greater than the programmed LRL regardless of the atrial rate (Figure 6.2B). AV sequential pacing will only occur at LRL if no intrinsic ventricular event is sensed after atrial pacing. The main advantage and indication of DDI is in the presence of paroxysmal atrial arrhythmias such as atrial fibrillation and/or flutter (Table 6.2). This pacing mode is commonly programmed as a mode switch to avoid tracking of these atrial tachyarrhythmias.

Ventricular pacing with inhibition and dual chamber sensing (VDI)

VDI pacing mode gives ventricular pacing (V), while sensing both chambers (D), and inhibits ventricular pacing if an intrinsic R wave is sensed. This pacing mode allows atrial sensing but does not provide P-synchronous pacing (non-tracking mode). In addition, it lacks atrial pacing for which it cannot provide AV sequential pacing. Thus, in sinus rhythm, there is AV dissociation in VDI mode regardless of rate. It is an alternative pacing mode in patients with atrial fibrillation and flutter, and it is available as a mode switch feature in some pacemakers.

Atrioventricular sequential, ventricular inhibited pacing (DVI)

DVI mode provides pacing in both the atrium and the ventricle (D), while only sensing and inhibiting pacing in the ventricle (V). Pacing is only inhibited (I) and reset by ventricular-sensed events, but ignores all intrinsic atrial complexes. The difference between DVI and DDI is that the former lacks atrial sensing. Thus, DVI commonly demonstrates asynchronous atrial pacing at LRL (Figure 6.2C). Similarly to DDI, ventricular pacing will never be greater than programmed LRL when in DVI mode due to the lack of atrial sensing. DVI was used in first-generation pacemakers but it is still programmable in many available dual chamber pacemakers. Nowadays, DVI can be used in patients with marked sinus bradycardia or atrial arrest with atrial lead malfunction (oversensing) in which AV synchrony is desired (Table 6.2).

Ventricular pacing, dual chamber sensing with P-synchronous ventricular pacing and inhibition (VDD)

VDD mode delivers ventricular pacing only (V), senses both the atrium and ventricle (D), while it inhibits ventricular pacing (I) and tracks (T) atrial-sensed events (P-synchronous pacing; Figure 6.2D). The most common use of this pacing mode is in devices with a single-pass lead which integrates an atrial-sensing electrode with a ventricular-pace/sense electrode. This system has been used in subjects with appropriate sinus node function who require ventricular back-up pacing due to high-degree AV block or during biventricular pacing. It can also be used in dual chamber pacemakers with appropriate sensing of normal sinus node with high atrial pacing threshold in an

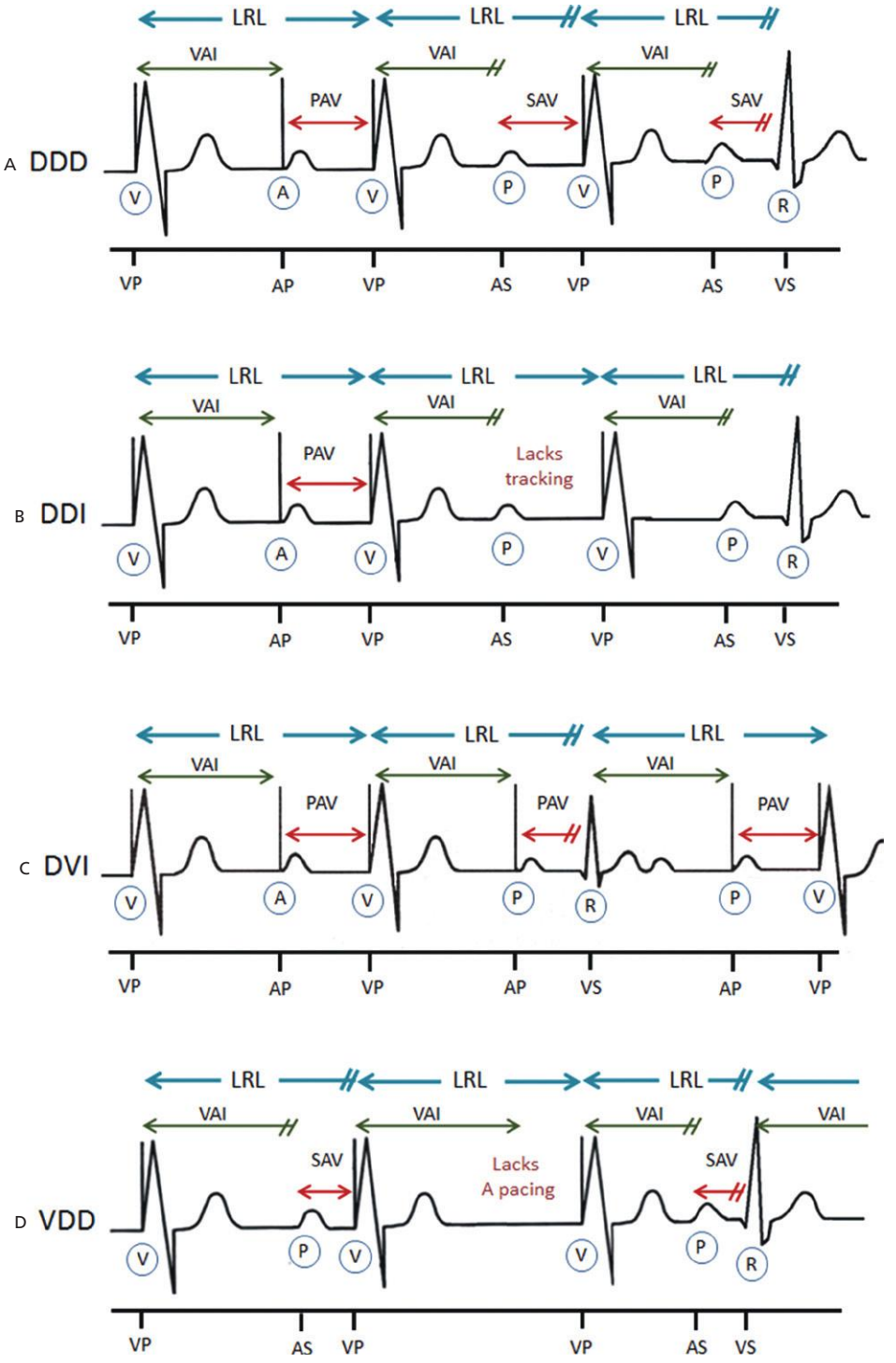


Figure 6.2 (A) DDD, (B) DDI, (C) DVI, and (D) VDD pacing modes. "Event markers" represent pacemaker's interpretation of different cardiac events. See text for details. A, atrial-paced event; LRL, lower rate limit; P, intrinsic P wave; PAV, paced AV interval; R, intrinsic R wave; SAV, sensed AV interval; V, ventricular-paced event; VAI, ventriculoatrial interval. (Source: Modified from Huizar JF, Kaszala K, Ellenbogen KA. Cardiac pacing modes and terminology. In: Sakena S, Camm AJ, eds. *Electrophysiological Disorders of the Heart*, 2nd Ed. Philadelphia, PA: Elsevier Saunders, 2012: 441–456. Reproduced with permission of Elsevier.)

attempt to maximize battery longevity[2,3] (Table 6.2).

Timing cycles

A given timing period or interval can continue until it completes its cycle; completion results in either the release of a pacing stimulus or the initiation of another timing cycle. Alternatively, a given period or interval can be reset by an intrinsic cardiac event, at which point it restarts the timing period again or initiates another timing period. Each portion of the pacemaker timing cycle should be considered in milliseconds (a thousandth of a second) and not in beats per minute (bpm). Although thinking of the patient's pacing rate in paced beats per minute may be easier, portions of the timing cycle are too brief to be considered in any unit other than milliseconds.

Blanking and refractory periods

All pacing modes that can sense cardiac events must include *blanking and refractory periods* in their basic timing cycle. The presence or absence of these periods depends on the pacemaker system as well as the pacing/sensing mode. These periods are essential to the appropriate pacemaker function as they prevent sensing of known but clinically inappropriate signals, such as the evoked potential and repolarization. The blanking and refractory periods of a pacemaker are analogous to the absolute and relative refractory periods of the heart, respectively, during which a stimulus delivered to the heart is ineffective because the myocardium is already depolarized and a subsequent depolarization cannot occur until the resting membrane potential is re-established. The blanking period (BP) is equivalent to an absolute refractory period, during which the sensing amplifier is "off" or "blind" to any cardiac event and thus cannot be detected. Once this period ends, the sense amplifier becomes alert and is receptive to the detection of native signals. The refractory period (RP) is comparable to the relative RP, when cardiac events can be sensed, but it usually does not trigger or reset timing cycles. In contrast to BPs, RPs allow detection of rapid cardiac events (Figure 6.3). In dual chamber pacing, BP is also used to prevent

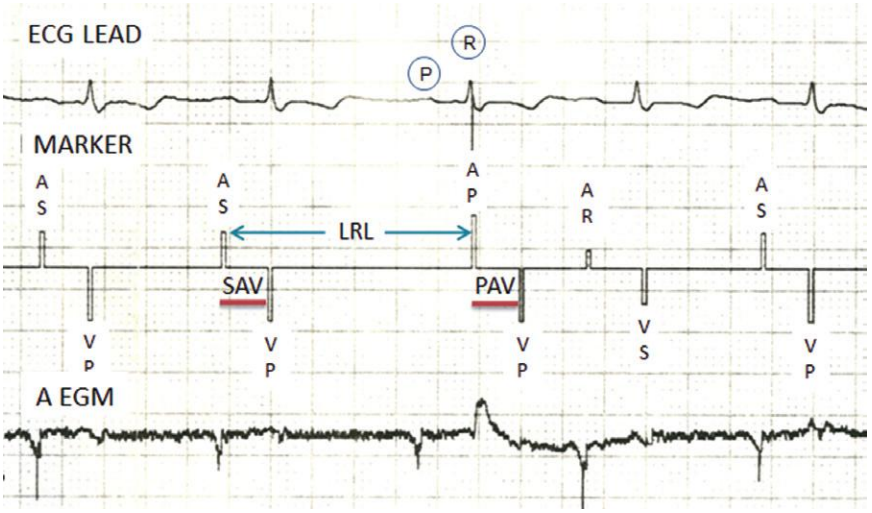


Figure 6.3 Blanking and refractory periods. Inappropriate AV sequential pacing (AP–VP) occurs after the lower rate limit expires despite sinus rhythm with intrinsic AV conduction due to the lack of atrial and ventricular sensing [third P wave (P) and QRS (R), respectively]. Lack of atrial sensing occurs due to a small atrial signal (A—EGM), while ventricular undersensing (third QRS) is co-incidental as it falls within the post-atrial ventricular blanking period (PAVB). The fourth P wave (labeled AR, atrial refractory) occurs within the post-ventricular atrial refractory period (PVARP) and does not initiate an AV interval. Therefore, P-synchronous ventricular pacing (triggered pacing) never occurs. AP, atrial paced; AS, atrial sensed; LRL, lower rate limit; PAV, paced AV interval; SAV, sensed AV interval; VP, ventricular paced; VS, ventricular sensed.

cross-talk (see "Atrioventricular interval, cross-talk, and safety pacing").

Timing cycles based on pacing mode

Cardiac events and timing cycles are based on a single, dual, or biventricular pacemaker systems and programmed pacing modes (Table 6.3).

Asynchronous single chamber pacing modes (AOO, VOO) pace the assigned chamber at LRL (only timing cycle), which cannot be reset by any intrinsic cardiac event. Dual chamber or AV sequential asynchronous (DOO) pacing has an equally simple timing cycle. The interval from atrial to ventricular pacing (AVI) and the interval from ventricular pacing to the subsequent atrial pacing [ventriculoatrial interval (VAI)], also referred to as atrial escape interval (AEI), are both fixed. These intervals are never reset, because the pacing mode is insensitive to any atrial or ventricular activity.

Atrial inhibited pacing (AAI) consists of the atrial blanking (ABP), atrial refractory period (ARP), and LRL (AA interval). ABP and ARP initiate after a paced or sensed atrial event in order to avoid oversensing of evoked potentials, atrial repolarization, or ventricular depolarization. During ABP, any signals are not sensed. In contrast, ARP allows sensing of rapid atrial signals (included in the counter); however, these signals are ignored as they will not reset timing cycles (Figure 6.4A). Atrial pacing will occur after the LRL times out, but pacing will be inhibited and LRL reset after an atrial event is sensed (Figure 6.5A). Nevertheless, an A–A interval (programmed LRL) could be inappropriately reset by a far-field R wave oversensing in the atrial channel after ABP and ARP have expired (Figure 6.5B).

Ventricular inhibited (VVI) pacing, the ventricular counterpart of AAI pacing, incorporates the same timing cycles, with the obvious differences that pacing and sensing occur in the ventricular channel and pacing output is inhibited by a sensed ventricular event (Figure 6.4B). A ventricular-paced or -sensed event initiates a ventricular blanking period (VBP) and a ventricular refractory period (VRP) during which the pacemaker will not reset the ventricular timer or LRL after a ventricular-sensed event (Figure 6.6).

DDD pacing mode embraces all timing cycles described on AAI and VVI pacing modes.

In addition, LRL is divided into two sections: the VAI or AEI, and the AVI, as depicted in Figure 6.4C. The VAI initiates after a ventricular-sensed or -paced event and does not terminate until an atrial event is sensed; however, atrial pacing will occur if the VAI expires without sensing an intrinsic atrial event. The AVI begins with an atrial-sensed or -paced event and extends to a ventricular event. Similarly, ventricular pacing will occur if the AVI elapses without the presence of an intrinsic ventricular event.

Table 6.3 Acronyms and description of cardiac events and timing cycles in a single chamber, dual chamber, and biventricular pacemakers/devices (Source: Modified from Huizar JF, Kaszala K, Ellenbogen KA. Cardiac pacing modes and terminology. In: Sakena S, Camm AJ, eds. *Electrophysiological Disorders of the Heart*, 2nd Ed. Philadelphia, PA: Elsevier Saunders, 2012: 441–456. Reproduced with permission of Elsevier.)

Cardiac events/timing cycles (abbreviation)	*Description*
Single chamber (atrial or ventricular) pacemaker	
Atrial sensed event (P/AS)	Sensed a native Atrial depolarization (P wave)
Atrial paced event (A/AP)	Delivered Atrial Pacing output
Ventricular sensed event (R/VS)	Sensed native Ventricular depolarization (QRS complex)
Ventricular paced event (V/VP)	Delivered Ventricular Pacing output
Atrial blanking period (ABP)	Atrial-sensing amplifier is "blind" and will not detect or respond to any atrial-sensed event

Table 6.3 (*Continued*)

Cardiac events/timing cycles (abbreviation)	*Description*
Ventricular blanking period (VBP)	Ventricular-sensing amplifier is "blind" and will not detect or respond to any ventricular-sensed event
Atrial refractory period (ARP)	An atrial sensed event will be noted but ignored, without affecting the pacemaker timing cycle
Ventricular refractory period (VRP)	A ventricular-sensed event will be noted but ignored, without affecting the pacemaker timing cycle
Lower rate limit (LRL)	Minimum pacing rate
Upper rate limit (URL)	Maximum pacing rate
Maximum sensor rate (MSR)	Maximum pacing rate by rate-modulated sensor
Dual chamber (atrial and ventricular) pacemaker	
Atrioventricular sequential pacing (AV)	Atrial-paced event followed by paced ventricular event
P-synchronous V pacing (PV)	Atrial-sensed event followed by paced ventricular event
VA interval (VAI)	Interval from ventricular-sensed or -paced event to atrial-paced event
PR	Atrial-sensed event followed by ventricular-sensed event (native intrinsic atrial and ventricular events)
AR	Atrial-paced event followed by ventricular-sensed event
AV interval or delay (AVI)	Programmed atrioventricular pacing interval
Paced AV interval (paced AVI)	AV interval/delay from atrial-paced event (A) to ventricular-paced event (V)
Sensed AV interval (sensed AVI)	AV interval/delay from atrial-sensed event (P) to ventricular-paced event (V)
Maximum or upper tracking rate (MTR)	Maximum ventricular pacing rate allowed in response to high sensed atrial rates
Post-atrial ventricular blanking period (PAVB)	Period where ventricular sensing is "off" after an atrial-paced event
Post-ventricular atrial blanking period (PVAB)	Period where atrial sensing is "off" after a ventricular-paced or -sensed event
Post-ventricular atrial refractory period (PVARP)	Period after ventricular event where the device can sense an atrial event but does not track it
Total atrial refractory period (TARP)	Sum of AVI and PVARP
Rate-modulated AV delay [RMAVD; also referred to as rate-responsive AV delay (RRAVD)]	AV delay that adjusts by shortening as the rate increases.
Cardiac resynchronization therapy/pacemakers	
RV post-atrial ventricular blanking period (RV-PAVB)	Period where RV sensing is "off" immediately after atrial pacing (avoids oversensing atrial signals)
LV post-atrial ventricular blanking period (LV-PAVB)	Period where LV sensing is "off" immediately after atrial pacing (prevents oversensing atrial signals)
RV refractory period (RVRP)	A RV-sensed event may be noted but ignored, without affecting the pacing timing cycle
LV refractory period (LVRP)	A LV-sensed event may be noted but ignored, without affecting LV pacing timing cycle
LV protection period (LVPP)	Period after a ventricular-paced or -sensed event that prevents inappropriate pacing during the vulnerable period
Biventricular pacing interval or LV offset	Timing gap between RV and LV pacing (RV–LV interval)

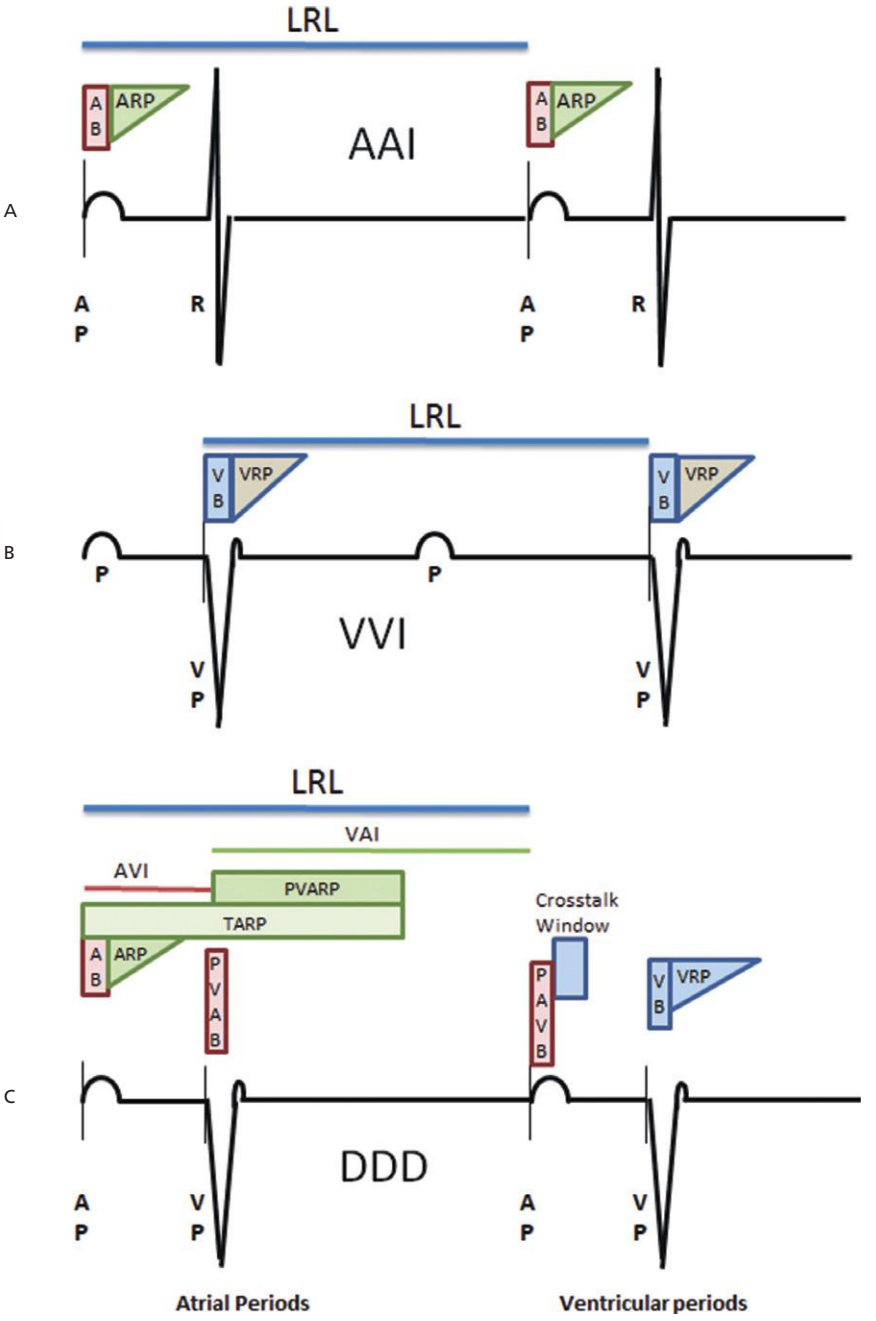


Figure 6.4 Timing cycles found on (A) AAI, (B) VVI, and (C) DDD pacing modes. See text and Table 6.3 for abbreviations. (Source: Modified from Huizar JF, Kaszala K, Ellenbogen KA. Cardiac pacing modes and terminology. In: Sakena S, Camm AJ, eds. *Electrophysiological Disorders of the Heart*, 2nd Ed. Philadelphia, PA: Elsevier Saunders, 2012: 441–456. Reproduced with permission of Elsevier.)

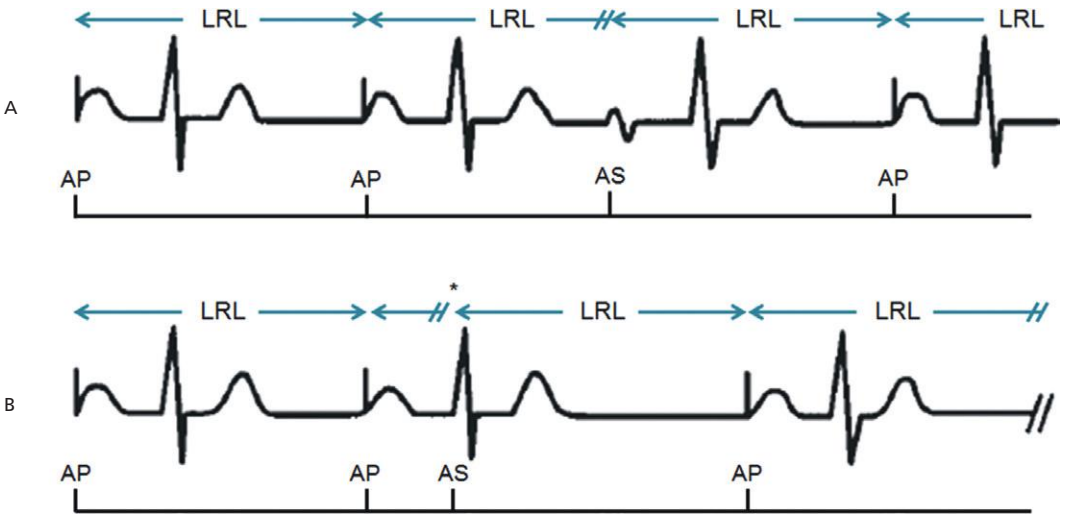


Figure 6.5 AAI pacing mode. (A) Atrial pacing (AP) occurs at the end of the lower rate limit (LRL) in the absence of an atrial-sensed (AS) event. If an intrinsic AS event occurs, LRL is restarted from that point. (B) Even though the LRL is programmed to 60 bpm (1000 ms), the interval between the second and third paced atrial events (AP) is >1000 ms. Examination of the event markers (pacemaker's interpretation) demonstrate that the QRS complex has been inappropriately sensed on the atrial-sensing channel (far-field R wave sensing beyond blanking and refractory periods), resetting the LRL.

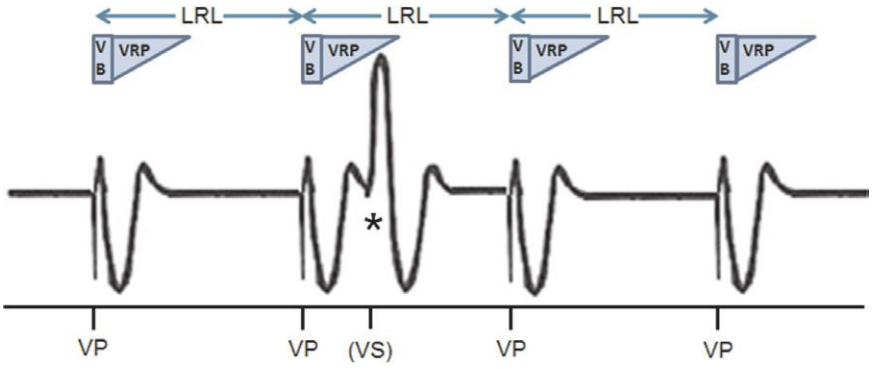


Figure 6.6 Ventricular refractory period (VRP) in VVI pacing mode. A premature ventricular contraction (PVC, *) occurs during VRP, initiated after a ventricular paced (VP) event. Since PVC (VS, ventricular-sensed event) falls within the VRP, the lower rate limit (LRL) is not interrupted or re-initiated. VB, ventricular blanking period.

Furthermore, a sensed or paced atrial event initiates an ABP followed by an ARP (Figure 6.4C). During the ABP and ARP, the atrial channel is refractory and will not reset timing cycles even in the presence of another native atrial event. Ventricular pacing occurs only at the end of the AVI or later [see "Upper rate behavior" (Wenckebach-like behavior)]. A sensed or paced ventricular event initiates a VBP followed by a VRP. VBP and VRP prevent sensing of the evoked potential and the resultant T wave on the ventricular channel of the pacemaker. After the blanking period, the ventricular-sensing channel is again operational, or "alert." If atrial activity is not sensed by the time of the expiration of the VAI, atrial pacing occurs, followed by the AVI. If intrinsic ventricular activity occurs before the VAI is completed, this timing cycle is reset.

A sensed or paced ventricular event also initiates a refractory period on the atrial channel, referred to as the post-ventricular atrial refractory period (PVARP). The PVARP is designed to prevent ventricular tracking of a retrograde P wave (see "PVARP and pacemaker-mediated tachycardia"). The combination of the PVARP and the AVI establishes the total atrial refractory period (TARP). TARP is the limiting factor for the upper rate limit (URL) or so-called MTR in P-synchronous dual chamber pacing modes, which instructs the pacemaker what the maximum atrial-sensed rate is to be tracked by ventricular pacing (see section: "Upper rate behavior" and "Total and post-ventricular atrial refractory periods").

DDI pacing mode includes the identical timing cycles described for DDD mode. DDI mode differs from DDD mode in the response to atrial sensing, as it cannot trigger ventricular pacing after atrial-sensed events (it lacks P-synchronous ventricular pacing; Figure 6.3B).

In contrast to DDD pacing mode, *DVI pacing mode* cannot trigger ventricular pacing in response to atrial events since it lacks atrial sensing. Furthermore, DVI pacing mode lacks timing cycles that involve atrial sensing, such as ABP, ARP, post-ventricular atrial blanking period (PVAB) and post-ventricular atrial refractory period (PVARP), and TARP. Thus, DVI pacing mode commonly demonstrates asynchronous atrial pacing at LRL (Figure 6.3C). For instance, a sensed R wave during the VAI (ventricular ectopy) will reset the VAI, delaying atrial pacing in DVI mode.

VDD pacing mode lacks atrial pacing (Figure 6.3D). Thus, the post-atrial ventricular blanking period (PAVB) and cross-talk window (found on DDD and DDI pacing modes) are absent. A sensed atrial event initiates the AVI. If an intrinsic ventricular event occurs before termination of the AVI, ventricular output is inhibited, and the LRL timing cycle is reset. Similarly, a P-synchronous ventricular pacing at the end of the AVI will reset the LRL. A ventricular-sensed or -paced event will initiate PVARP and VAI. If no atrial event occurs, the pacemaker escapes with a paced ventricular event at the LRL (pacemaker behaves as VVI in the absence of a sensed atrial event at the base rate).

Overall, pacemaker behavior depends on the programmed pacing mode and base rate behavior. However, other programmable features may affect device behavior (Table 6.4). These are discussed throughout the chapter.

Atrioventricular interval, cross-talk, and safety pacing

AVI refers to a programmable interval initiated by a sensed or paced atrial event (P or A event, respectively) followed by ventricular pacing after the time interval expires (Figure 6.7). If a ventricular event is sensed before the time interval is completed, the AVI will terminate and initiate the VAI. At the beginning of the AVI, the atrial channel is briefly blind (ABP) followed by an ARP to allow detection of abnormal rapid atrial signals during the AVI (Figure 6.8).

The potential exists for signals other than those of intrinsic ventricular activity to be sensed during the AVI and inhibit ventricular output. Thus, atrial pacing artifact inappropriately sensed by the ventricular-sensing amplifier could result in ventricular pacing inhibition, referred to as *cross-talk*. To prevent *cross-talk*, atrial pacing also initiates a PAVB to avoid ventricular oversensing of atrial-paced events (Figure 6.7B). In DDD pacemakers, this blanking period may be programmable, ranging from 12 to 125 ms. The blanking period is traditionally of short duration because it is important for the ventricular-sensing circuit to be returned to the "alert" state relatively early during the AVI so that intrinsic ventricular activity can inhibit pacemaker output if it occurs before the AVI ends.

Even though the atrial pacing artifact is effectively ignored because of the PAVB, the trailing edge of the atrial pacing artifact occurring after the PAVB can occasionally be sensed on the ventricular channel. In a pacemaker-dependent patient, inhibition of ventricular output by cross-talk results in ventricular asystole. To prevent such a catastrophic outcome, DDD pacing mode has a safety mechanism called the "ventricular triggering period" or the "cross-talk sensing window" (Figure 6.7C). If activity is sensed on the ventricular-sensing amplifier during the AVI immediately after the PAVB, it is assumed that cross-talk cannot be differentiated from intrinsic ventricular activity. Sensing during this window will result in a triggered rather than an inhibited output. This early ventricular pacing

Table 6.4 Features that may affect device behavior*

Device behavior	*Pacing features/algorithms*
Intrinsic rate slower than programmed base rate	Rate/scan hysteresis Sleep or rest rate Sinus preference Special algorithms (e.g. +PVARP after PVC) Atrial-based timing in DDD after PVC
Base rate (AV,AR) higher than programmed rate	Sensor-driven rate Rate smoothing Fallback Mode-switching response rate Sudden bradycardia/rate drop response Atrial overdrive suppression Special algorithms (e.g. +PVARP after PVC) Magnet mode rate Atrial and ventricular auto-threshold test
Intrinsic AVI (PR,AR) longer than programmed paced or sensed AVI	AV or PV hysteresis Algorithms to allow intrinsic AV conduction Sinus rate with intact AV conduction exceeding MTR
Paced or sensed AVI shorter than programmed paced or sensed AVI	Rate-modulated or dynamic AV delay Negative AV or PV hysteresis Safety pacing Managed ventricular pacing (MVP, AAI ⇔ DDD) Non-competitive atrial pacing (NCAP) Auto-threshold test
Loss of atrial tracking (DDD)	Automatic mode switch MSR > MTR

*Note: device behaviors are not necessarily continuous; the effects can be seen on a single cycle or during a brief period. PVC, premature ventricular contraction; for other acronyms, see Table 6.3.

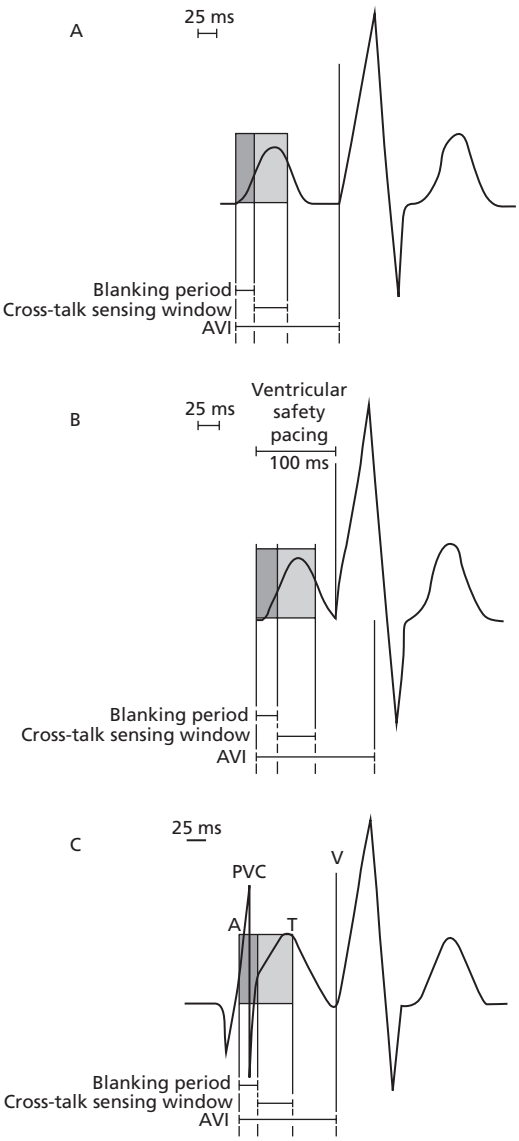


Figure 6.7 Representation of atrioventricular interval (AVI). (A) AVI corresponds to a programmed value following a paced or sensed atrial beat before a ventricular pacing artifact is delivered. The post-atrial ventricular blanking period (PAVB) is found in the initial portion of the AVI, followed by the cross-talk sensing window. (B) If the ventricular-sensing amplifier senses any event during the cross-talk sensing window, ventricular safety pacing is delivered, usually 100–110 ms after the atrial event. (C) An intrinsic ventricular event [such as a premature ventricular contraction (PVC)] during the PAVB period is not sensed by the ventricular-sensing amplifier; thus ventricular pacing is delivered at the programmed AVI.

typically occurs with an AVI of 100–120 ms (can be programmed to 50–150 ms in some pacemakers) to prevent asystole. This has been referred as "safety pacing" or "non-physiological AV delay" or the "110-ms phenomenon." Safety pacing is designed to prevent ventricular asystole if cross-talk were to occur in a pacemaker-dependent patient.

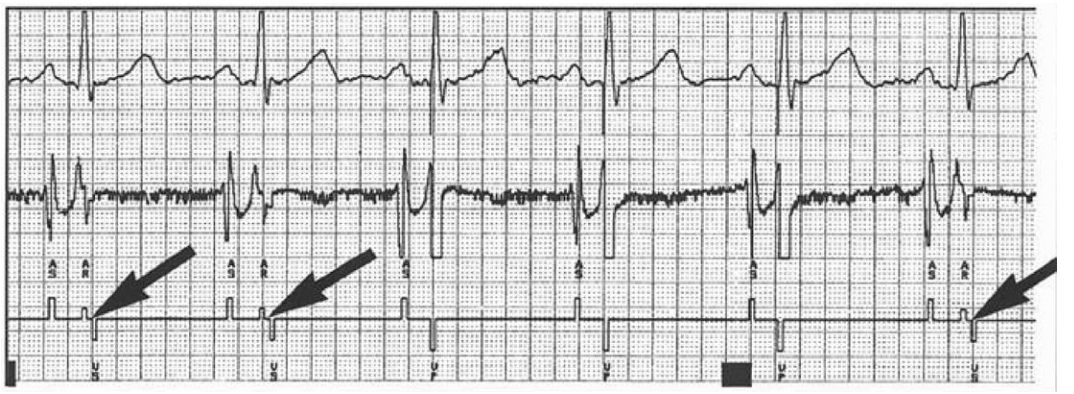


Figure 6.8 Far-field R wave oversensing. The R wave is inappropriately sensed during the atrial refractory period (ARP) by the atrial amplifier. Surface ECG, atrial electrogram, and event markers (arrows) demonstrate occasional atrial refractory (AR) events due to far-field R wave sensing within the ARP. AR events co-incide with the QRS complex, but are detected on the atrial channel before being detected by the pacemaker on the ventricular channel (VS).

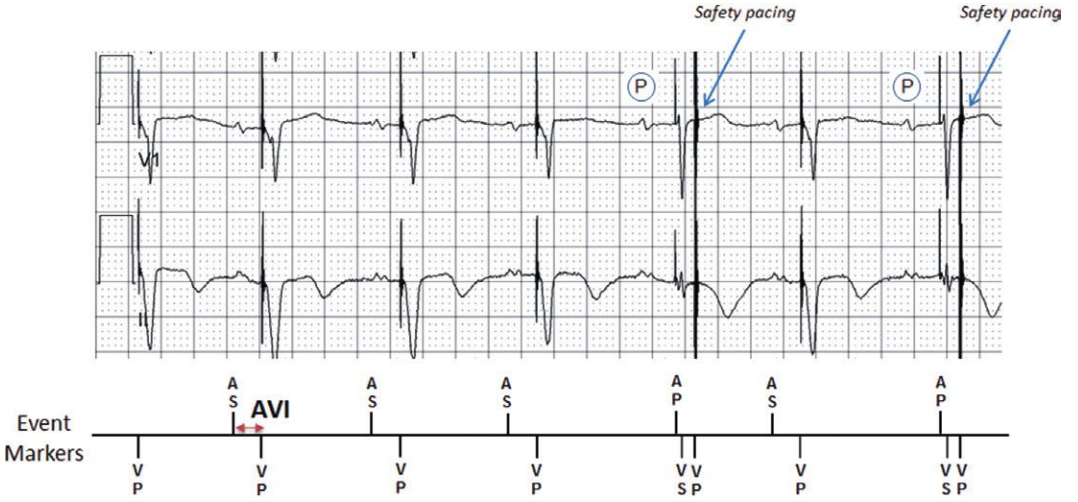


Figure 6.9 ECG demonstration of safety pacing due to atrial undersensing in DDD pacing mode. As noted by event markers, P-synchronous ventricular pacing occurs in the first four ventricular-paced events (VP) with a programmed sensed and paced AV interval (AVI) of 160 and 190 ms, respectively. The fourth and sixth P waves (P) are not sensed (fail to terminate VAI and initiate AVI), yet they demonstrate intrinsic AV conduction with a ventricular-sensed event (VS) briefly after atrial pacing (AP) (lower rate limit of 60 bpm expires). Safety pacing (fifth and seventh VP, shorter AV delay 110–120 ms) occurs as a VS event is sensed during the cross-talk sensing window.

Occurrence of cross-talk and safety pacing should be suspected if AV pacing is noted at a shorter than programmed AVI on ECG (Figure 6.9). Elimination of cross-talk can be achieved by extending the PAVB, decreasing atrial output, or reducing the ventricular sensitivity. If true intrinsic ventricular activity occurs during the cross-talk sensing window, safety pacing will result in a fusion beat. Although the safety pacing phenomenon accompanying a late-cycle premature ventricular contraction (PVC) has been interpreted as a sensing failure, it actually reflects normal sensing.

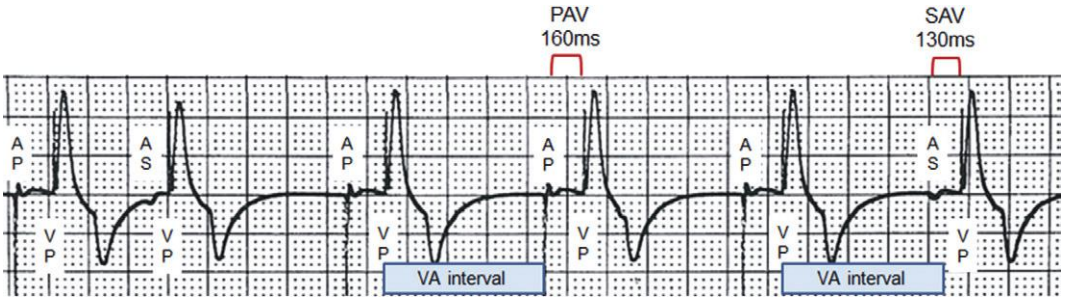


Figure 6.10 ECG tracing demonstrates differential atrioventricular interval (AVI). An AVI initiated by a sensed event and those initiated by a paced event show consistent differences. Thus, the most likely explanation is a differential AVI. The paced AVI is 50 ms longer than the PV or sensed AV intervals. (Source: Relay Models 293-03 and 294-03. Intermedics Cardiac Pulse Generator Physician's Manual. Angleton, TX: Intermedics, 1992. Reproduced with permission of Intermedics.)

After the blanking period and the cross-talk sensing window have timed out, the ventricular-sensing circuit returns to the alert status, in which a detected event terminates the AVI with subsequent inhibition of ventricular pacing.

Differential atrioventricular interval

The differential AVI is an attempt to provide an intra-atrial conduction time of equal duration whether atrial contraction is paced or sensed. The PV interval initiated with atrial sensing, referred to as "sensed AV delay (SAV)," commences only when the atrial depolarization is detected by the pacemaker, and commonly occurs 20–60 ms after the onset of the P wave on a surface ECG. Conversely, the AVI initiated with atrial pacing, referred to as "paced AV delay (PAV)," commences immediately with the pacing artifact. Therefore, in general, the AVI that follows a sensed atrial event should be shorter than one that follows a paced atrial event in an effort to achieve similar functional AVIs (Figure 6.10). Most dual chamber pacemakers allow the paced and sensed AV delays to be programmed independently with differences of up to 100 ms. Nonetheless, a differential AVI is preset or automatically calculated in other pacemakers (Figure 6.11).

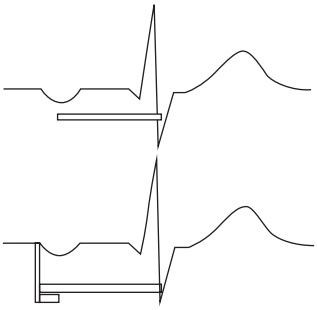


Figure 6.11 Schematic of automatic calculation of differential atrioventricular interval (AVI), designated "AV delay hysteresis." When an atrial-paced event occurs, the AR interval is measured. When an atrial-sensed event follows an atrial-paced event, a new PR interval is measured. The AV delay hysteresis is set equal to the maximum value (AR or PR) minus the PR interval. (Source: Modified from Chorus II Model 6234, 6244. Dual Chamber Pulse Generator Physician's Manual. Minnetonka, MN: ELA Medical, 1994. Reproduced with permission of ELA Medical.)

Dynamic or rate-adaptive atrioventricular interval

Pacemaker algorithms may be used in dual chamber pacing modes to shorten the AVI as the atrial rate increases, either by an increase in sinus rate or sensor-driven paced rate (Figure 6.12). Dynamic AVI is intended to optimize cardiac output by mimicking the normal physiological decrease in the PR interval that occurs in the normal heart as the atrial rate increases. The rate-related shortening of the AVI can be useful to improve atrial sensing, and to enhance atrial tracking at faster rates by shortening the TARP (AVI + PVARP) and thereby extending the atrial-sensing window.

The rate-adaptive AVI algorithm varies according to the pacemaker and manufacturer. A common

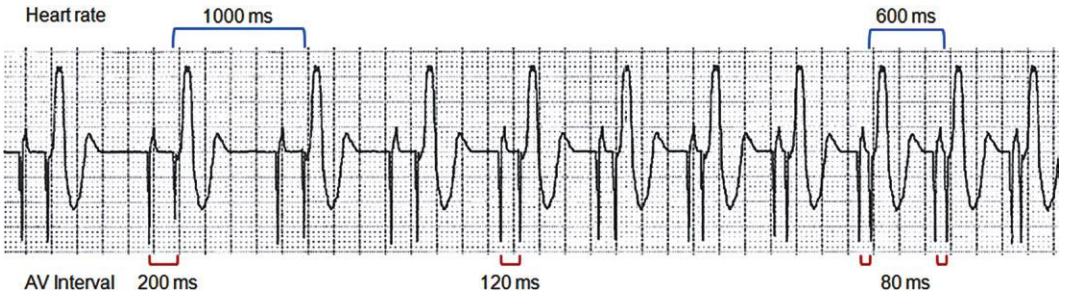


Figure 6.12 Dynamic atrioventricular (AV) delay. As heart rate increases, AV delay shortens from 200 ms to 80 ms. (Source: Hayes DL, Ketelson A, Levine PA *et al.* Understanding timing systems of current DDDR pacemakers. *Eur JCPE* 1993; 3: 70–86. Reproduced with permission of the Mayo Foundation.)

method allows linear shortening of the AVI from a programmed baseline AVI to a programmed minimum AVI. Another method allows a limited number of stepwise shortenings of the AVI, which may or may not be programmable.

Atrioventricular interval hysteresis

The term AVI hysteresis has been used variably, but most commonly describes alterations in the paced AVI relative to the patient's intrinsic AV conduction. For example, a longer paced AVI is permitted to allow maintenance of intrinsic AV conduction, previously referred to as *positive hysteresis*. The term *positive AV hysteresis* is largely of historic significance. Nowadays, several algorithms have been developed to avoid the deleterious effects of chronic right ventricle (RV) pacing (see "Algorithms to minimize right ventricular pacing"), including abnormal ventricular activation sequence and heart failure symptoms.[4] In contrast, the term *negative hysteresis* can still be found in a few contemporary devices. This feature is intended to temporarily shorten the AVI (to 10–150 ms) if an intrinsic ventricular event is sensed in the AVI, which could be relevant in biventricular pacing and hypertrophic cardiomyopathy.

Ventriculoatrial interval (VAI)

The VAI interval is only present in dual chamber pacing modes, regardless of tracking feature (DDD, DDI, DVI). This interval has been also called "atrial escape interval (AEI)." The VAI is initiated after an intrinsic ventricular event is sensed (prior to completion of the AVI) or paced (after the AVI expires). This interval will be terminated prematurely if an intrinsic atrial event occurs, which in turns initiates an AVI. However, this interval is reset/re-initiates if an intrinsic ventricular event is sensed. If no atrial- or ventricular-sensed event occurs during the VAI, an atrial pacing stimulus will occur after conclusion of this interval. In most pacemakers, the VAI is fixed and non-programmable, and together with the AVI, determines the LRL. The VAI is variable in (1) rate-modulated pacing modes [the sensor-indicated rate (SIR) will increase based on VAI shortening]; and (2) atrial-based timing (see "Rate-modulated pacing" and "Base rate behavior").

Total and post-ventricular atrial refractory periods

The post-ventricular atrial refractory period (PVARP) is a programmable interval in dual chamber pacing modes with atrial sensing (DDD, DDI, VDD), initiated after a sensed or paced ventricular event. This period is intended to avoid inappropriate tracking of sensed signals due to ventricular repolarization or retrograde P waves. If an atrial event occurs during PVARP, timing cycles (VAI, LRL) are not reset. Nevertheless, sensing of atrial signals during PVARP allows proper mode switch (non-tracking pacing mode) when atrial fibrillation, flutter, or tachycardia occurs (see "Mode switch").

In a P-synchronous pacing mode, PVARP should be extended to include retrograde P wave if VA conduction is present to avoid pacemaker-mediated tachycardia (PMT, also referred to as endless-loop

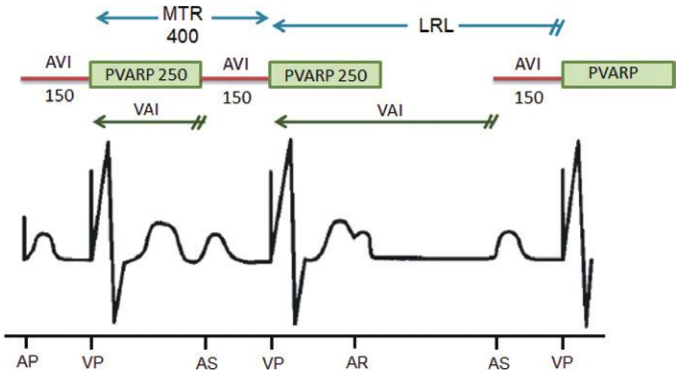


Figure 6.13 Upper rate limit (URL) limited by total atrial refractory period (TARP). In DDD pacing mode, the atrioventricular interval (AVI) and post-ventricular atrial refractory period (PVARP) are programmed at 150 ms and 250 ms, respectively (TARP 400 ms). Thus, pacemaker limits maximum tracking rate (MTR) up to 150 bpm (400 ms). After the first paced ventricular complex, an intrinsic P wave (AS) is sensed immediately after the completion of the PVARP. This AS event initiates AVI and upon completion, ventricular tracking occurs. However, the subsequent P wave (AR) is sensed within the PVARP and therefore, VAI is not ended and the P wave is not tracked with ventricular pacing. Ventricular tracking (VP) will only occur until the next intrinsic P wave (AS) occurs outside PVARP.

tachycardia; see "Pacemaker-mediated tachycardia"). Appropriate PVARP programming is also important to reduce tracking of atrial arrhythmias.

Total atrial refractory period (TARP) is the sum of the AVI and PVARP. TARP is the limiting factor for the URL (maximum tracking or sensor rate) in which the pacemaker can pace and track P waves or atrial-sensed events (Figure 6.13). For example, if the AVI is 150 ms and the PVARP is 250 ms, the TARP is 400 ms or 150 bpm. In this case, a 250-ms PVARP initiates after a ventricular-paced event, and only after this interval has expired can an atrial event be sensed. If an atrial event is sensed immediately after termination of the PVARP, it initiates an AVI of 150 ms. After the AVI ends, a paced ventricular event will occur in the absence of an intrinsic R wave, resulting in a V–V cycle length of 400 ms or 150 bpm. Thus, programming a long PVARP limits the MTR and maximum sensor rate (MSR).

Dynamic PVARP

In current pacemakers, a heart rate or SIR determined dynamic PVARP adjustment may be enabled. In tracking pacing modes (DDDR, DDD, VDD), PVARP is extended during lower heart rates in order to protect against pacemaker-mediated tachycardia (see "Pacemaker-mediated tachycardia"), while it is shortened at higher rates to allow P-synchronous ventricular pacing at faster rates (allows the programming of a higher MTR) and to reduce the likelihood of competitive atrial pacing. In non-tracking pacing modes (DDI, DDIR), PVARP is extended to prevent inhibition of atrial pacing by an atrial event early during the VAI, and shortened at high SIR to reduce the likelihood of competitive atrial pacing (Figure 6.14).

Rate-modulated pacing

The "sensor function" of a pacemaker refers to the modulation of the paced rate in response to an input signal other than the presence or absence of native depolarization. Nowadays, there is a wide variety of sensors that provide input to pacemakers based on: (1) motion (either acceleration or vibration); (2) changes in impedance as a measure of minute ventilation and/or contractility (Closed Loop Stimulation, Biotronik)[5]; and (3) duration of the QT interval.

The sensor input to the pacing system temporarily adjusts the rate of the pacemaker. If the patient is active and rate modulation is enabled, the heart rate is determined by either the native rate or the SIR, whichever is faster. The SIR behaves in a

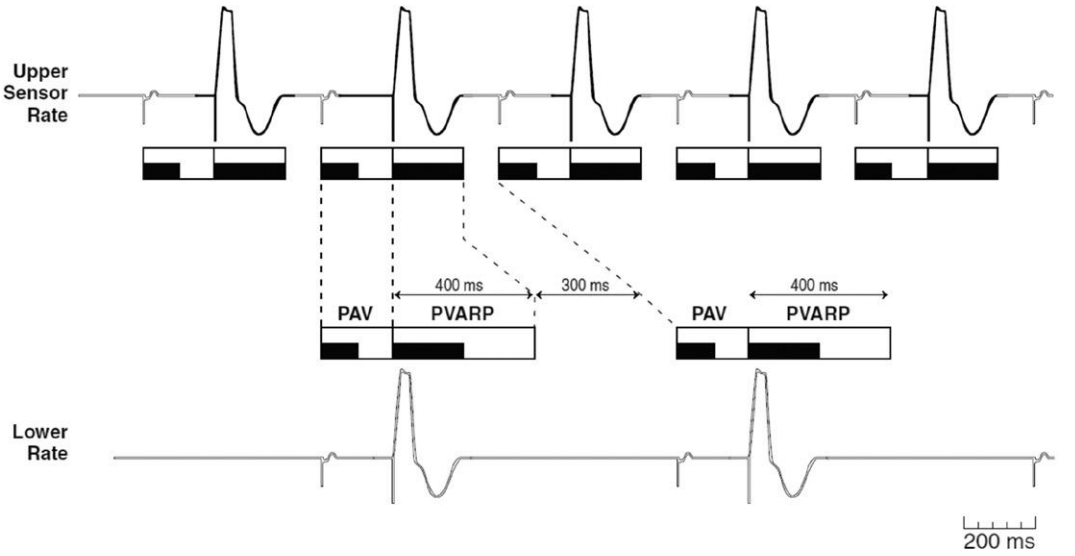


Figure 6.14 Dynamic post-ventricular atrial refractory period (PVARP) in DDDR, DDD, and VDD pacing modes. PVARP is extended to 400 ms (adjusted to maintain a 300-ms sensing window) at low heart rates, while it shortens to a minimum of the programmed post-ventricular atrial blanking period (PVAB, solid bar) at upper or maximum sensor or tracking rates (MSR, MTR). When the pacemaker is operating in the DDIR mode, the sensor-varied PVARP is approximately 400 ms at low rates and the programmed PVAB at high rates. (Source: Adapta, Versia and Sensia Manual, Medtronic, Inc. Reproduced with permission of Medtronic, Inc.)

manner identical to the programmed base rate. In essence, the sensor-driven pacing rate acts as if the lower rate limit (LRL) has been increased. SIR is also a unique term found in rate-modulated pacing only, and refers to the pacing rate based on the sensor input. If the native rate is faster than the SIR, the pacemaker is either inhibited or tracks the atrial complexes. If the SIR is faster than the intrinsic rate, the heart rate is controlled by the pacemaker. Rate modulation requires a programmed URL, referred to as the MSR.

Single chamber inhibited and rate-modulated pacing

Single chamber rate-modulated pacing modes (AAIR, VVIR) have the same timing cycles as their non–rate-modulated counterparts. The difference lies in the variability of the V–V or A–A intervals (Figure 6.15).

Long programmed refractory periods should be avoided when rate-modulated pacing is enabled, since it could prevent appropriate sensing of rapid intrinsic events functioning inadvertently with an

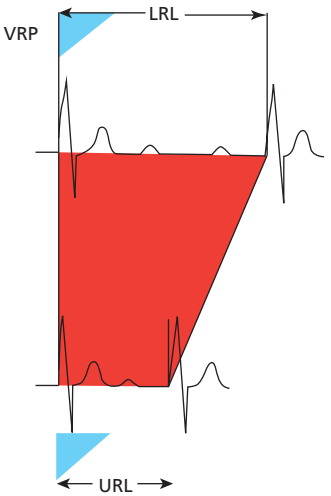


Figure 6.15 The VVIR timing cycle consists of a lower rate limit (LRL), an upper rate limit (UR), and a ventricular refractory period (VRP, represented by blue triangles). As indicated by sensor activity, the V–V interval shortens accordingly (blue area represents the range of sensor-driven VV interval). In most VVIR pacemakers, the VRP remains fixed despite the changing VV cycle length. In selected VVIR pacemakers, the VRP shortens as the cycle length shortens.

asynchronous pacing behavior. Most pacemakers have a rate-dynamic/variable refractory period, which depends on the SIR and allows appropriate sensing of intrinsic events when the cycle length shortens.

Single chamber and dual chamber rate-modulated asynchronous pacing

The asynchronous pacing modes (i.e. AOO, VOO, DOO, as explained previously) have fixed intervals that are insensitive to all intrinsic events and timers that are never reset. If rate modulation is incorporated in an asynchronous pacing mode, the basic cycle length is altered by sensor activity. In the rate-modulated asynchronous pacing modes (AOOR, VOOR, DOOR), any alteration in cycle length is attributable to sensor activity or input signal and not to the sensing of intrinsic cardiac events (P or R wave). In the DOOR pacing mode, the AVI may be programmed in some devices to shorten progressively as the rate increases, whereas in other units it remains fixed at the initial programmed setting.

Dual chamber rate-modulated pacing (DDDR, DDIR)

Dual chamber rate-modulated pacing modes (DDDR, DDIR) are similar to the previously described DDD and DDI modes, respectively, except that paced rates can exceed the programmed LRL through sensor-driven activity. In addition to P-synchronous pacing as a method for increasing the heart rate (DDD only), the sensor incorporated in the pacemaker may also increase the heart rate. Therefore, the rhythm may be sinus driven (alternatively called "atrial driven" or "P synchronous") or sensor driven (Figure 6.16). Depending on the sensor incorporated and the level of exertion of the patient, the basic cycle length shortens from the programmed LRL up to the MSR.

Although the MSR and MTR are closely related, they are not identical. The tracking rate refers to the rate at which the pacemaker is sensing and tracking intrinsic atrial activity. The MTR is the maximum ventricular-paced rate that is allowed in response to sensed atrial rhythms. The MTR may result in fixed block, Wenckebach, fallback, or rate-smoothing responses, depending on the design of the system (see "Upper rate behavior" and "Rate enhancements"). The sensor-controlled rate or SIR is the rate of the pacemaker that is determined by the sensor input signal. The MSR is the maximum rate that the pacemaker is allowed to achieve under sensor control. If the SIR is higher than the

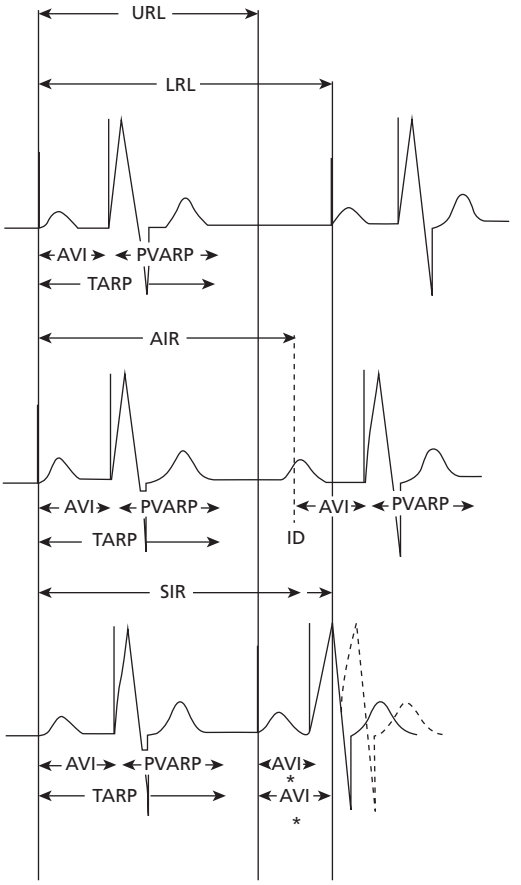


Figure 6.16 DDDR pacing mode. A device functioning with heart rates above the programmed lower rate limit (LRL) is explained on the basis of the atrial-indicated rate (AIR) or sensor-indicated rate (SIR). Top: AV sequential pacing at the LRL as the patient is inactive and no intrinsic R wave is sensed after the atrioventricular interval (AVI) expires. Middle: P-synchronous ventricular pacing occurs, tracking the AIR since the patient's atrial or sinus rate increases above the LRL and SIR. Bottom: Atrial pacing based on the SIR (above the AIR), reaching the upper rate limit (URL). Rate-adaptive or rate-variable AVI allows shortening of the AVI as the SIR increases. Because a rate-modulated AV delay (*) is incorporated, the total atrial refractory period (TARP) may shorten by virtue of the changing AVI even though the post-ventricular atrial refractory period (PVARP) does not change at faster rates.

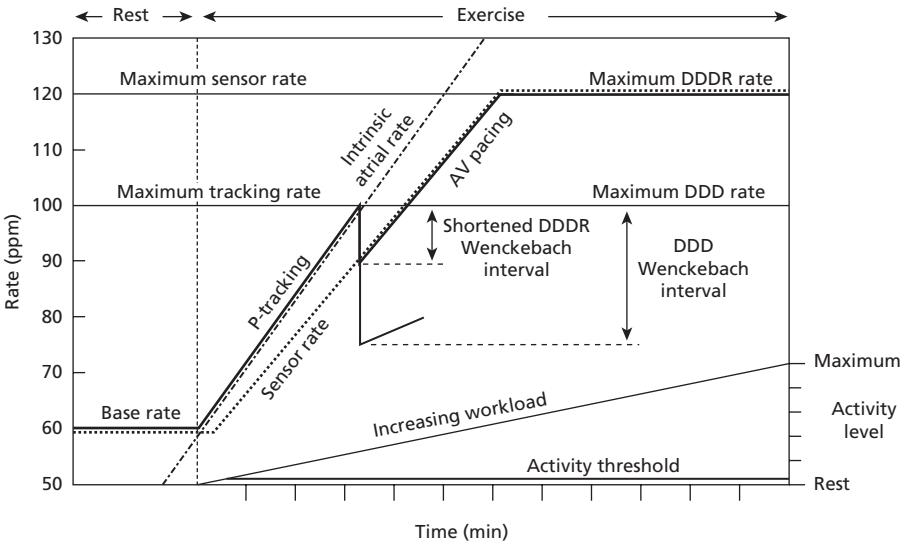


Figure 6.17 Rate response of the DDDR pacemaker and its behavior at both maximum tracking and maximum sensor rate (MSR). The dashed–dotted line represents the intrinsic atrial rate (P-synchronous tracking), and the diagonal dashed line represents the sensor-indicated rate during progressively increasing workloads. The heavy black line shows the ventricular paced rate, assuming complete heart block, as it progresses from the P-tracking mode to atrioventricular (AV) sequential pacing through a period of Wenckebach-type block. The DDD Wenckebach interval is shortened by sensor-driven pacing, i.e. "sensor-driven rate smoothing." Maximum shortening of the Wenckebach period is accomplished by optimal programming of the sensor rate–response variables (threshold and slope programming for an activity-driven sensor). (Source: Higano ST, Hayes DL, Eisinger G. Sensor-driven rate smoothing in a DDDR pacemaker. *Pacing Clin Electrophysiol* 1989; 12: 922–929. Reproduced with permission of John Wiley & Sons Ltd.)

intrinsic atrial rate, it will determine pacing rate. In contrast, if the SIR is lower than the intrinsic atrial rhythm, the pacemaker will track atrial events up to the MTR. Thus, the pacing rate may be in part sensor driven and in part sinus driven (P wave tracking), and not purely one or the other (Figure 6.17), depending on the sinus node function and programmed pacemaker and sensor parameters.

In DDDR pacing mode, the MSR can be programmed above, equal to, or below the MTR. If the MSR is programmed above the MTR, P-synchronous pacing (tracking) will only occur with atrial rates up to the MTR. If the SIR is above the MTR, the device will behave as DDIR, allowing AV sequential pacing but lacking P-synchronous pacing between the MTR and MSR. For example, in a DDDR pacing mode programmed with a LRL, MTR, and MSR of 60, 120, and 130 bpm, respectively, AV sequential pacing rate will occur between 60 and 130 bpm, but P-synchronous ventricular pacing will only occur between 60 and 120 bpm. In contrast, if the MTR is programmed above the MSR, AV sequential pacing will not occur above the MSR, but P-synchronous pacing (tracking) will occur above the MSR and up to the MTR. For example, in a DDDR programmed with a LRL of 60 bpm, MTR of 130 bpm, and MSR of 120 bpm, respectively, AV sequential pacing will occur at a SIR between 60 and 120 bpm, whereas P-synchronous pacing can occur at atrial rates between 60 and 130 bpm.

Frequently, the MSR is programmed equal to the MTR. A MSR above the MTR could be useful in unique clinical scenarios, such as: (1) undersensed paroxysmal atrial tachyarrhythmias (flutter/fibrillation) that prevent or delay appropriate mode switch, resulting in inappropriate tracking of these arrhythmias (see "Mode switch"), yet rate response is desired at higher rates than the programmed MTR; and (2) sick sinus rhythm with chronotropic

incompetence, intermittent paroxysmal atrial tachycardia, and inappropriate or undesired tracking at higher atrial rates.

Another dynamic component of *DDDR timing cycles* is the atrial-sensing window (ASW). The ASW is the portion of the RR cycle that is not part of the PVARP or the AVI. It is the period during which the atrial-sensed events are tracked. If the PVARP or AVI (or both) is extended, there may effectively be no ASW (i.e. TARP limits increased tracking rate) and then even a DDD pacemaker functions as a DVI system. Conversely, in DDDR pacing mode with a SIR higher than the MTR, it may appear that there is P wave tracking at rates greater than the MTR. Sensed atrial events in this case would inhibit sensor-driven atrial pacing, but ventricular pacing would take place at the SIR irrespective of the atrial event (functioning as DDIR).[6]

Base-rate behavior

A dual chamber pacemaker will obey the rules centered on the base-rate behavior and adjust its response based on sensed events. Base-rate behavior is non-programmable and varies among manufacturers and even among different models from the same manufacturer. Dual chamber pacemakers have historically been designed with a ventricular- or atrial-based timing system. Nowadays, most pacemakers have a combination of both ventricular- and atrial-based systems, referred to as hybrid-based behavior. Hybrid-based timing is designed specifically to avoid the potential rate variations or limitations that could occur with either a pure atrial- or ventricular-based timing system.

Designation of a pacemaker's timing system as atrial- or ventricular-based gained increased importance with the advent of rate-adaptive pacing. The difference between atrial- and ventricular-based dual chamber pacemakers was of little clinical importance in non–rate-adaptive pacemakers, although the difference created some minor confusion in the interpretation of paced ECGs. Thus, understanding base-rate behavior will help distinguish between appropriate or inappropriate pacemaker function.

Ventricular-based timing

The ventricular-based timing system is distinguished by a "fixed" VAI. A ventricular-sensed event occurring during the VAI will reset this timer (restarting the VAI again), while a ventricular-sensed event during the AVI terminates the AVI and initiates a fixed VAI. Thus, the AR interval (atrial stimulus to sensed R wave) is shorter than the programmed AVI in the presence of intrinsic AV conduction after an atrial-paced event. Since the VAI is fixed regardless of the presence or absence of AV conduction, the resultant atrial pacing rate (AA interval) and intrinsic RR interval are shorter than the programmed LRL, given as the difference between the AR and AV intervals (Figure 6.18A). When a native R wave occurs during the VAI, such as a ventricular premature beat, the fixed VAI is reset. This results in an RR interval rate equal to the LRL, determined by the sum of the VAI and AVI (Figure 6.19A). In both cases, a ventricular-sensed event resets the VAI, regardless of where it occurs.

Atrial-based timing

An atrial-based timing system is characterized by a "fixed" AA interval, regardless of AV conduction and VA interval. As long as the LRL pacing remains stable, there is no discernible difference between the two timing systems. In contrast to a ventricular-based system, an atrial-based timing system will not reset the basic AA timing if a sensed R wave occurs during the AVI (either intrinsic AV conduction or PVC). Hence, the atrial pacing rate will remain at the programmed LRL (Figure 6.18B). However, a PVC during the VAI (after the AVI has ended) can reset the AA timing, resulting in a longer AA interval and PVC–R interval than the programmed LRL (Figure 6.19B). Thus, the LRL may be violated in atrial-based timing, mimicking the compensatory pause commonly seen in normal sinus rhythm with ventricular ectopy.

Comparison of atrial- and ventricular-based systems

A difference between these two base rate systems is noticed in some circumstances, such as 2:1 AV block and rate-modulated pacing.

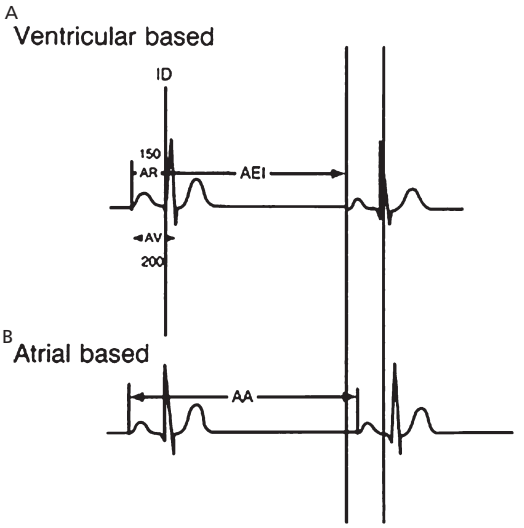


Figure 6.18 (A) Ventricular-based timing; fixed ventriculoarterial interval (VAI), the so-called atrial escape interval (AEI), is initiated by intrinsic R wave [intrinsic atrioventricular (AV) conduction] after an atrial-paced event (AR interval). The base pacing interval consists of the sum of the AR and the AEI; thus, it is shorter than the programmed minimum rate interval. The tracing represents a pacemaker programmed to a lower rate limit (LRL) of 60 bpm (pacing interval of 1000 ms) with an AVI of 200 ms, resulting in a fixed AEI of 800 ms (AEI = LRL − AVI). If AV nodal conduction occurs at 150 ms (AR interval = 150 ms), the conducted or sensed R wave inhibits ventricular pacing and initiates the 800-ms fixed AEI. Thus, the resulting atrial pacing and RR intervals are shorter than the programmed LRL by the difference between the AR and the AVI (950 ms or 63 bpm). (B) The atrial-based timing in patients with intact AV nodal conduction after an AR interval inhibits ventricular output but does not reset the basic AA timing interval. Thus, atrial pacing occurs at the programmed base rate. (Source: Levine PA, Hayes DL, Wilkoff BL, Ohman AE. Electrocardiography of rate-modulated pacemaker rhythms. Sylmar, CA: Siemens-Pacesetter, 1990. Reproduced with permission of St. Jude Medical, Inc.)

Intermittent 2:1 AV block at the lower rate will result in alternating heart rates between sequential AV pacing at programmed LRL and atrial pacing ventricular inhibition (AR) with a slightly faster rate than the LRL (Figure 6.20A). Although ventricular-based timing may result in an increase in the paced rate during AR pacing (see "Effects of ventricular- and atrial-based timing systems on rate-modulated pacing modes"), the LRL is never violated.

In contrast, an atrial-based timing system will demonstrate the alternation of the longer AVI with the shorter AR interval, which results in alternating faster and slower ventricular rates than, but never the same as, the programmed LRL (Figure 6.20B). When an AV complex follows an AR complex, the effective paced ventricular rate for that cycle is lower than the programmed LRL. In this scenario, atrial-based timing violates programmed LRL.

Interpretation of an ECG from a patient with a dual chamber pacemaker is helped by knowing whether the pacemaker has atrial- or ventricular-based timing. A ventricular-based timing system can be identified (using calipers) as a fixed VAI measured backwards from an atrial-paced event to the point of ventricular sensing, since a ventricular event (paced or sensed) always initiates a VAI (Figure 6.18A and Figure 6.19A). In contrast, an atrial-based timing system is identified as the fixed AA interval measured backwards from the atrial-paced event to the point of atrial sensing or ventricular sensing if a ventricular event occurs during the VAI (Figure 6.19B). However, this could be potentially challenging as inappropriate ventricular sensing, such as T wave oversensing, could be responsible for resetting the AA interval, which can only be proven by simultaneous acquisition of event markers (interpretation of cardiac events).

Effects of ventricular- and atrial-based timing systems on rate-modulated pacing modes

In a ventricular-based timing with enabled rate modulation, the effective atrial-paced rate theoretically may be considerably higher than the programmed MSR if AR conduction were present (Figure 6.21A). This is possible since the VAI shortens as the sensor input increases to the same extent, regardless of intrinsic AV conduction. For instance, a device programmed with a MSR of 150 bpm (400 ms) and a AVI of 200 ms will have a 200-ms VAI at the MSR. If AV conduction is intact with an AR interval of 150 ms, the actual A–A pacing interval would be 350 ms (AR interval + VAI, or 150 + 200 ms) or 171 bpm, which is markedly higher than the programmed MSR of 150 bpm. Although this potentially faster rate may not be a

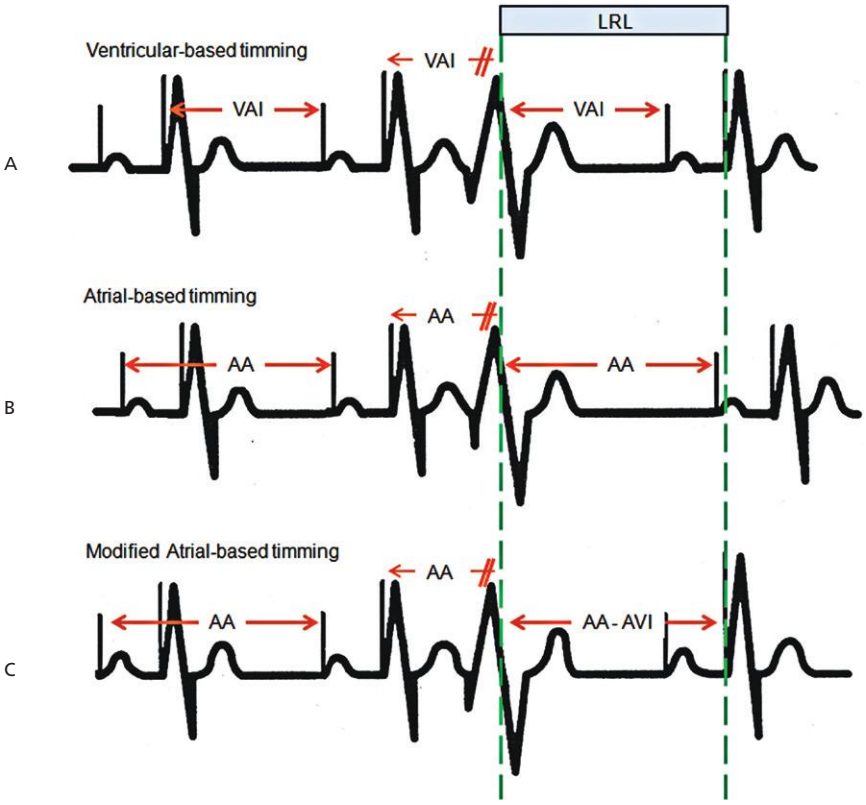


Figure 6.19 Different responses to premature ventricular contraction (PVC) depending on base-rate behavior. (A) Ventricular-based timing resets the ventriculoarterial (VA) interval (VAI) after PVC, so that the subsequent ventricular pacing (VP) interval is equal to the programmed base rate [PVC–VP interval equal to lower rate limit (LRL)]. (B) In contrast, atrial-based timing resets the AA interval after PVC, resulting in violation of the LRL due to the addition of the atrioventricular interval (AVI) (PVC–VP interval is longer than LRL). (C) After PVC, the modified atrial-based timing subtracts the AVI from the AA timing, resulting in a similar response (PVC–VP interval equal to LRL) to ventricular-based timing. (Source: Levine PA, Hayes DL, Wilkoff BL, Ohman AE. Electrocardiography of rate-modulated pacemaker rhythms. Sylmar, CA: Siemens-Pacesetter, 1990. Reproduced with permission of St. Jude Medical, Inc.)

problem or may even be advantageous for some patients, it could create problems for other patients. In contrast, atrial-based timing does not violate the MSR as intrinsic AV conduction (shorter AVI) does not affect or disturb the AA interval (Figure 6.21B).

Rate acceleration in a DDDR ventricular-based timing can be minimized by incorporating a rate-modulated AV delay. As the sinus or sensor-driven rate progressively increases, the rate-modulated AV delay causes the AVI to progressively shorten (Figure 6.21C). Shortening the AVI at faster rates (in response to sensor input) results in a shorter TARP (shorter AVI + PVARP), which increases the intrinsic atrial rate that can be sensed and reduces the likelihood of both a fixed-block upper rate response and functional atrial undersensing. Furthermore, the enabled rate-modulated AV delay will add to the VAI the time subtracted from the AVI, so that the ventricular rate drive is ruled by the sensor. Thus, rate-modulated AV delay provides a more physiological AVI at the faster rate and minimizes the degree of rate increase over the programmed MSR if AR conduction is intact.

Another option available in some devices is a forced extension of the VAI, which extends the VAI to avoid violation of the programmed MSR if intrinsic AV conduction is present (Figure 6.21D).

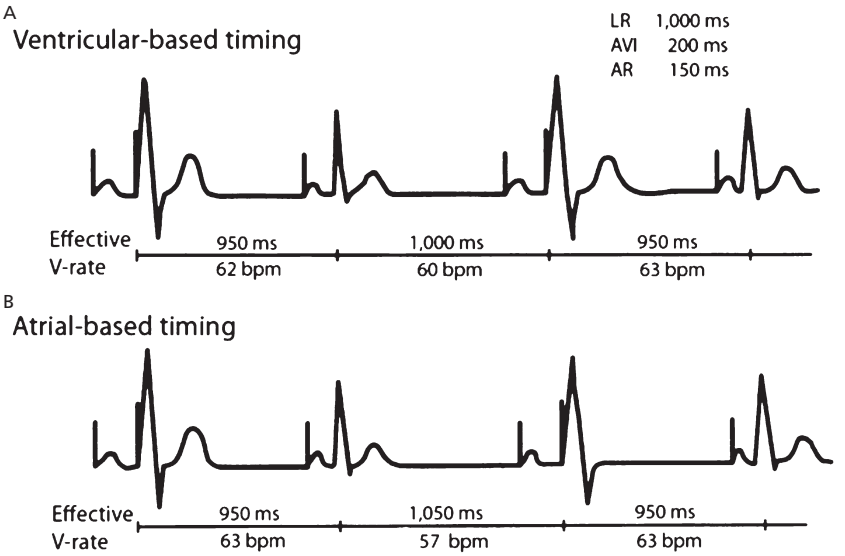


Figure 6.20 Schematic representations of 2:1 AV block during different base-rate behaviors. (A) With a ventricular-based timing system, the interval between consecutive AV- and AR-paced complexes (VR interval) is slightly faster (62 bpm) than the programmed LRL (60 bpm), while the interval between consecutive AR- and AV-paced complexes (RV interval) results in an effective ventricular rate at the lower rate limit (LRL) for that pacing cycle. (B) In an atrial-based timing system, the effective ventricular-paced rate alternates between rates that are faster and slower than the programmed rate. The cycle between an AR and AV complex results in a ventricular rate (RV interval) that is slower (57 bpm) than the programmed LRL. Meanwhile, the cycle between an AV and an AR complex causes the ventricular rate (VR interval) to be faster (63 bpm) than the programmed LRL. While the effective atrial pacing rate is stable at the programmed LRL regardless of base-rate behavior, the effective ventricular rate (that induces cardiac output) varies depending on base-rate behavior. (Source: Levine PA, Hayes DL, Wilkoff BL, Ohman AE. Electrocardiography of rate-modulated pacemaker rhythms. Sylmar, CA: Siemens-Pacesetter, 1990. Reproduced with permission of St. Jude Medical, Inc.)

Hybrid-based timing

Hybrid-based systems are intended to avoid the heart rate variations noted with pure atrial- or ventricular-based timing systems noted above (Figure 6.18 and Figure 6.20).[2] These systems use primarily an atrial-based timing, whereby an atrial-sensed or -paced event will reset the timing cycle (much like the sinus node itself), while ignoring a sensed R wave during stable AR pacing, and eliminating the rate acceleration in ventricular-based timing designs. To avoid drawbacks of atrial-based timing, the device will change to ventricular-based timing after PVCs or during intrinsic AV conduction (Figure 6.22A), whereas some other devices will demonstrate modified atrial-based timing after PVC (Figure 6.19C). Once an intrinsic R wave occurs (return of AV conduction) before the AVI expires, atrial-based timing is restored, but only after the AVI is first subtracted (Figure 6.22B). Nonetheless, understanding these hybrid systems has become more challenging with the release of novel algorithms to promote intrinsic AV nodal conduction (Figure 6.23).

Upper rate behavior

As the sinus rate increases (shorter PP interval) in a P-synchronous ventricular pacing mode (DDD, VDD), the atrial-sensed event terminates the VAI, inhibits atrial pacing, and starts an AVI. If the intrinsic AV conduction is shorter than the PV interval (time from an intrinsic P wave to a ventricular-paced event or sensed AVI), ventricular pacing is completely inhibited. However, P-synchronous ventricular pacing occurs in a 1:1

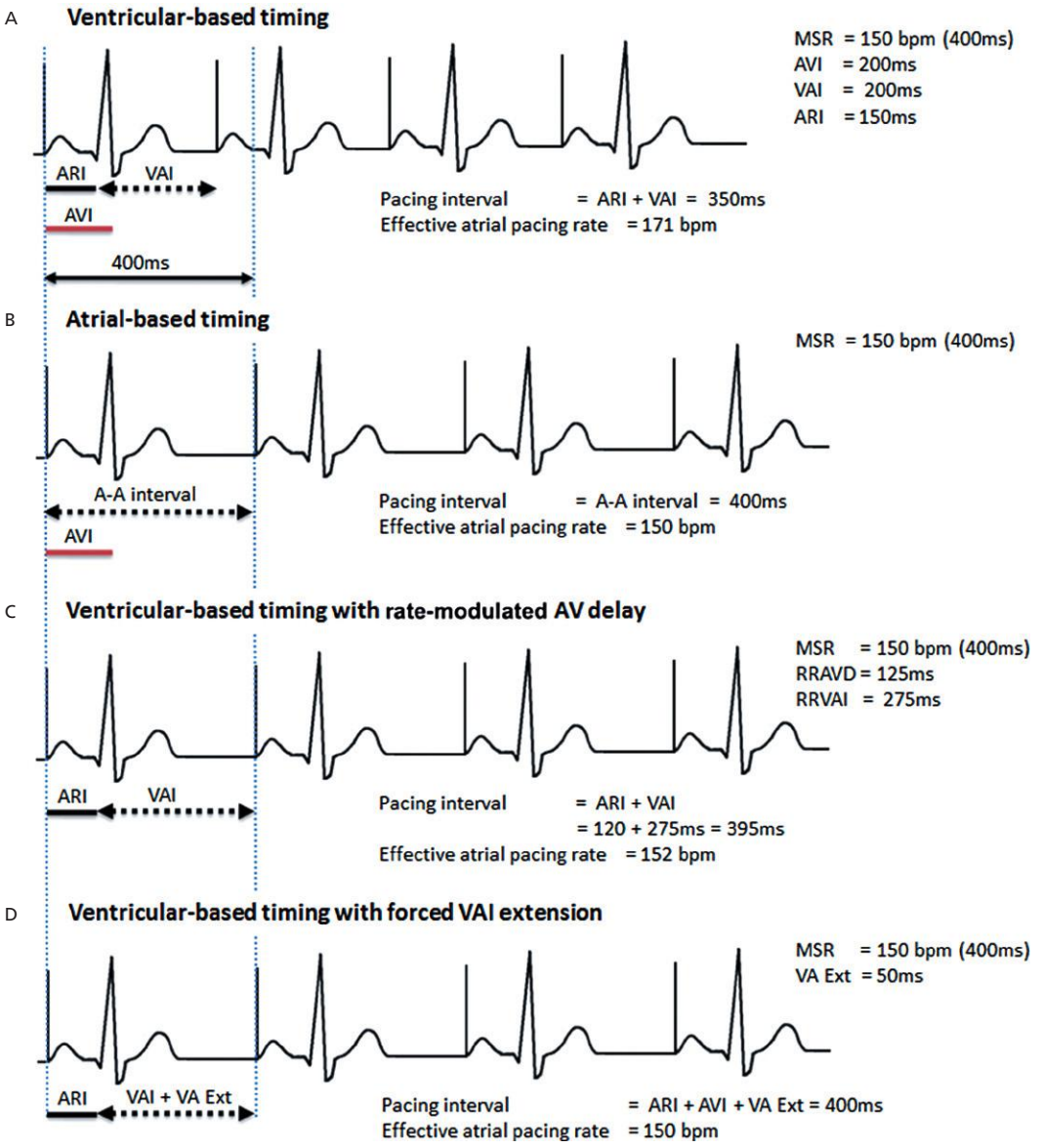


Figure 6.21 Effect of different base-rate behavior systems on rate-modulated pacing in patients with intact stable atrioventricular (AV) nodal conduction. (A) Ventricular-based timing. Even though the maximum sensor rate (MSR) is programmed at 150 bpm (400 ms), the effective atrial pacing rate achieved is 171 bpm. This can be explained since the effective atrial pacing rate is the sum of the interval from atrial stimulus to sensed R wave [AR interval (ARI)] and the ventriculoatrial interval (VAI), i.e. 150 + 200 = 350 ms (171 bpm). (B) Atrial-based timing. The R wave sensed during the AV interval (AVI) does not alter or reset the AA timing and atrial pacing rate occurs at the sensor-indicated rate (SIR). (C) Rate-modulated AV delay (RMAVD) in the ventricular-based timing system. RMAVD minimizes the increase in the paced atrial rate above the programmed SIR. A programmed RMAVD of 125 ms in ventricular-based timing (A) causes the AVI to shorten to 125 ms when the SIR reaches the MSR (75 ms subtracted from the programmed AVI of 200 ms). Subsequently, the 75 ms subtracted from the AVI are added to the VAI [rate responsive VAI or rate-modulated AV delay (RMVAI) of 275 ms], maintaining the programmed MSR of 150 bpm. However, if intact AV conduction (ARI) is present at 120 ms (5 ms faster than RMAVD), the overall AA pacing interval will be shorter by only 5 ms (395 ms or 152 bpm). (D) Forced extension of VAI in ventricular-based timing. A programmed VA extension (50 ms) is added to the VAI (AA timing = AR + VAI + VA extension) as a function of sensor input, providing an alternative (if available) to maintain pacing at MSR. (Source: (C) Levine PA, Hayes DL, Wilkoff BL, Ohman AE. Electrocardiography of rate-modulated pacemaker rhythms. Sylmar, CA: Siemens-Pacesetter, 1990. Reproduced with permission of St. Jude Medical, Inc.)

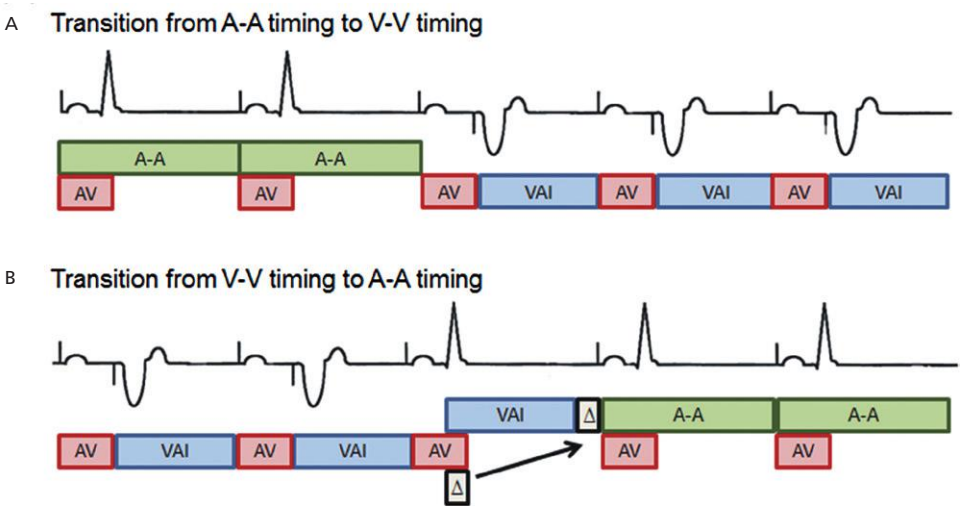


Figure 6.22 Hybrid base-rate behavior. (A) Timing changes from atrial- to ventricular-based behavior when intrinsic atrioventricular (AV) nodal conduction is no longer present. (B) Timing changes from ventricular- to atrial-based behavior after a ventricular-sensed event is noted (Δ, difference between PR interval and AV interval in the first cycle during which intrinsic conduction occurs). Δ is applied to the next VA interval (VAI) to provide a smooth transition without affecting VV intervals. (Source: Modified from Huizar JF, Kaszala K, Ellenbogen KA. Cardiac pacing modes and terminology. In: Sakena S, Camm AJ, eds. *Electrophysiological Disorders of the Heart*, 2nd Ed. Philadelphia, PA: Elsevier Saunders, 2012: 441–456. Reproduced with permission of Elsevier.)

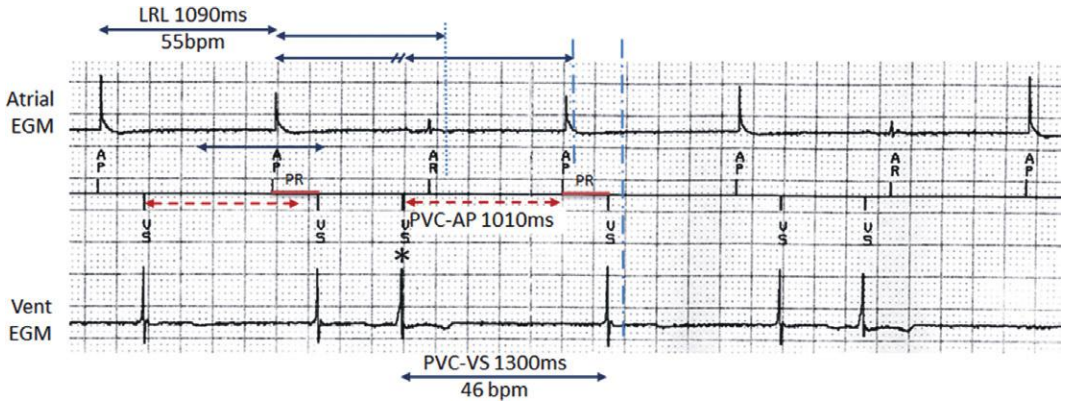


Figure 6.23 Modified atrial-based timing in managed ventricular pacing (MVP, Medtronic). MVP mode (AAI ⇔ DDD pacing mode) demonstrates atrial pacing at a lower rate limit (LRL) of 55 bpm (1100 ms) even with a PR interval (AP–VS) of 280–300 ms. A premature ventricular contraction (PVC, *) with a retrograde P wave is rendered refractory (AR, lacks resetting AA timing) since it occurs during the post-ventricular atrial refractory period (PVARP). In MVP mode, the PVC terminates the AA interval and re-initiates a modified AA timing which postpones the initially scheduled AP event (vertical red dashed line). Modified atrial-based timing is calculated as AA interval = LRL − 80 ms (1090 − 80 = 1010 ms) to minimize violation of the LRL. In a pure atrial-based timing, a new AA interval after a PVC would have resulted in a PVC–AP event at 1090 ms (blue dash–dotted line) with substantial violation of the LRL (PVC–VS of 1400 ms = 42 bpm).

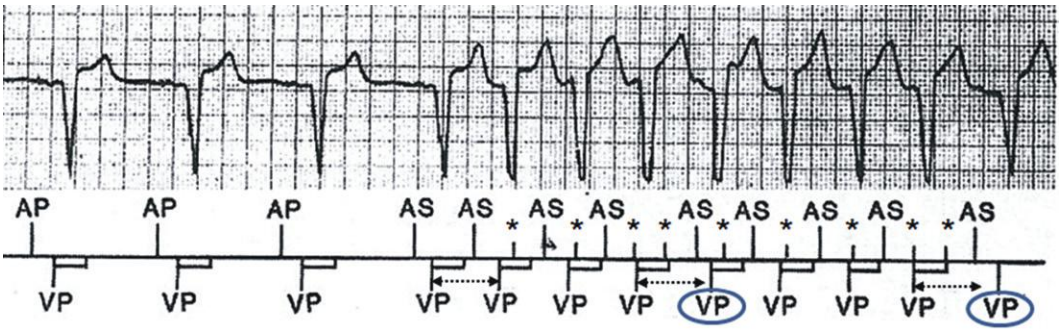


Figure 6.24 Upper rate behavior during non-sustained atrial tachycardia/flutter. As illustrated by the event markers, the ECG tracing represents initial atrioventricular (AV) sequential pacing (AP–VP) at the lower rate limit (55 bpm), followed by non-sustained atrial flutter. Rapid atrial signals are sensed (AS) and tracked with ventricular pacing (VP) at maximum tracking rate (MTR, dashed arrows). However, several atrial signals (*) fall within the post-ventricular atrial refractory period (PVARP) (represented by rectangles after VP). A 2:1 pacemaker behavior is noted in the first beats, while the fourth and eighth beats (ringed) demonstrate a 3:1 behavior since the prior two signals occurred during the post-ventricular blanking period (PVAB) and PVARP. (Source: Levine PA, Hayes DL, Wilkoff BL, Ohman AE. Electrocardiography of rate-modulated pacemaker rhythms. Sylmar, CA: Siemens-Pacesetter, 1990. Reproduced with permission of St. Jude Medical, Inc.)

relationship between the programmed LRL and the programmed MTR if the intrinsic AVI is longer than the programmed sensed AVI.

MTR determines the upper rate behavior or maximum paced ventricular rate in a P-synchronous pacing mode. MTR has also been referred to as "upper rate limit" and "ventricular tracking limit." MTR is limited by the TARP (AVI + PVARP; Figure 6.13). P-synchronous ventricular pacing (tracking) is delivered at the end of the AVI only if the MTR has been completed. If the MTR interval has not yet been completed at the end of the AVI, the release of the ventricular output pulse is delayed until the MTR interval ends (Figure 6.24). This delay has the functional effect of lengthening the PV interval and places the ensuing ventricular-paced beat closer to the next P wave. Eventually, a P wave will fall within the PVARP with lack of ventricular tracking as the AVI is never initiated. Thus, an atrial or sinus rate exceeding the programmed MTR can demonstrate an AV nodal Wenckebach-like behavior, as ventricular pacing can occur with a progressive lengthening of the PV interval with intermittent pauses and a group beating pattern on the ECG (Figure 6.25A).

When the PP interval (sinus rate) is shorter than the TARP, those P waves falling into the PVARP will not be tracked by ventricular pacing. As a result, an abrupt fixed-block behavior (2:1, 3:1, etc.) will occur depending on the native atrial rate and programmed PVARP (Figure 6.25B), which can result in serious symptoms. Thus, programming a long PVARP can result in a fixed-block response at a relatively low sinus or atrial rate.

Thus, upper rate behavior can demonstrate Wenckebach-like behavior or fixed block (e.g. 2:1). A 2:1 block behavior will be present when the PP interval or atrial rate is shorter than TARP. In contrast, a Wenckebach-like behavior will occur if the PP interval is shorter than the MTR but longer than the TARP (TARP = AVI + PVARP). This can be summarized by the equation: Wenckebach interval = MTR interval − TARP (Figure 6.25A).

DDDR pacing systems further increase the complexity of the upper rate behavior. Between the programmed LRL and MSR, the pacemaker can be driven by intrinsic atrial activity to cause P-synchronous ventricular pacing, or by a sensor with an input signal that is not identifiable on the ECG, or by both, to result in AV sequential or AR pacing (Figure 6.17). The eventual upper rate also depends on the type of sensor incorporated into the pacemaker and how the sensor is programmed.

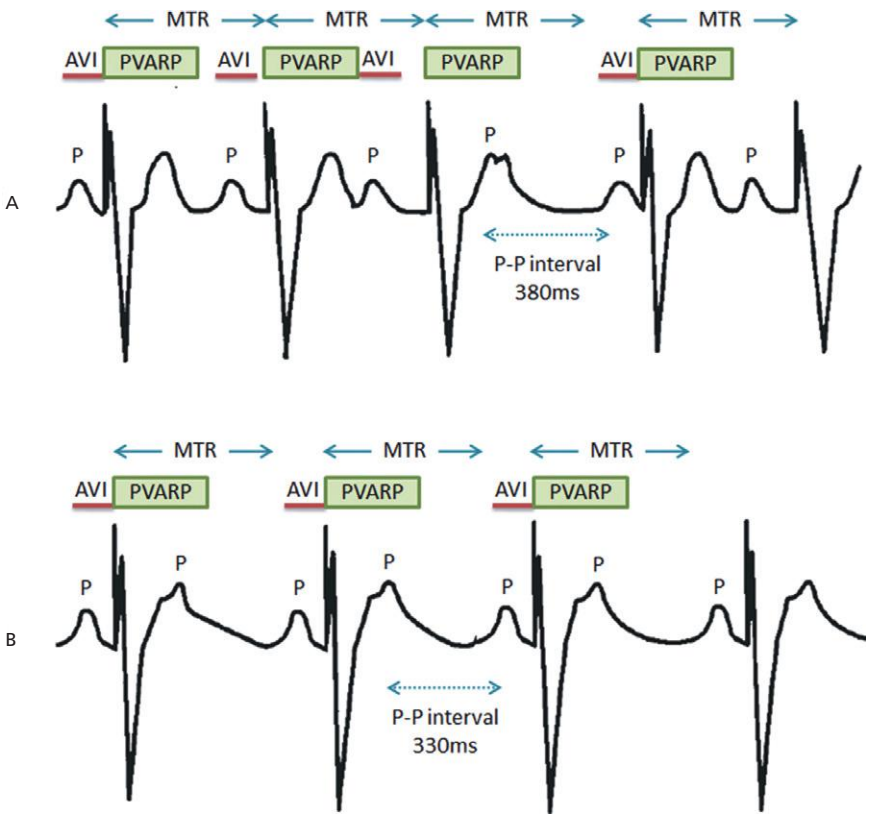


Figure 6.25 Wenckebach-like and 2:1 pacemaker behavior. A pacemaker is programmed with an atrioventricular interval (AVI) of 125 ms, a post-ventricular atrial refractory period (PVARP) of 225 ms and a maximum tracking rate (MTR) of 400 ms (Wenckebach interval = MTR − AVI + PVARP = 400 − 125 + 225 = 50 ms). (A) A Wenckebach-like behavior is noted since atrial rates or PP intervals are between 350 and 400 ms (50-ms Wenckebach interval). An atrial signal sensed within the atrial-sensing window (after completion of the PVARP) will initiate an AVI. Despite completion of the AVI (125 ms), P-synchronous ventricular pacing will not be delivered until the MTR is met with a PP interval of 380 ms (faster than the MTR of 400 ms), resulting in a longer than programmed AVI. This gradual prolongation of the PV interval [atrial sense (AS) to ventricular paced (VP) interval] ensures that ventricular pacing occurs closer to the next P wave, until the atrial event falls within the PVARP (the fourth P wave does not initiate an AVI). (B) In contrast, the pacemaker demonstrates a 2:1 AV block with PP intervals of 330 ms (PP interval faster than TARP = 125+225 = 350 ms), as AVI is not initiated in those P waves falling within the PVARP.

Rate enhancements

Several pacemaker algorithms are now available in pacemakers that may alter the pacing rate from either the programmed lower rate, sinus-driven or sensor-driven rates. These features are described below (Table 6.5).

Base rate during mode switch/fallback

During paroxysms of atrial fibrillation, pacemakers have automatic algorithms to switch pacing mode to a non-tracking mode (DDI, VDI, VVI), which avoids tracking high atrial rates (see "Mode switch"). The programmed LRL in a non-tracking pacing mode could be too low if heart rate is too slow during atrial fibrillation and higher heart rates may be needed to compensate for the loss of atrial transport. For this reason, devices have the ability to program a different LRL when mode switch occurs. For example, a pacemaker can be programmed DDD with an LRL of 60 bpm during sinus rhythm, whereas a higher base rate may be

Table 6.5 Rate smoothing/stabilization and fallback algorithms

Algorithm	*Device*	*Function/programmability*	*Indications*	*Notes/comments*
Rate smoothing (RS)[7,8] (Figure 6.27)	GDT, BS	Allow a percentage programmable increase or decrease (3–24% with 3% increments) in atrial and/or ventricular cycle length between LRL and MTR (P-synchronous pacing mode), MSR (adaptive pacing mode) or URL (non– P-synchronous or single chamber pacing modes)	Symptomatic variations of ventricular rate such as: sick sinus syndrome, AF/flutter, PACs, PVCs, and pacemaker Wenckebach-like behavior Pause-dependent induction of torsades de pointes	RS is not active if rate is above MTR or MSR and during VRR, search hysteresis, ATR fallback, PMT termination and sudden brady response
Atrial and ventricular rate stabilization (ARS, VRS)[16] (Figure 6.28)	MDT	ARS and VRS intend to eliminate long pauses after PAC or PVC, respectively. They do not respond to sustained tachyarrhythmias. VRS operates when the rate that corresponds to the RR median interval is less than or equal to a fixed rate of 85 bpm. Medial RR interval is the median value of the last 12 measured ventricular intervals (maximum rate, interval increment)	Symptomatic pause after PVC or PAC and pause-dependent induction of polymorphic VT (Td)	ARS is suspended during mode switch and detected arrhythmia. ARS and VRS cannot be enabled if rate hysteresis is programmed "on"
Ventricular rate regularization (VRR)[7] (Figure 6.26B)	GDT, BS	Operates between LRL and programmable VRR max pacing rate (60–150 bpm). Continually active in single chamber pacing modes. Active only after mode switch (non-tracking pacing mode) has occurred in dual chamber pacing modes	Increase biventricular pacing in CRT during AF/flutter Symptomatic variations of ventricular rate during atrial arrhythmias (AF/flutter) Pause-dependent induction of polymorphic VT (Td)	Updates VRR-indicated pacing rate on each cardiac cycle (pacing interval estimated on a weighted sum of the current V–V cycle length and previous VRR-indicated pacing intervals)
Fallback[7,8] (Figure 6.26)	GDT, BS	Occurs automatically after switch mode, gradually decreasing pacing rate to ATR/VTR fallback LRL, VRR rate (if enabled) Fallback mode (non-tracking pacing mode) Fallback time (how quickly paced rate will decrease to ATR)	Symptoms related to sudden drop in heart rate from MTR (while counters are met for mode switch to occur) to LRL or SIR	Only available when programmed to a dual chamber pacing mode RS, rate hysteresis, AV search and PVARP extension are disabled during fallback mode

AF, atrial fibrillation; ATR, atrial tachycardia response; BS, Boston Scientific; CRT, cardiac resynchronization therapy; GDT, Guidant; PAC, premature atrial contraction; PMT, pacemaker-mediated tachycardia; PVC, premature ventricular contraction; SIR, sensor-indicated rate; for other acronyms, see Table 6.3.

programmed to 70–80 bpm during mode switch to DDI, VDI, or VVI pacing mode. If rate modulation were also activated, any increase in sensor-driven rates would start at the appropriate base for the functional pacing mode at the time.

Fallback mode is a feature available in some pacemakers. This feature becomes active immediately after mode switch has occurred. The fallback mode (non-tracking pacing mode) will slowly and progressively decrease the pacing rate throughout a fallback programmable time from MTR (P-synchronous ventricular pacing while mode switch counter is met) to a programmable fallback LRL (Table 6.5). Fallback mode is intended to avoid a sudden heart rate drop from the MTR to the LRL or intrinsic ventricular rate that otherwise would occur without fallback (Figure 6.26). After fallback time has been completed, fallback LRL will be maintained in programmed fallback pacing mode, but it does not avoid heart rate variability between fallback LRL and maximum pacing rate, a special attribute of ventricular rate regularization (see "Rate smoothing/stabilization").

Rate smoothing/stabilization

These features were developed and are now available to avoid sudden and marked atrial and/or ventricular interval variability. Some of these features include *rate smoothing (RS)*, *atrial and ventricular rate stabilization (ARS, VRS)*, and *ventricular rate regularization (VRR)*. These algorithms have a slightly different function and programmability between manufacturers, as noted in Table 6.5.

One of the first algorithms, *rate smoothing*, uses the most recent RR interval, whether intrinsic or paced, to calculate an allowable increase or decrease in cycle length based on a programmable rate smoothing percentage[7] (Figure 6.27). For example, if the VV cycle length is stable at 900 ms during P-synchronous pacing with rate smoothing enabling at 6% increase, the subsequent VV cycle cannot accelerate by more than 54 ms (846 ms) if sinus rate suddenly accelerates.

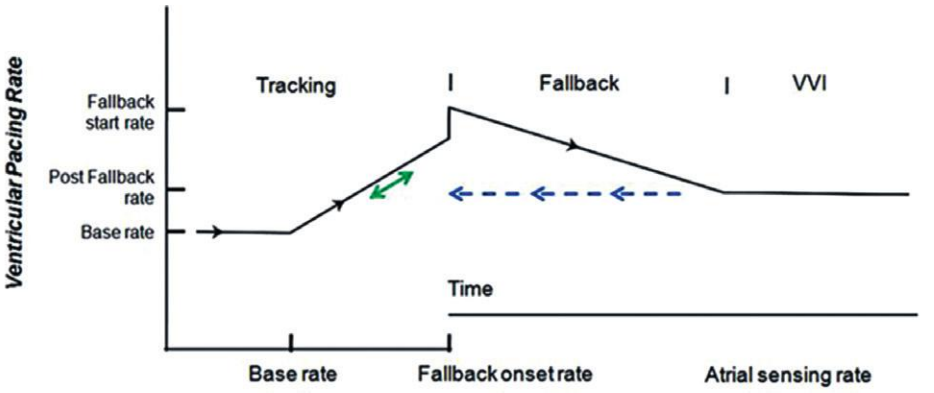
ARS and VRS have a similar rationale as rate smoothing. However, ARS and VRS work only during premature atrial contractions (PACs) and PVCs, respectively, and are rendered non-operational during sustained tachyarrhythmias (Table 6.5 and Figure 6.28). *Ventricular rate regularization (VRR)* is a variant of rate smoothing; however, it will only function during mode switch (Figure 6.26B).

Rate-modulated pacing (sensor input to base rate pacing)

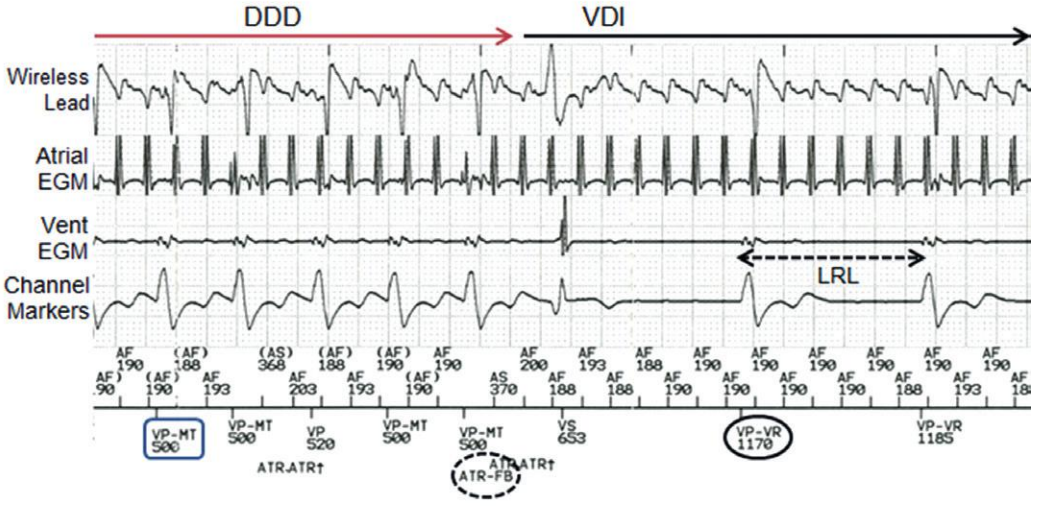
DDDR pacing can result in a type of rate smoothing. If the sensor is optimally programmed, then as the atrial rate exceeds the MTR (during exercise), the RR interval displays minimal variation between sinus-driven and sensor-driven pacing. As shown in Figure 6.29, the variation in RR interval is markedly lessened with the sensor "on" (DDDR) rather than "passive" (DDD). In the DDDR mode, the RR interval is allowed to lengthen only as much as the difference between the MTR and the sensor-indicated rate.

Figure 6.26 Fallback mode and ventricular rate regularization features. (A) Diagram illustrating the fallback mode feature. P-synchronous pacing (DDD mode) occurs between the base rate and up to the maximum tracking rate (MTR). Once the atrial rate exceeds the mode switch rate (also referred as the fallback onset rate), pacing mode will switch from DDD to a programmable non-tracking pacing mode (DDI, VDI, VVI). The fallback (FB) feature prevents sudden drop on ventricular pacing (VP) from the MTR to the lower rate limit (LRL). When fallback time is enabled, the device will slowly decrease the VP rate from the MTR to the LRL in the timeframe instructed. Once atrial rate decreases below the mode switch rate, the device will return back to DDD pacing mode. (B) DDD pacing mode initially tracks an atrial flutter of 300 bpm (3:1 block) at an MTR of 120 bpm (VP–MT 500 ms; blue square) until mode switch counters are met and the pacing mode switches to VDI (ATR-FB, dashed oval) at the LRL of 50 bpm (1200 ms). A sudden drop in VP rate (from MTR 120 to 52 bpm) occurs since fallback is not enabled. The VP rate occurs slightly higher than the programmed LRL of 50 bpm (VP–VR 1170 ms or 52 bpm, ringed with a solid oval) due to ventricular rate regularization (VRR, max rate 100 bpm) after an intrinsic R wave at 653 ms. (C) Fallback is enabled with a 15-s fallback time in the same patient as in (B). After the mode switch rate counter is met and the device switches from DDD to VDI pacing mode (ATR–FB), the VP rate gradually decreases (VP–FB, solid circles) from the MTR to the LRL (dashed arrow), avoiding the sudden drop in VP rate.

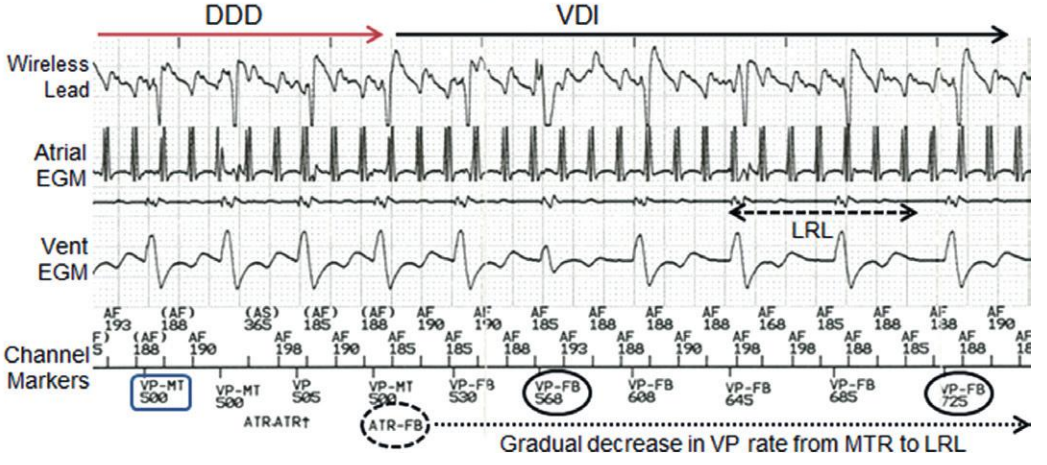
A


Ventricular Pacing Rate
Fallback start rate
Post Fallback rate
Base rate
Tracking
Fallback
VVI
Time
Base rate
Fallback onset rate
Atrial sensing rate

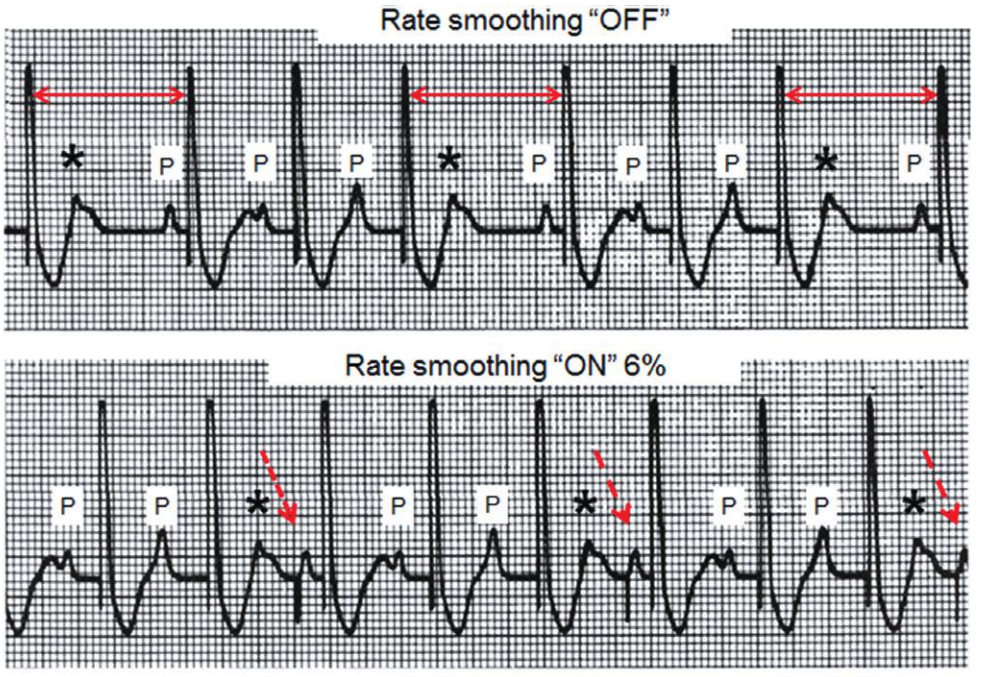
B


DDD
VDI
Wireless Lead
Atrial EGM
Vent EGM
Channel Markers
LRL
VP-MT 500
VP-MT 500
VP 520
VP-MT 500
VP-MT 500
VS 653
VP-VR 1170
VP-VR 1185
ATR-ATR↑
ATR-FB

C


DDD
VDI
Wireless Lead
Atrial EGM
Vent EGM
Channel Markers
LRL
VP-MT 500
VP-MT 500
VP 505
VP-MT 500
VP-FB 530
VP-FB 568
VP-FB 608
VP-FB 645
VP-FB 685
VP-FB 725
ATR-ATR↑
ATR-FB
Gradual decrease in VP rate from MTR to LRL

A



B

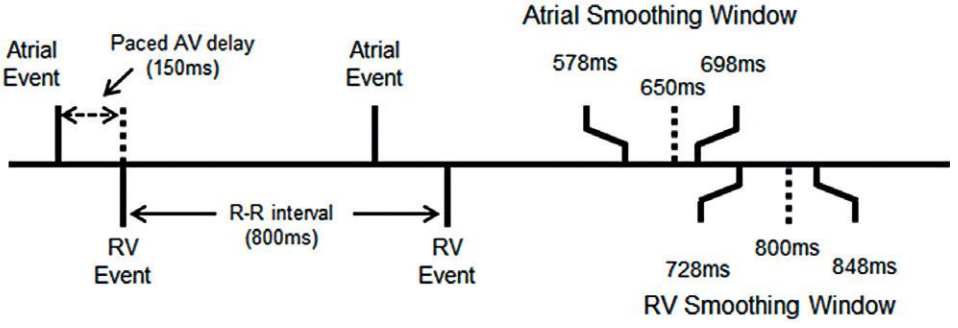


Figure 6.27 Rate smoothing. (A) ECG demonstrates a Wenckebach-like behavior (P-synchronous ventricular pacing) with significant pauses (solid red arrows) due to an atrial rate above the maximum tracking rate (MTR). P waves gradually occur sooner after ventricular pacing (VP) until a P wave falls within the post-ventricular atrial refractory period (PVARP) (*), failing to initiate AVI and lacking P-synchronous ventricular pacing. An enabled rate smoothing down (6% of the preceding RR interval) will minimize pauses by delivering atrioventricular (AV) sequential pacing (dashed red arrows) after P wave during PVARP (*), allowing the VV interval to lengthen by only 36 ms over the preceding VV interval at an MTR of 100 bpm. (B) Calculation of atrial and ventricular smoothing windows. With a previous RR interval of 800 ms, programmed AV delay of 150 ms and enabled rate smoothing up and down (9% and 6%, respectively), the ventricular smoothing window is 728–848 ms (800 − 9% or 72 ms to 800 + 6% or 48 ms = 728–848 ms), whereas the atrial smoothing window is 578–698 ms (ventricular smoothing window − AV delay = 728 − 150 ms to 848 − 150 ms = 578–698 ms). (Source: (A) Boston Scientific Corporation. Reproduced with permission of Boston Scientific. (B) Cognis TM 100-D device manual. Reproduced with permission of Boston Scientific.)

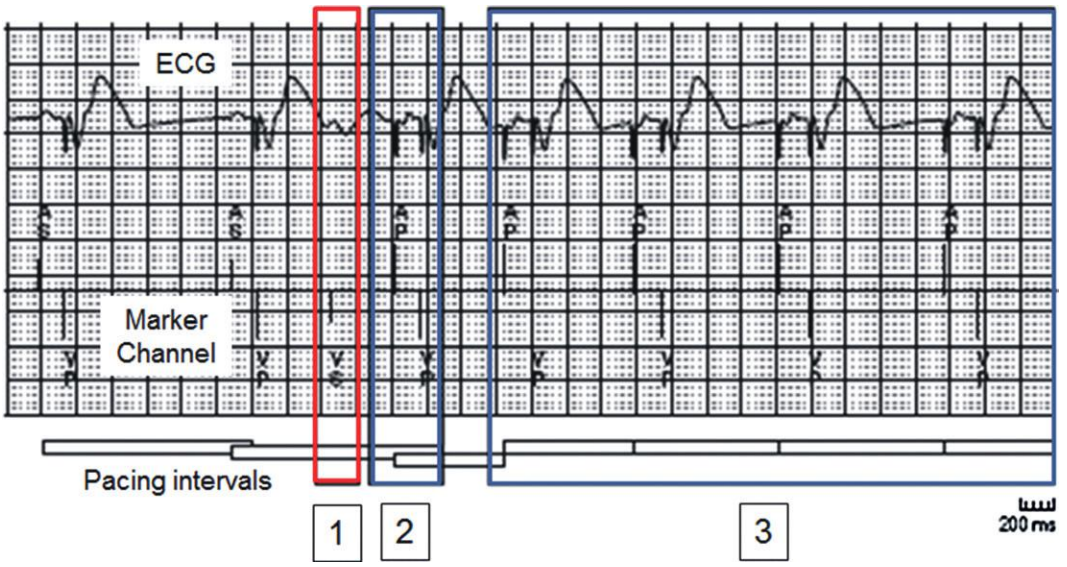


Figure 6.28 Ventricular rate stabilization (VRS). A short coupled premature ventricular contraction (1, VS) causes atrioventricular (AV) sequential pacing at the previous V–V interval plus interval increment (2), with (3) a gradual prolongation of AV sequential pacing. (Source: Entrust ICD system—Reference Manual, Medtronic, Inc. Reproduced with permission of Medtronic, Inc.)

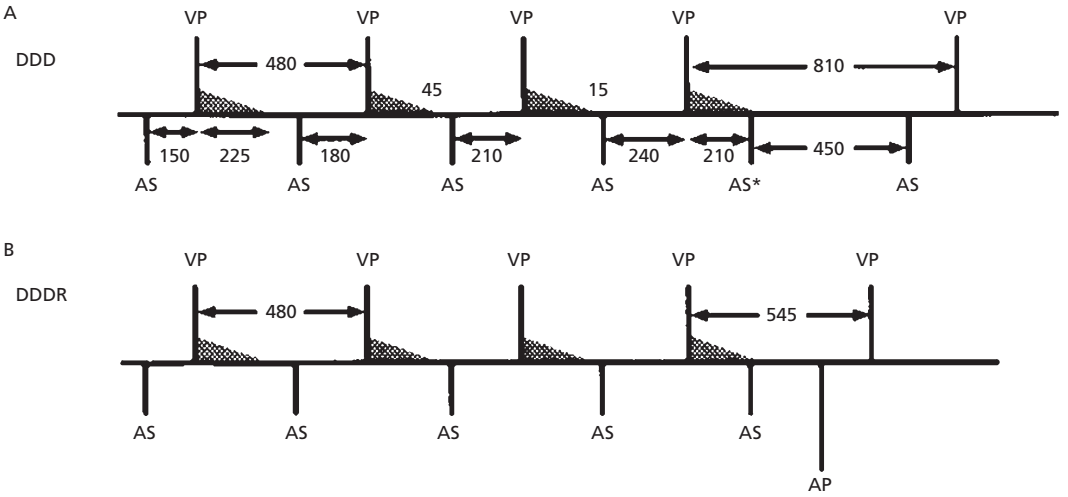


Figure 6.29 Rate modulation (DDDR pacing mode) acting as rate smoothing. (A) DDD pacing mode demonstrates Wenckebach behavior as the atrial rate (450 ms, 133 bpm) is higher than the maximum tracking rate (MTR) (125 bpm). The fifth atrial-sensed (AS) event (*) [210 ms after the preceding ventricular paced (VP) event] is sensed but does not trigger ventricular pacing [the atrioventricular interval (AVI) is not initiated] since it falls within the post-ventricular atrial refractory period (PVARP) (225 ms). The resultant VP–VP interval is 810 ms (74 bpm), significantly longer than the preceding cycles of 480 ms (125 bpm). (B) DDDR pacing mode (with otherwise identical programmed intervals as in A) avoids the prolonged VP–VP interval, due to a sensor-driven pacing rate of 545 ms (110 bpm). Thus, only a 65-ms difference exists between the programmed upper rate limit (URL) and the sensor-indicated rate—a minor difference in cycle lengths. (Source: Modified from Markowitz TH. Dual chamber rate responsive pacing [DDDR] provides physiologic upper rate behavior. *Physio Pace* 1990; 4: 1–4. Medtronic, Inc. Reproduced with permission of Medtronic, Inc.)

Algorithms to allow intrinsic sinus rate

Different algorithms exist to search for and allow the intrinsic sinus rate to predominate (Table 6.6). These algorithms may be responsible for intrinsic or pacing rates below the SIR and/or the LRL.

Rate hysteresis (first-generation algorithm) allows prolongation of the first pacemaker escape interval to a programmed hysteresis rate only after a sensed intrinsic event occurs above a programmed LRL (Figure 6.30A). In contrast, *scan hysteresis* (Figure 6.30B), *search hysteresis*, and *sinus preference* (Figure 6.30C) automatically lower pacing rate after determined paced beats or interval to a programmed hysteresis rate or sinus preference zone, respectively, searching for an intrinsic sinus rate.

Rest rate is intended to reduce paced rhythm during rest, including sleep, in order to mimic physiological decrease in heart rate during physical inactivity. Other contemporary pacemakers offer a "circadian response," or "*sleep rate*," that allows a lower rate to be programmed for the approximate time during which the patient is sleeping. A separate, potentially faster LRL may then be programmed for waking hours. For example, the LRL during waking hours may be programmed to 70 bpm and during sleeping hours to 50 bpm. This feature is tied to a clock, and the usual waking and sleeping hours are programmed into some pacemakers, while other pacemakers require an additional verification of inactivity by sensor to allow decrease in the LRL to occur.

These algorithms have different programmable settings, search and trigger thresholds and interventions (Table 6.6). Overall, these features are believed to lower battery drain and increase longevity, particularly in patients with high pacing thresholds.

Algorithms for cardioinhibitory neurogenic syncope

Different algorithms have been developed to respond to the sudden drop in intrinsic heart rate observed in subjects with severe cardioinhibitory neurogenic syncope. Some of these algorithms include hysteresis rate, sudden bradycardia response (SBR), and rate drop response (RDR). Algorithm features vary in the trigger and response in this clinical scenario (Table 6.7).

Hysteresis rate (described above) has been proposed as a strategy to prevent a sudden decrease of heart rate in cardio-inhibitory neurogenic syncope (Figure 6.31) only if "advanced functions" (cycle count, intervention rate and duration, recovery time) are enabled.[5,8,9] This algorithm intervenes if the patient's intrinsic rate falls below the "hysteresis rate" for a period longer than the "cycle count" setting, pacing at the "intervention rate" for a period stipulated by the "intervention duration" setting. The device will return to the programmed base rate setting as instructed by the "recovery time" parameter.

Similarly, *RDR* or *SBR* reacts to a defined drop in heart rate by pacing at an elevated rate in both chambers for a specific programmed duration (Figure 6.32).[8–10] At the conclusion of the programmed duration, the pacing rate gradually returns to the programmed lower rate (Table 6.7).

Most recently, sensors that assess beat-to-beat contractility (Closed Loop Stimulation, Biotronik) are being used to prevent cardioinhibitory neurogenic syncope, with the rationale that they can detect early changes in autonomic tone and contractility preceding syncope. Thus, these sensors can react accordingly with a proportional increase in pacing rate to prevent inappropriate drop in heart rate.[5]

Overall, there are limited and controversial clinical data supporting the beneficial effect of these algorithms in the prevention of cardioinhibitory neurogenic syncope.[3,11–13]

Mode switch

The mode switch feature indicates that the pacemaker is capable of automatically reprogramming itself from one pacing mode to another as a result of an inappropriate rapid atrial rhythm.[14,15] The change in pacing mode occurs after specific criteria for atrial arrhythmia have been met. Mode switch occurs between a baseline P-synchronous (tracking) pacing mode [DDD(R), VDD(R)] to a non-tracking pacing mode [DDI(R), VVI(R), VDI(R)].

Mode switch is particularly useful for patients with paroxysmal supraventricular arrhythmias; otherwise rapid ventricular pacing may occur in DDD or DDDR pacing mode (see "Upper rate

Table 6.6 Algorithms to allow intrinsic sinus rate (SR)

Algorithm	*Settings*	*Search/trigger*	*Intervention*	*Notes/comments*
Rate hysteresis (MDT,SJM, BS) (Figure 6.30A)	Hysteresis rate or offset (HyR)	A sensed event above base rate or LRL will trigger HyR	Pacing rate is lowered from the base rate or SIR to the HyR as long as intrinsic events are sensed	First occurrence of a pace event at HyR will re-establish pacing rate to base rate or LRL Available in single (AAI® or VVI®) or dual chamber pacing modes
Search hysteresis (SJM, BS)	Hysteresis rate or offset (HyR) Search interval	A sensed event above base rate or LRL will trigger HyR Some devices (SJM, BS) provide a search interval to lower the pacing rate to HyR, looking for an intrinsic event	Pacing rate is lowered from the base rate or SIR to the HyR as long as intrinsic events are sensed	First occurrence of a pace event at HyR will re-establish pacing rate to base rate or LRL Available in single (AAI® or VVI®) or dual chamber pacing modes
Scan hysteresis (BTK) (Figure 6.30B)	Hysteresis rate (HyR) Number of cycles (1–10)	After 180 paced cycles, the pacing rate is lowered to HyR for a programmed number of cycles	If no SR is sensed above HyR, pacing will be restored at LRL or SIR Intrinsic rate will be allowed if SR is sensed above HyR	
Sinus preference (SP)[10] (MDT) (Figure 6.30C)	SP zone Search interval	Sinus search: after search interval expires, a gradual drop from SIR to SP zone limit will occur until SR is sensed or rate drops to SP zone limit. If no AS events are noted for eight paced beats at SP zone limit, a gradual increase to SIR will occur	If AS is noted, SR is allowed to predominate below SIR unless or until it drops below SP zone limit	Second modality: sinus breakthrough operation initiates only if SR is detected above SIR, tracks SR within the SP zone limit, but never below the LRL Cannot be enabled with MVP (AAIR ⇔ DDDR)[10]
Sleep rate[10] (MDT)	Bed time Wake time Sleep rate	During 30 min following bed time, pacing rate gradually decreases from LRL to sleep rate During 30 min following wake time, pacing rate gradually restored to LRL	Suspends LRL and replaces with a slower rate than LRL (sleep rate)	In rate-modulated modes, SIR increases in the presence of sensor-indicated activity
Rest rate (SJM)	Rest rate	Device analyzes activity data for a 7-day period Triggered if sensor detects inactivity or rest >15–20 min	LRL decreases to rest rate. Heart rate increases to base rate when activity is sensed	This setting is operational regardless of day time
Night rate program (BTK)	Night rate Night begins Night ends	Programmable schedule for any time of the day or night (nominally begins at 10:00 PM)	LRL is lowered to a programmable night rate	In rate-modulated modes, the night program is temporarily suspended during accelerometer-indicated activity

AS, atrial sensed; BS, Boston Scientific; BTK, Biotronik; MDT, Medtronic; St. Jude Medical; SIR, sensor-indicated rate; for other abbreviations, see Table 6.3.

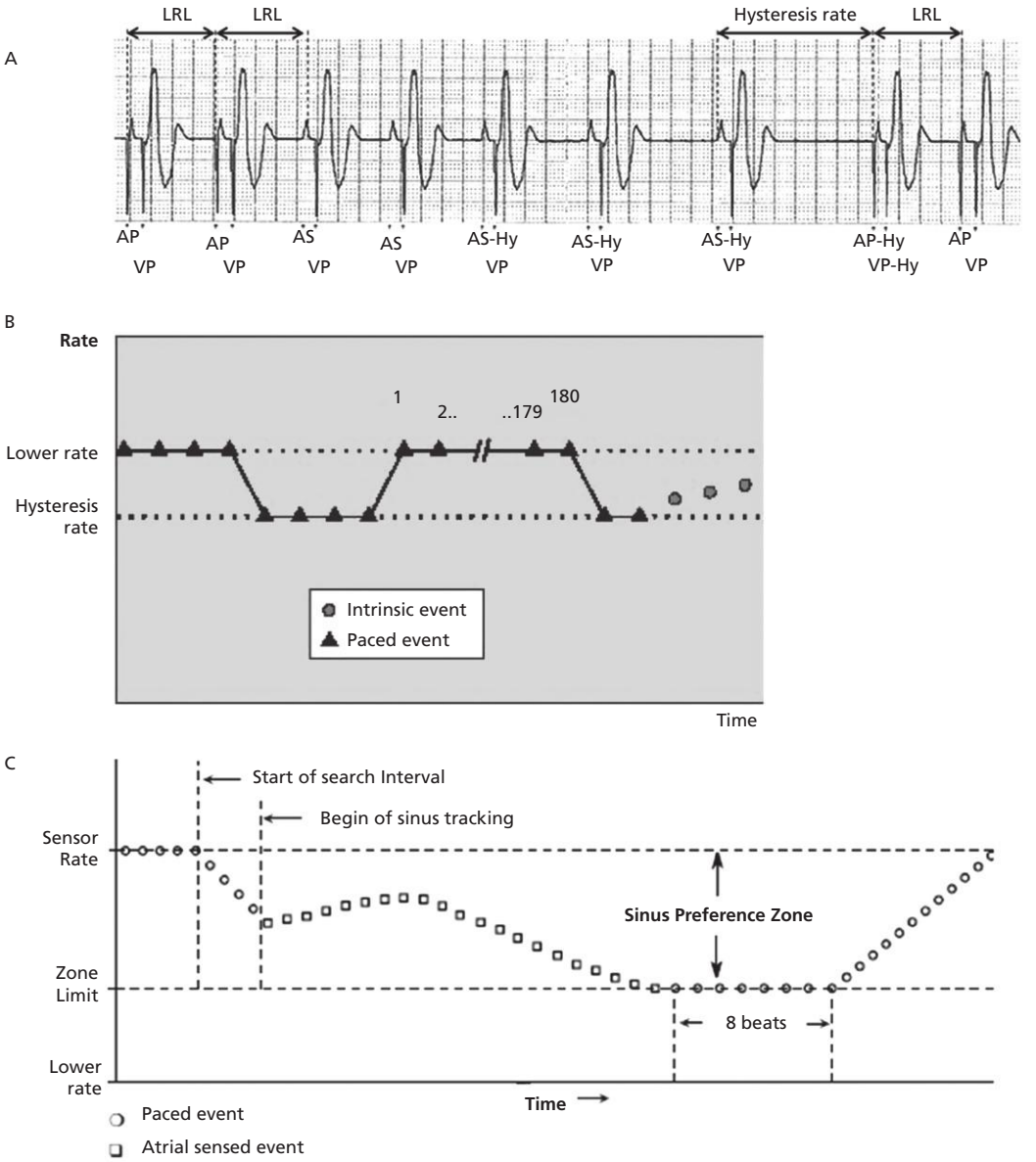


Figure 6.30 Algorithms to allow intrinsic sinus rate. (A) Rate hysteresis, (B) scan hysteresis, (C) sinus preference. Refer to Table 6.6 for details on function of these pacemaker features. (Source: (A) Insignia I Ultra System Guide, models 1190/1290/1291. St Paul, MN: Guidant Corporation, 2006. Reproduced with permission of Medtronic, Inc. (B) CYLOS Pacemaker Feature Handbook, section 2.2.2, page 33 and last published 3/4/2009 (Reference MN010), Biotronik, Lake Oswego, Oregon, USA. Reproduced with permission of Biotronik. (C) Adapta, Sensia, Versa Pacemaker reference Guide. St Paul, MN: Medtronic, Inc., 2006. Reproduced with permission of Medtronic, Inc.)

Table 6.7 Algorithms for cardioinhibitory neurogenic syncope

Feature	*Trigger*	*Response/intervention*	*Comments*
Rate hysteresis with advanced functions (SJM, BTK) (Figure 6.31)	Heart rate falls below *hysteresis rate* for a period longer than *cycle count*	DDD pacing at *intervention rate* setting for the time specified in *intervention duration*	Device returns to LRL after *recovery time* is completed
Rate drop response (RDR) (MDT) (Figure 6.32A)	Two triggers available: **1** Drop detection: if sensed or paced ventricular rate drops by the programmed *drop size* or more to below the programmed *drop rate* within the programmed *detection window* **2** Low rate detection: if atrium or ventricle is paced at LRL for a consecutive number of *detection beats*	Pacing at *intervention rate* for a programmed *intervention duration*. When intervention duration expires, pacing slowly decreases in approx. 5-bpm steps until the intrinsic rate is sensed or LRL is reached	Low rate detection is only applicable to DDI pacing mode If the intrinsic ventricular rate drops too slowly to meet the RDR drop detection criteria, the pacemaker paces at LRL if the intrinsic rate drops below the programmable lower rate
Sudden bradycardia response (SBR) (BS) (Figure 6.32B)	SBR is confirmed after continuously sensed atrial rate for a programmable time (*SBR detect time* 1–15 min) suddenly decreases such that atrial pacing occurs at the LRL or SIR for a programmable *number of beats* (1–8 cycles)	Pacing occurs in DDD(R) mode at the greater of either (1) the previous average atrial rate plus the SBR *therapy rate offset*, not to exceed the MTR, or (2) SIR (DDDR mode only) Therapy rate offset is calculated by using average atrial rate before bradycardia and adding programmable positive offset	SBR minute ventilation (MV) sensor provides ability to inhibit SBR if SBR rate and duration criteria are met but patient's current MV sensor input is lower than a programmed value (MV offset) Rate smoothing is not available if SBR is enabled

BS, Boston Scientific; BTK, Biotronik; MDT, Medtronic; St. Jude Medical; SIR, sensor-indicated rate; for other acronyms, see Table 6.3.



Figure 6.31 Advanced rate hysteresis. DDD pacing mode at 100 bpm (intervention rate) occurs in response to a drop in heart rate (63 bpm) below a programmed hysteresis rate of 65 bpm. After 256 cycles of pacing at 100 bpm, pacing is suspended for the pacemaker to "search" for the intrinsic lower rate. If the lower rate is greater than the hysteresis rate, pacing is inhibited until the rate again falls below the hysteresis rate. (Source: Lloyd MA, Hayes DL, Friedman PA. Programming. In: Hayes DL, Lloyd MA, Friedman PA, eds. *Cardiac Pacing and Defibrillation: A Clinical Approach.* Armonk, NY: Futura, 2000; 247–323. Reproduced with permission of the Mayo Foundation.)

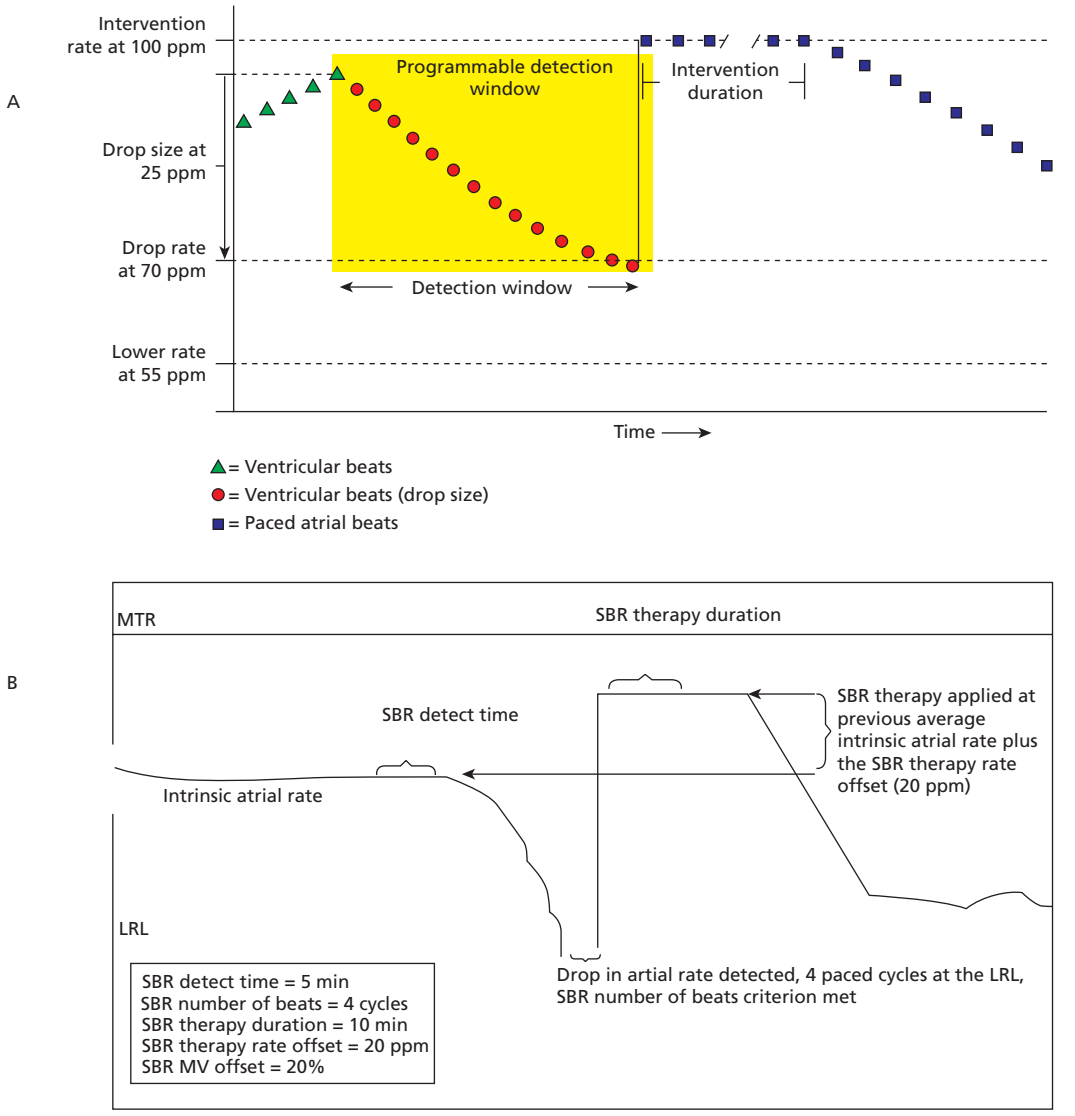


Figure 6.32 (A) Rate drop response (RDR). Algorithm detects a heart rate drop based on a programmed drop size of 25 bpm and a drop rate at 75 bpm with a 1-min detection window. Thus, the device responds by pacing at 100 bpm (intervention rate) for a programmable period of time. (B) Sudden bradycardia response (SBR) intervenes by pacing at 20 bpm above the intrinsic atrial rate (SBR therapy rate offset) for a total of 10 min [SBR therapy duration) in response to a drop in the atrial rate, meeting the SBR criteria (after 5-min detection time, a drop in heart rate occurs, pacing four cycles at the lower rate limit (LRL)]. MV, minute ventilation, see Table 6.7 for details. MTR, maximum tracking rate. (Source: (A) Adapta, Versia and Sensia Manual, Medtronic, Inc. Reproduced with permission of Medtronic, Inc. (B) Altrua Pacemaker Manual. Reproduced with permission of Boston Scientific.)

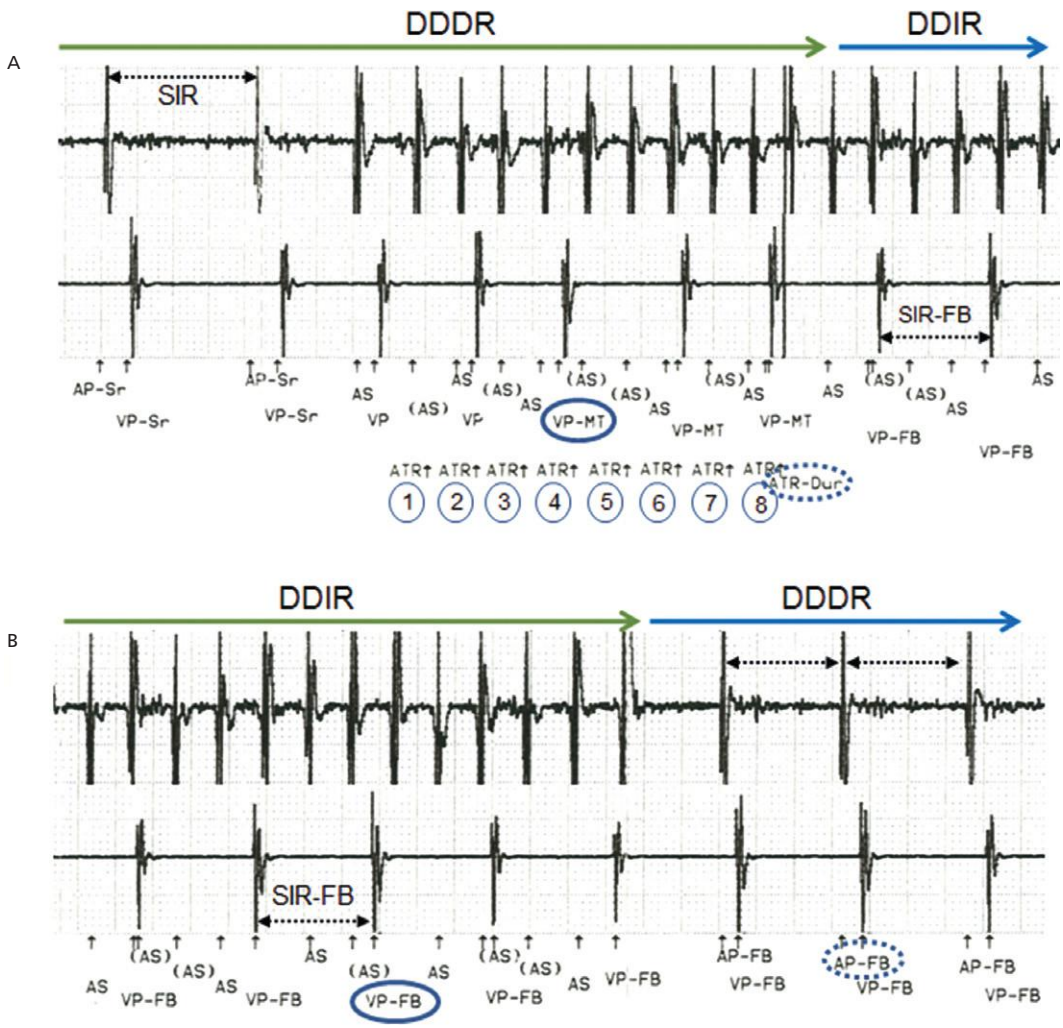


Figure 6.33 Mode switch. (A) Pacing mode changes from DDDR to DDIR after the mode switch duration criteria (eight events—ATR) are met (ATR-Dur, dotted blue oval). The initial tracing demonstrates atrioventricular (AV) sequential pacing at the sensor-indicated rate (SIR, AP-Sr and VP-Sr). After the second beat, atrial flutter starts spontaneously tracking atrial-sensed (AS) events [outside the post-ventricular atrial refractory period (PVARP)] at the programmed maximum tracking rate (MTR) (VP–MT, solid blue oval) while the DDDR pacing mode continues. Once a mode switch criterion is met, right ventricular (RV) pacing will occur at the programmed mode switch/fallback heart rate (SIR–FB) without tracking AS) events (DDIR). (B) The same patient demonstrates ventricular pacing (VP) at the fallback (VP-FB) rate while the patient is in atrial flutter. After sudden termination of his atrial flutter, AV sequential pacing occurs at the fallback rate (AP–FB and VP–FB), returning to DDDR pacing mode once the criterion is met.

behavior"). This feature avoids inappropriate tracking of atrial tachyarrhythmias and pacemaker Wenckebach-like behavior while an atrial arrhythmia is present (Figure 6.33).

Mode switch algorithms have become more refined and have slight variations between pacemaker manufacturers and models (Figure 6.34). Most pacemakers have a programmable mode switch rate. Only until the atrial mode switch rate is met for a specified number of intervals (often a non-programmable counter) or time duration, the pacemaker is automatically reprogramed

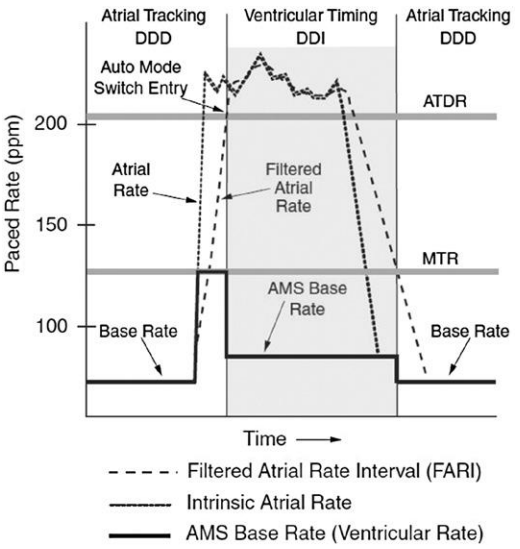


Figure 6.34 Diagram illustrates switching from atrial tracking to a non-tracking mode (DDI). During DDI pacing a separate base rate may be programmed in some devices. After the atrial arrhythmia has terminated, the mode will switch back to the DDD mode. ATDR, atrial tachycardia detection rate. (Source: Bradycardia Devices—Help Manual. Sylmar, CA 2008, St. Jude Medical, Inc. Reproduced with permission of St. Jude Medical, Inc.)

to a non-atrial tracking mode and remains in this mode until a specified number of long intervals have occurred and altered the counter, at which point mode switching reverts to an atrial tracking mode (Figure 6.33B). Because a counter must be met before mode switching occurs, short transient bursts of atrial arrhythmias may still be tracked, and other algorithms, such as rate smoothing (see "Rate enhancement"), may be needed to prevent symptomatic palpitations.

The non-tracking mode to which the mode switch occurs is frequently a programmable option. It is most commonly DDIR and, less commonly, VDIR or VVIR. DDIR may be the preferable non-tracking mode switch as it will allow maintenance of AV synchrony after the atrial tachyarrhythmia has terminated, but before mode switching has been declared completed.

Appropriate mode switch depends on proper sensing of high atrial rates. Thus, identifying rapid atrial events that occur during the refractory period is essential. In many dual chamber pacemakers, this period includes the terminal portion of the AV delay and the latter portion of the PVARP. The first part of the PVARP (absolute portion), referred to as the PVAB, prevents sensing of the far-field R wave. However, some pulse generators are limited by atrial events that fall within the TARP (AVI + PVARP) and rely on algorithms to detect atrial tachyarrhythmias (see "Algorithms for atrial arrhythmia detection and atrial pace/sense competition").

To ensure sensing of pathological atrial tachyarrhythmias whose signal amplitudes may fluctuate and may be very small, the atrial channel is usually programmed to a highly sensitive value (e.g. low value for atrial sensitivity: 0.15–0.35 mV). High atrial sensitivity, together with R waves after the PVAB, can predispose the detection of ventricular signals on the atrial channel. The pacemaker may label these ventricular signals as "P" waves and thus respond as if the atrial rate were high when the rhythm is actually normal sinus rhythm. The result is a form of double-counting, resulting in a "false" mode switch (Figure 6.35). To prevent far-field R wave sensing, the PVAB can be programmed (from 50 to 250 ms) in most devices. There is an inverse relationship between the duration of the PVAB and the detection of atrial arrhythmia, with the shorter PVABs allowing detection of higher atrial rates (increased sensitivity to atrial tachyarrhythmias). However, increasing the PVAB increases the specificity of rhythm detection and minimizes inappropriate mode switch. The PVAB may also limit the ability to detect atrial arrhythmias, particularly atrial flutter and tachycardias, since an atrial deflection may occur just after the paced or sensed ventricular event, creating the so-called "2:1 lock-in" phenomenon (see "Algorithms for atrial arrhythmia detection and atrial pace/sense competition").

However, far-field R wave sensing (intrinsic AV conduction) with subsequent inappropriate mode switch can occur even with an extended PVAB if the intrinsic ventricular signal is detected on the atrial channel before the ventricular channel of the pacemaker (PVARP and PVAB will be initiated only after ventricular signal is detected in the ventricular channel). In this scenario, the pre-VABP can assist to prevent far-field R wave sensing and inappropriate mode switch (Figure 6.8). Although the site of native ventricular depolarization cannot

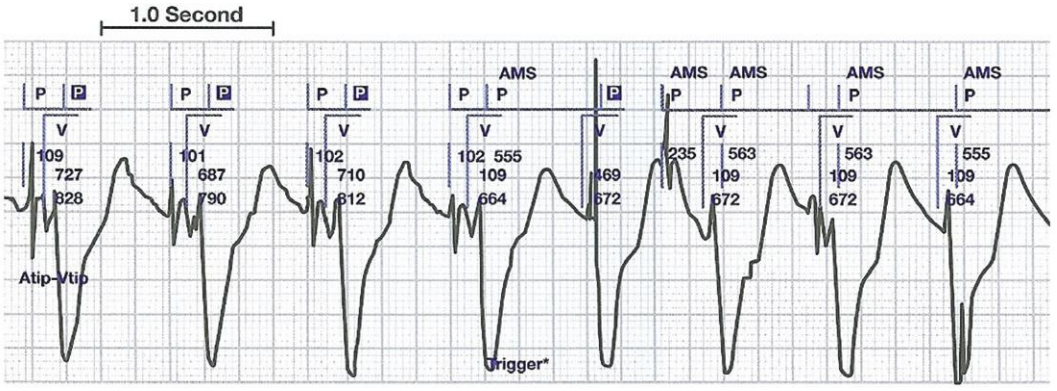


Figure 6.35 Inappropriate or false mode switch. Summed (Atip–Vtip) electrogram demonstrates oversensing of ventricular pacing by the atrial channel after the post-ventricular atrial blanking period (PVAB) has expired, resulting in double counting and inappropriate atrial mode switch (AMS) to a non-tracking pacing mode (VVI) at a higher AMS base rate.

be predicted, the algorithm sets up a programmable monitoring interval (0–60 ms) following the detected atrial event. If an R wave is detected during the pre-VABP, the atrial event is labeled a far-field R wave and is not used in the calculation of high atrial rates.

Algorithms for atrial arrhythmia detection and atrial pace/sense competition

Algorithms have been developed to identify rapid atrial-sensed events, including PACs and supraventricular arrhythmias (including atrial flutter and fibrillation) (Table 6.8). Frequently, these algorithms are available only in DDD(R) pacing mode. Appropriate identification of these atrial arrhythmias is important not only to allow appropriate mode switch when they persist (avoid tracking these arrhythmias), but also to avoid short coupling atrial pacing within the atrial vulnerable period that could result in the induction of other atrial arrhythmias.

Blanked flutter search

Blanked flutter search (Medtronic) monitors for AA intervals that may indicate 2:1 blanking of atrial events. If an AS event is "blanked," the device will extend PVARP and VAI to uncover AS. A second AS event noted above MS rate will be added to the counter for mode switch (MS).

2:1 Lock-in protection algorithm

This 2:1 lock-in protection algorithm (Biotronik) prevents the failure to mode switch due to the sensing of every other atrial flutter wave, the so-called "2:1 lock-in" response. After eight beats with a rate of greater than 100 bpm, the AV delay is extended to uncover intrinsic atrial events hidden previously within the PVAB (Figure 6.36).

Atrial flutter response

This feature initiates a programmable atrial flutter response (AFR, Boston Scientific) window or interval (130–230 bpm, 10 bpm increments) if an atrial-sensed event is detected inside the PVARP. If a second atrial-sensed event is detected within the AFR interval, this interval will be reset and the atrial-sensed event will not be tracked as it is considered refractory (Figure 6.37). High-rate atrial sensing may continuously retrigger the AFR window, effectively resulting in mode switch.

Non-competitive atrial pacing

Non-competitive atrial pacing (NCAP, Medtronic) allows delay in atrial pacing if this is scheduled to be delivered within a given interval after an atrial-sensed event (Figure 6.38). If an atrial-sensed event occurs within the PVARP (which will not terminate the VAI or reset timing cycles), a programmed NCAP interval will begin. Atrial pacing will not occur even if the programmed VAI ends; it will be delayed until the NCAP interval expires. If a second

Table 6.8 Atrial arrhythmia detection and atrial pace/sense competition algorithms

Feature	*Trigger*	*Response/intervention*	*Comments*
Blanked flutter search (MDT)	Monitors for eight consecutive AA intervals that are less than twice the total atrial blanking period (SAV + PVAB) and where one half of the AA interval is less than the detect rate interval	Extend PVARP and the VAI to uncover any blanked AS events. If AA interval is shorter than the detect rate interval, 2:1 sensing of an atrial tachyarrhythmia is assumed	Once rapid consecutive A–A intervals or 2:1 blanking of AS events are detected, the detect duration delay timer is started. Mode switch will occur once this timer expires
2:1 Lock-in protection algorithm (BTK) (Figure 6.36)	Evaluates VAIs when rate >100 bpm, and after eight beats with a rate of >100 bpm	Extends AV delay to uncover intrinsic AS events hidden previously by atrial blanking	Immediately mode switches (without meeting the X/Z out of eight criterion) to terminate the 2:1 lock-in
Atrial protection interval (API) (SJM)	High atrial pacing rates	Provides a 125-ms alert period at the end of PVARP and prior to next atrial pacing (non-competitive atrial pacing window) at high atrial pacing rates. If an intrinsic P wave is sensed during this 125-ms period, atrial pacing is inhibited	Non-programmable feature, only available in dual chamber pacing modes
Atrial flutter response (AFR) (GDT, BS) (Figure 6.37)	AS event detected inside PVARP	Initiates a programmable AFR window (130–230 bpm), which is subsequently reset or restarted if another AS event is noted. Paced atrial events scheduled inside an AFR window will be delayed until the AFR window has expired	If there are fewer than 50 ms remaining before ventricular pacing (LRL expires), atrial pacing is inhibited for the cycle. Ventricular pace is not affected by AFR and will take place as scheduled by LRL or SIR. Available in DDD(R) and DDI(R) modes
Non-competitive atrial pacing (NCAP) (MDT) (Figure 6.38).	AS event that occurs within PVARP	Initiates programmable NCAP interval (200–400 ms, 50-ms increments), which will delay atrial pacing until NCAP ends, even if programmed VAI expires. Another NCAP will be initiated if a second AS event occurs during NCAP interval	NCAP can result in subsequent shortening of AV interval to avoid violation of the LRL or SIR (minimum paced AVI allowed is 30 ms)

AS, atrial sensed; BS, Boston Scientific; BTK, Biotronik; MDT, Medtronic; St. Jude Medical; SAV, sensed AV delay; SIR, sensor-indicated rate; for other acronyms, see Table 6.3.

atrial refractory-sensed event occurs during the NCAP interval, a new NCAP interval will be initiated. Thus, short coupling atrial pacing (within the atrial vulnerable period) is prevented, avoiding potential induction of atrial tachyarrhythmias. However, this can result in subsequent shortening of the AVI to avoid violation of the LRL or SIR (minimum allowed paced AVI is 30 ms). This algorithm becomes more important with enabled rate modulation (DDDR) as the SIR may indicate pacing at faster rates. NCAP is applicable when the device is operating in the DDDR or DDD mode.[16]

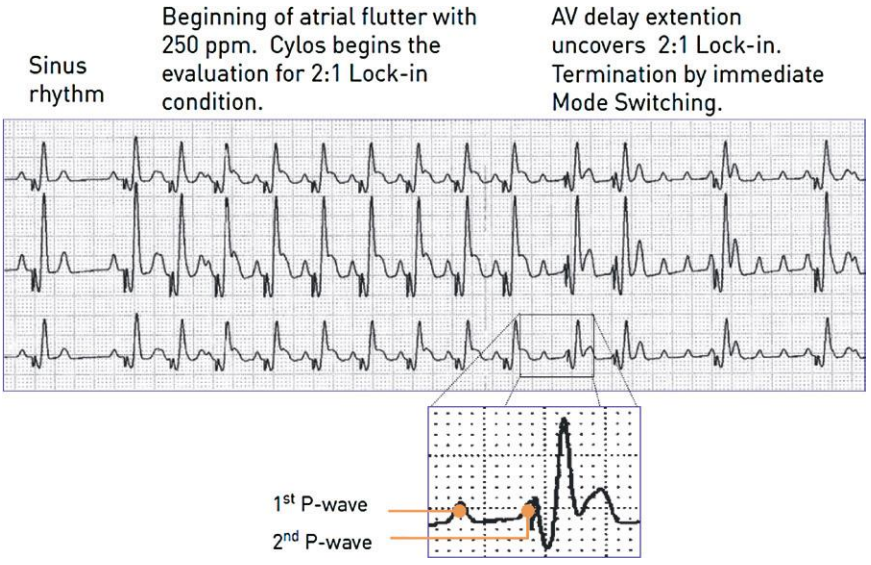


Figure 6.36 2:1 Lock-in protection algorithm. Initial tracking of an atrial flutter with a 2:1 P-synchronous ventricular pacing occurs since every other P wave (after ventricular pacing) falls within a post-ventricular atrial blanking period (PVAB) and is not included in the mode switch counter. After eight beats of atrial rates above 100 bpm, this algorithm extends atrioventricular (AV) delay, allowing sensing of the second P wave previously "hiding" within the PVAB (reproduced with permission of Biotronik, Inc. from the *Cylos Pacemaker Feature Handbook*. Lake Oswego, OR: Biotronik, Inc., 2006).

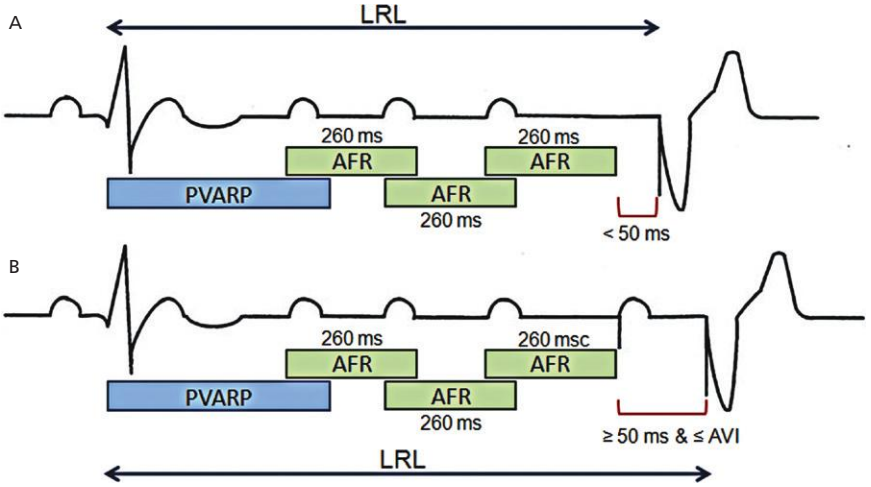


Figure 6.37 Atrial flutter response (AFR). Atrial detection inside the post-ventricular atrial refractory period (PVARP) starts a 260-ms AFR interval, which is reset if another atrial event is detected within the AFR window. (A) A ventricular pace (VP) stimulus will take place on the scheduled lower rate limit (LRL) interval or sensor-indicated rate. (B) An atrial pace will only occur if the AFR window expires at least 50 ms before the scheduled VP. This prevents competitive pacing. (Source: Altrua 20 and Altrua 40—Multiprogrammable Pacemakers. St Paul, MN: Boston Scientific Corp., 2008. Reproduced with permission of Boston Scientific.)

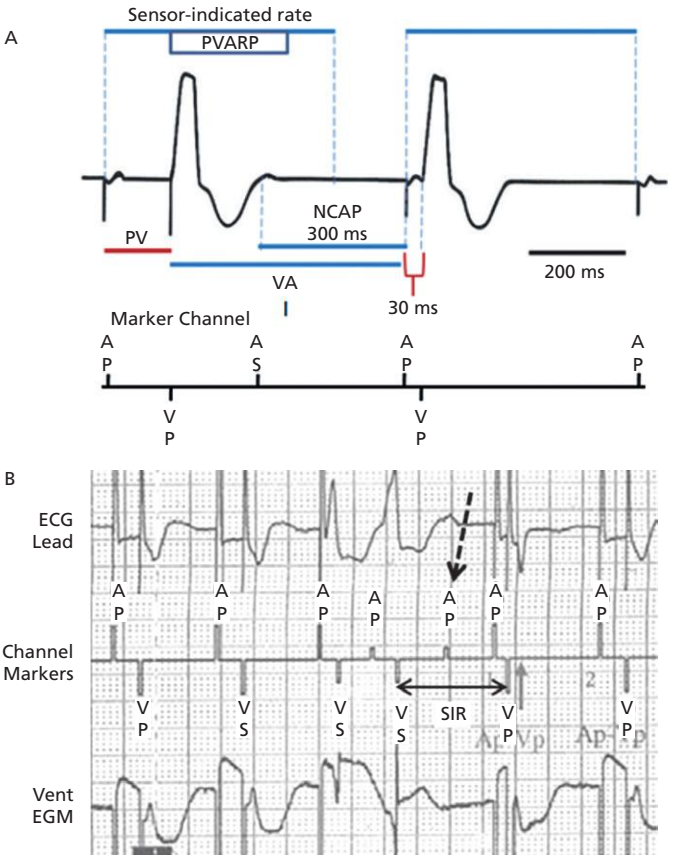


Figure 6.38 Non-competitive atrial pacing (NCAP). (A) A 300-ms NCAP window is initiated after an atrial-sensed (AS) event occurs within the post-ventricular atrial refractory period (PVARP). Even though the sensor-indicated rate (SIR) has expired, atrial pacing will not occur until the NCAP window is completed and then only if at least a 30-ms atrioventricular (AV) interval is allowed between atrial and ventricular pacing (AP, VP) (modified with permission of Medtronic, Inc. from the *Adapta, Sensia, Versa Pacemaker Reference Guide*. St Paul, MN: Medtronic, Inc). (B) Premature ventricular contraction (VS) results in retrograde VA conduction. The second retrograde P wave (dashed arrow) labeled "AR" is not tracked with VP as it was sensed during the PVARP (it does not initiate an AV interval). The scheduled AP event is delayed by 300 ms (until the NCAP interval expires), resulting in a foreshortening of the AV delay (60 ms) to avoid violating the SIR. (Source: Courtesy of S. Serge Barold, MD.)

Atrial protection interval

Atrial protection interval (API, St. Jude Medical) is a feature to minimize competitive atrial pacing. This feature provides a 125-ms alert period at the end of the PVARP (non-competitive atrial pacing window) and prior to the next atrial pacing event to allow an intrinsic P wave to be sensed, which subsequently will inhibit atrial pacing during high atrial pacing rates.[9]

Despite these algorithms, some patients may present with inappropriate sensing of atrial arrhythmias and atrial sense/pace competition. In this situation, re-programming bradycardia parameters or adding dynamic PVARP can assist to avoid induction of atrial arrhythmias due to short coupled atrial pacing. For example, pacing parameters providing a 300-ms interval between the end of the ARP and the next scheduled atrial pace will prevent atrial sense/pace competition. This can be accomplished by lowering the upper sensor rate (USR), shortening the paced AVI, and shortening the PVARP to force a 300-ms interval with no atrial pacing after the PVARP. However, shortening the PVARP can potentially result in pacemaker-

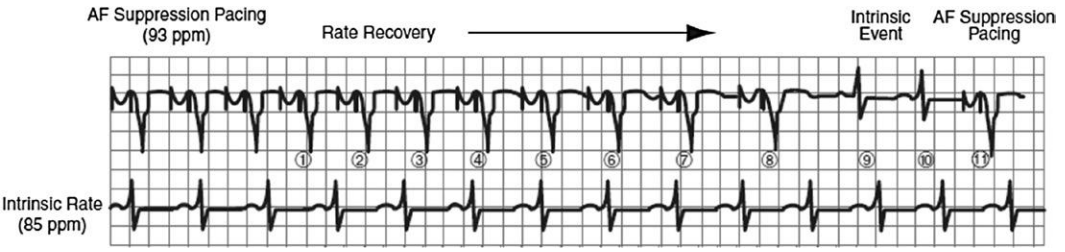


Figure 6.39 Atrial fibrillation (AF) suppression algorithm. The intrinsic heart rate is 85 bpm with enabled AF suppression (rate 93 bpm). Paced beat "1" (representing the final cycle of overdrive pacing) marks the initiation of rate recovery of this algorithm, adding 12 ms to each cycle through the eighth cycle. The interval is extended to 729 ms (83 bpm) and a P wave (at 85 bpm) is detected (beat 9). This is followed by another P wave in the tenth cycle (the second of two intrinsic events). This signals the device to resume AF suppression pacing in the 11th cycle. (Source: Bradycardia Devices—Help Manual. Sylmar, CA 2008, St. Jude Medical, Inc. Reproduced with permission of St. Jude Medical, Inc.)

mediated tachycardia (see "Pacemaker-mediated tachycardia"). On the other hand, dynamic PVARP allows a longer PVARP at the LRL, and a shorter PVARP at a faster intrinsic rate or SIR (Figure 6.13). This promotes AV synchrony and prevents atrial pacing if an atrial event is sensed early in the VAI.

Algorithms to prevent atrial fibrillation

Numerous atrial fibrillation (AF) prevention algorithms have been developed based on the concept that atrial pacing may decrease the occurrence of atrial premature beats that will trigger AF.[17] These algorithms include pace conditioning/rate soothing (Figure 6.39), PAC suppression, post-PAC response, post-exercise response, and post-AF response. The rationale, triggers, and intervention of each of these algorithms are described in Table 6.9. Overall, they are designed to promote atrial pacing above the sinus rate (shortening VA or AA interval) after a PAC, exercise, atrial tachyarrhythmia (mode switch), and/or even a sinus beat.

These algorithms are utilized in some commercially available pacemakers. Unfortunately, contradicting data exist with regard to the efficacy of these algorithms to prevent recurrent AF.[17–20] For instance, the Atrial Dynamic Overdrive Pacing Trial (ADOPT)[18] demonstrated that AF suppression (rate smoothing) decreased symptomatic AF burden in patients with sick sinus syndrome and AF. However, the AT500 verification study[21] (atrial rate stabilization, atrial preference pacing, and post-mode switch overdrive pacing plus termination algorithms), the Atrial Therapy Efficacy and Safety Trial[22] (ATTEST, AT500 pacemaker), and the Atrial Septal Pacing Efficacy Clinical Trial (ASPECT)[23] did not demonstrate improvement in median AF frequency or in overall AF burden. Most recently, the Study for Atrial Fibrillation Reduction (SAFARI)[24] demonstrated that all these prevention pacing therapies (Table 6.9) are safe and effective in reducing AF burden, particularly in subjects with an AF burden of greater than 6%.

Algorithms to minimize right ventricular pacing

Over the past few years, several algorithms (Table 6.10) have been developed and refined in order to avoid deleterious effects of chronic right ventricular (RV) pacing, such as increase in heart failure, impairment of functional status, left ventricular (LV) dilation, and deterioration of left ventricular systolic function.[4] Patients with underlying LV dysfunction appear to have the greatest hemodynamic deterioration with RV pacing. These algorithms clearly can be beneficial in patients with intact AV conduction. Some of the initial algorithms minimize pacing by extending the AVI by a programmed additional *delta* interval (AV hysteresis, Search AV+, VIP). These algorithms are frequently limited to a maximum AVI extension (limited by TARP) and may result in some ventricular pacing and fusion with intrinsic conduction.

Table 6.9 Algorithms to prevent atrial fibrillation

Algorithm	*Commercial name*	*Trigger/rationale*	*Response/intervention*	*Comments*
Pace conditioning	Dynamic atrial overdrive (SJM), atrial preference pacing (GDT, BTK, MDT)	Trigger: sinus-sensed beat Attempts to decrease likelihood of PAC by increasing heart rate upon PAC detection	Limited increase in atrial pacing rate by 15 bpm above physiological sinus rate to resume atrial pacing	Results in significant percentage of atrial pacing
Rate soothing	AF suppression (SJM) (Figure 6.39)	Trigger: 1–2 sinus-sensed beats Prevent atrial arrhythmias by atrial overdrive pacing just above pacing rate	Increase atrial pacing at rate by 3 bpm and slowly decrease pacing rate until sinus rhythm is sensed or LRL is reached	Similar to pace conditioning but without large (15 bpm) pacing rate increase
PAC suppression	ProACT (GDT)	Trigger: atrial event classified as PAC Decrease possibility of PAC by increasing heart rate upon PAC detection	Pacing rate is increased by 15 bpm for a certain duration	
Post-PAC response	Atrial rate stabilization (MDT)	Trigger: beat classified as PAC Avoid pauses after PAC	First beat after PAC is delivered at average cycle length of PAC rate and physiological rate, and subsequent beat is delivered at physiological rate	Beneficial if significant pauses precede AF initiation
Post-exercise response		Trigger: post-exercise Avoids	Post-exercise pacing rate slowly increases to 90% of physiological rate. If heart rate decreases abruptly after exercise, pacing rate is increased at post-exercise pacing rate	Useful in vagal- and exercise-induced AF
Post-AF response	Post-mode switch overdrive pacing (MDT)	Trigger: termination of preceding atrial tachyarrhythmia	Programmable high rate atrial pacing rate (70–100 bpm) with gradual decline until sinus rhythm is sensed or LRL is reached	Potential benefit in patients with immediate recurrence of AF

AF, atrial fibrillation; BS, Boston Scientific; SJM, BTK, Biotronik; GDT, Guidant; St. Jude Medical; PAC, premature atrial contraction; for other acronyms, see Table 6.3.

Table 6.10 Algorithms to minimize ventricular pacing

Algorithm	*Initial mode*	*Trigger*	*Intervention*	*Return to initial pacing settings*	*Advantage/disadvantage/notes*
Search AV hysteresis (GDT/BS) (Figure 6.40A)	DDD(R)	VS event after AVI prolongs to programmable AVI hysteresis (extension) for up to eight consecutive cycles. Search is initiated after a programmable number (32–1024) of consecutive *paced* cycles (VP only)	Remains in DDD(R). AVI hysteresis as long as intrinsic R wave is sensed	AVI hysteresis (extension) remains in effect until a *single* VP occurs during the AVI extension period	*Advantages*: Does not allow blocked P waves *Disadvantages*: AVI extension is limited by TARP. P-synchronous VP may occur with a very long AVI. Fusion of VP and intrinsic R may occur at the end of AVI extension
Search AV+ (GDT/BS)	DDD(R)	Same as Search AV hysteresis. Search of intrinsic R wave initiates after a programmable number of both *paced* and *sensed* cycles (VS and VP)	Remains in DDD(R). Same as Search AV hysteresis	AVI extension remains in effect until a *2 of 10* VP occurs during the AVI extension period	*Advantages*: Same as search AV hysteresis. Allows for a more frequent search and more time with AVI extension than Search AV hysteresis *Disadvantages*: Same as Search AV hysteresis
AV hysteresis (BTK)	DDD(R)	AVI extends to a programmable AVI hysteresis delay for two scan cycles every 59 cycles with preset AVI; trigger criteria are met if three of the previous four scan sequences reveal intrinsic conduction	AVI hysteresis delay (extension) remains as long as intrinsic R wave is sensed	Five VP during the previous eight cardiac cycles will switch to initial preset AVI	*Advantages*: Same as Search AV+ *Disadvantages*: Same as Search AV hysteresis
Ventricular intrinsic preference (VIP), (SJM) (Figure 6.40B)	DDD(R)	AVI will be periodically extended (search interval) to an additional programmable delta (VIP extension) for a programmed number of cycles searching for VS event	AVI + delta (VIP extension) persists as long as VS is sensed. Remains in DDD(R)	If no intrinsic AV conduction is noted after AVI + delta, AV pacing will reset to initial preset AVI	*Advantages*: Same as Search AV hysteresis *Disadvantages*: Same as Search AV hysteresis

(*Continued*)

Table 6.10 (*Continued*)

Algorithm	*Initial mode*	*Trigger*	*Intervention*	*Return to initial pacing settings*	*Advantage/disadvantage/notes*
Managed ventricular pacing (MVP), (MDT) (Figure 6.41A)	AAI(R)	Persistent loss of AV conduction (two of four recent non-refractory AA intervals without an R event or blocked P wave)	Back-up P-synchronous VP at 80 ms is delivered if AA interval occurs without VS event. Switches to DDD(R) once trigger criteria are met	Periodic one-cycle assessment of AV conduction. First one occurs after 1 min, and subsequently at progressively longer intervals (2, 4, 8 . . . min) up to 16 h, and then occur every 16 h thereafter. AAI mode is restored when intrinsic AV conduction is noted	*Advantages*: Regardless of PR interval, intrinsic conduction is allowed after AP or AS. Allows physiological AV nodal Wenckebach *Disadvantages*: Do not allow 2:1 AV block
AAISafeR2 (Sorin) (Figure 6.41B)	AAI(R)	**1** Two consecutive blocked Ps **2** >3 blocked out of 12 AP/AS **3** Pause > programmed duration (2–4 s) **4** >6 abnormal PR/AR intervals > programmed duration (PR >350 ms and AR >450 ms)	Switches to DDD(R) once trigger criteria are met		*Advantages*: Same as MVP. Most aggressive algorithm to allow and maintain intrinsic conduction. Programmability, different triggers for mode switch. Allows 2:1 AV block to persist *Disadvantages*: Potential for symptomatic 2:1 AV block
RythmIQ (BS) (Figure 6.41C)	AAI and back-up VVI 15 bpm slower than LRL (lowest and fastest 30 and 60 bpm)	Three slow ventricular beats of 11 in rolling window. Slow beat is defined as: **1** Ventricular paced beat **2** VS at least 150 ms slower than AAI LRL or SIR	Switches to DDD(R) once trigger criteria are met	AV Search+ (see above) is activated at programmed settings and if AVI extension continues for at least 25 cardiac cycles, and fewer than two of the last 10 cycles are VP, then the device automatically switches the pacing mode back to AAI (R) with VVI back-up	*Advantages*: Regardless of PR interval, intrinsic conduction is allowed after AP or AS. Does not require drop in ventricular beat *Disadvantages*: Pacemaker syndrome (AV dyssynchrony) while on AAI/back-up VVI. Frequent PVCs can easily trigger switch to DDD(R)

AP, atrial-paced event; AS, atrial-sensed event; AV, atrioventricular; AVI, AV interval; MVP, managed ventricular pacing; PVC, premature ventricular contraction; SIR, sensor-indicated rate; VIP, ventricular intrinsic preference; VP, ventricular-paced event; VS, ventricular-sensed event; for other acronyms, see Table 6.3.

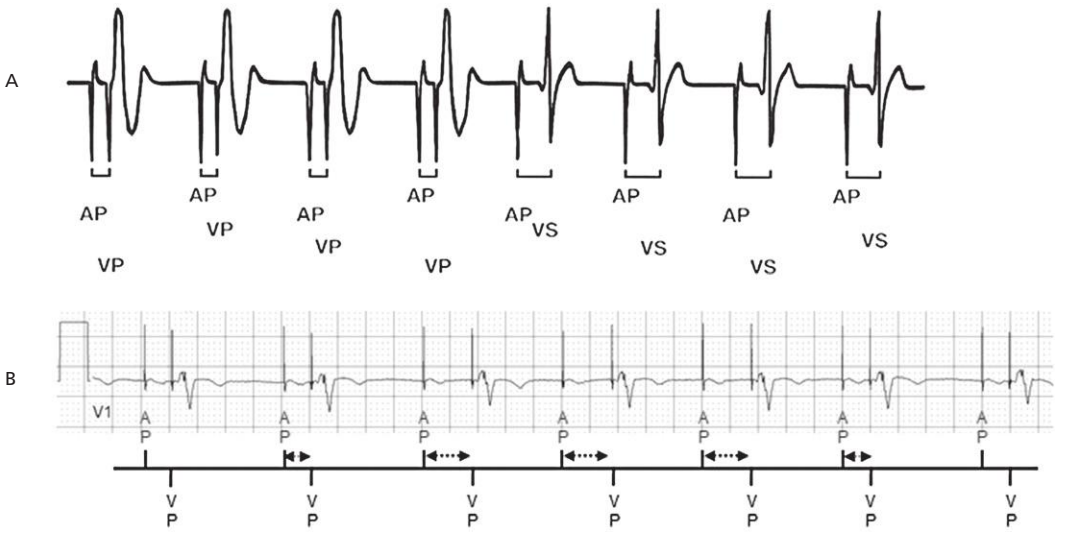


Figure 6.40 Algorithms to promote intrinsic atrioventricular (AV) conduction—Part I. (A) AV hysteresis; intrinsic R waves are sensed after the AV interval (AVI) is lengthened (programmable AV extension) allowing intrinsic AV conduction. (B) Ventricular intrinsic preference (VIP): paced AVI (200 ms) is extended to programmable delta for three beats (dashed arrows, AVI + delta = 200 + 140); however, no intrinsic R wave is sensed at extended AVI (340 ms) and sequential AV pacing resumes with the initial preset AVI. (Source: (A) Adapted from Insignia I Ultra System Guide, models 1190/1290. Reproduced with permission of Boston Scientific.)

The most recent algorithms (Managed ventricular pacing, SafeAAIR[2], and RhythmIQ) use a single atrial pacing mode (AAI®) that switches to a dual chamber pacing mode in the event of transient AV block (second-degree or high-degree AV block) (Figure 6.40 and Figure 6.41).

These algorithms have different triggers, interventions, advantages, and disadvantages (Table 6.10), and some of them have been shown to result in a significant decrease in ventricular pacing.[25,26] These algorithms should be used with caution, especially in patients with AV block or when prolonged pause may increase the risk of ventricular arrhythmias.

Pacemaker-mediated tachycardia

Pacemaker-mediated tachycardia (PMT), commonly known as endless-loop tachycardia, is seen in patients with repetitive retrograde VA conduction. PMT can *only* occur in DDD or VDD pacing modes (P-synchronous ventricular pacing) and has also been referred to as pacemaker circus movement tachycardia, repetitive re-entrant pacemaker VA synchrony, re-entrant VA pacemaker tachycardia, or antidromic re-entrant dual chamber pacemaker tachycardia.[27]

PMT is a "re-entrant" arrhythmia that initiates only in those patients with intact VA conduction, where the device senses a retrograde P wave (after the PVARP expires) regardless of the trigger. Thus, a retrograde P wave initiating PMT can be triggered by: (1) PVC; (2) failure of atrial capture during AV sequential pacing (Figure 6.42); (3) at the end of ventricular threshold testing in VVI mode, where the device switches immediately to DDD pacing mode sensing retrograde P wave; and (4) inappropriately long PVARP (Figure 6.43).

Once a retrograde P wave is sensed, AVI is initiated. Upon completion of the AVI and MTR interval, ventricular pacing is delivered (anterograde limb) and this can once again result in VA conduction (retrograde limb), with retrograde P wave perpetuating this re-entry. Once established, this re-entrant mechanism continues until it is interrupted or until the retrograde limb of the

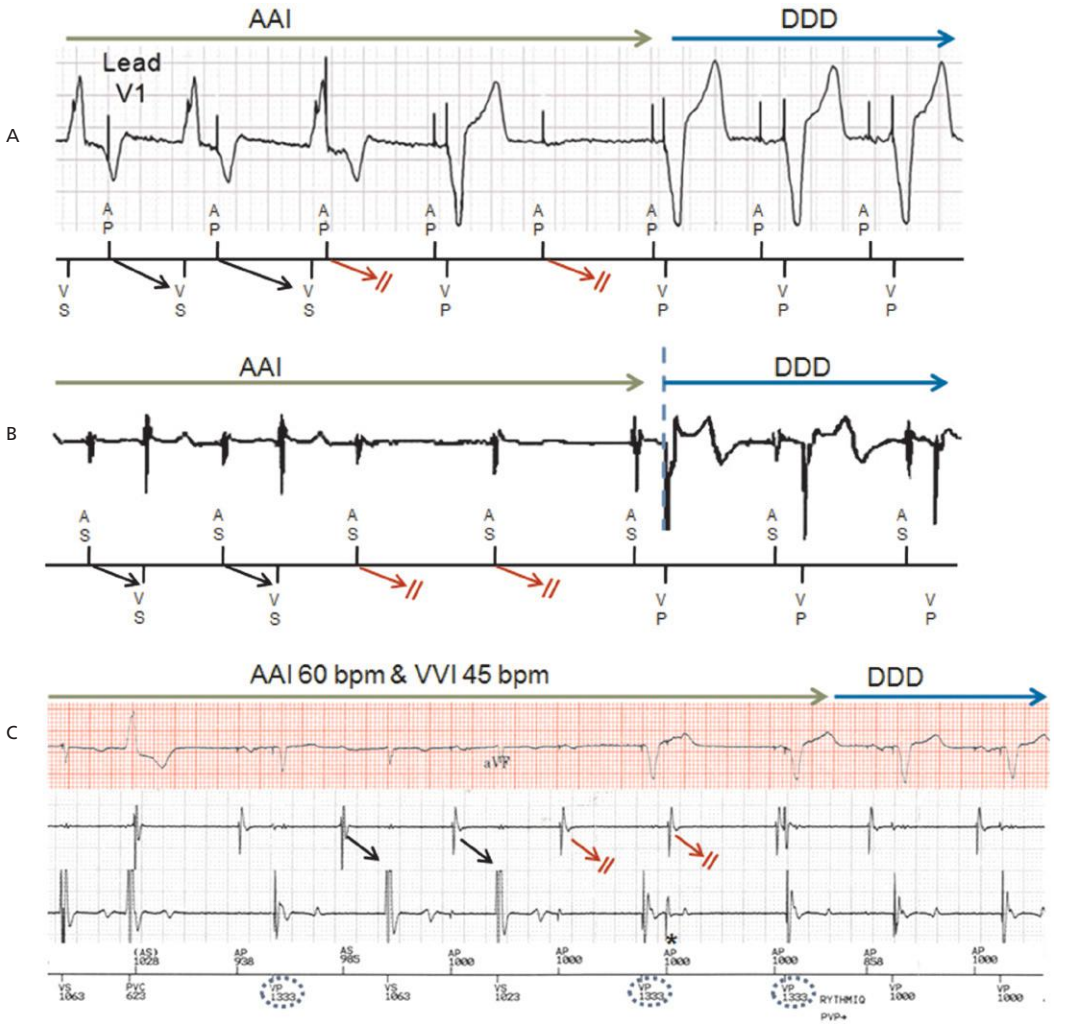


Figure 6.41 Algorithms to promote intrinsic atrioventricular (AV) conduction—Part II. (A) Managed ventricular pacing (MVP): AAI switches to DDD pacing mode due to AV nodal Wenckebach (Mobitz I AV block) after two of four P waves do not demonstrate intrinsic AV conduction. Back-up P-synchronous ventricular pacing is delivered after transient loss of AV conduction with an AVI of 80 ms. (B) Sorin SafeR; AAI changes to DDD mode after two consecutive P waves lack intrinsic AV conduction (high-degree AV block). (C) RythmIQ: Simultaneous AAI 60 bpm and VVI 45 bpm (15 bpm below the AAI lower rate limit). The criterion of three slow ventricular beats (dashed ovals—event markers) in an 11 rolling window is met, changing to a DDD pacing mode at 60 bpm. A premature ventricular contraction (PVC, event marker) resets AA timing, resulting in atrial pacing (AP) 1000 ms after the PVC (PVC–AP interval of 1000 ms). Note that PVC also resets the VV interval and ventricular pacing (VP—slow ventricular beat) occurs at the programmed VVI 45 bpm (1333 ms) even though intrinsic AV conduction is noted (fusion beat) on the aVF lead. (Source: (A & B) Modified from Huizar JF, Kaszala K, Ellenbogen KA. Cardiac Pacing modes and terminology. In: Sakena S, Camm AJ, eds. *Electrophysiological Disorders of the Heart*, 2nd Ed. Philadelphia, PA: Elsevier Saunders, 2012: 441–456. Reproduced with permission of Elsevier.)

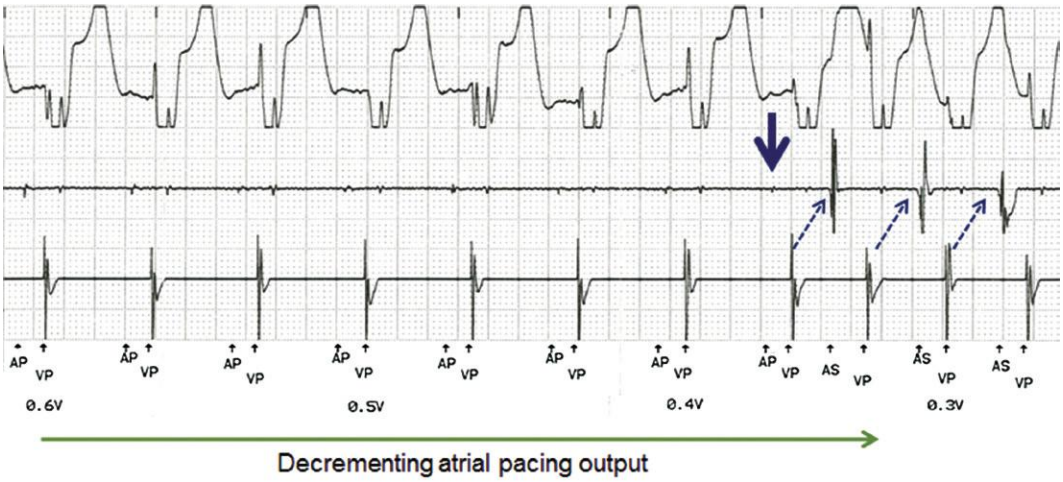


Figure 6.42 Pacemaker-mediated tachycardia (PMT) initiated during an atrial threshold test in DDD pacing mode. This test induced PMT due to loss of atrial capture (solid arrow) followed by ventricular pacing with retrograde VA conduction (dashed arrows). Retrograde atrial signal outside the post-ventricular atrial refractory period (PVARP) [terminates the ventriculoatrial interval (VAI) and initiates an atrioventricular interval (AVI)] is tracked by ventricular pacing (maximum tracking rate 120 bpm), which will perpetuate itself as long as the retrograde atrial signal does not occur within the PVARP.

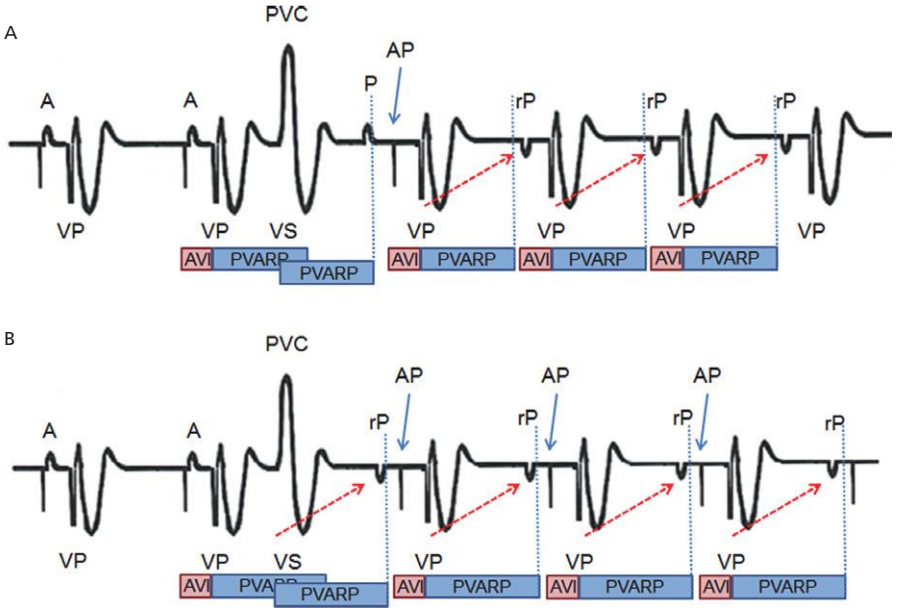


Figure 6.43 (A) Paradoxical mechanism of pacemaker-mediated tachycardia (PMT) initiation by an inappropriately long post-ventricular atrial refractory period (PVARP). Early premature ventricular contraction (PVC) re-initiates PVARP and VA interval (VAI). A sinus P wave falls within the PVARP (without resetting VAI), followed by ineffective atrial pacing (AP) due to atrial refractoriness. Ventricular pacing (VP) occurs after the atrioventricular interval (AVI) is completed, causing a retrograde P wave (rP) due to unopposed ventriculoatrial (VA) conduction (dashed red arrows) with subsequent initiation of PMT. (B) Repetitive non–re-entrant VA synchrony. To avoid PMT, a long PVARP is programmed. A rP after an early PVC falls within the PVARP, followed by an ineffective AP (after the VAI is completed), initiating an AVI. VP occurs after completion of the AVI, and finds unopposed VA conduction (retrograde P wave), falling again within the PVARP, causing repetitive ineffective AP and VP with VA conduction.

circuit is exhausted. The ventricular pacing rate (VVI) cannot violate the programmed MTR or URL; thus PMT often occurs at the MTR. The cycle length of the PMT is the sum of the VA conduction time and the programmed sensed AV delay. If the VA conduction time is sufficiently long, PMT could occur below the MTR. PMT may be asymptomatic if the programmed MTR is low; however, symptoms may be significant if the MTR is programmed relatively high.

Algorithms to prevent, identify, and terminate pacemaker-mediated tachycardia

Many mechanisms have been adopted to prevent, identify, and terminate PMT (Table 6.11). Among the early preventive algorithms is *PVARP extension after PVC*, since they are the most common triggers. Extension of the PVARP after a PVC prevents tracking of retrograde P wave (PMT initiation) as this will force it to fall within the PVARP. However,

Table 6.11 Different algorithms for pacemaker-mediated tachycardia (PMT)

Algorithm	*Trigger*	*Intervention*	*Prevent PMT*	*Diagnose and treat PMT*
PVC response (BS, MDT, SJM, BTK)	"PVC" beat (R without a preceding P wave)	Programmed PVARP is extended immediately after sensed PVC beat	Yes	No
PMT termination (BS)	16 successive VP at MTR following AS events. VA interval stability: PMT is declared if all the 15 VA intervals are <32 ms longer or shorter than first VA interval	Extend PVARP to fixed 500 ms for one cardiac cycle to break PMT	No	Yes
PMT intervention (MDT)	Nine consecutive VP events of <400 ms that end with an AS event. On eighth consecutive VA interval, activity sensor is checked (assess exercise-related tachycardia); PMT is declared if SIR < pacing rate and intervention will occur	Forces a 400-ms PVARP extension after the ninth VP event	No	Yes
PMT protection (BTK)	Eight consecutive VP events in which atrial events lie within a programmed PMT VA criterion (default 350 ms). PMT is confirmed by stable VA interval after decreasing MTR by 10 bpm or shortening AVI to next programmable length by 10 bpm	PVARP extension by measured V–V interval plus 50 ms	No	Yes
PMT response (SJM) (Figure 6.44)	Eight consecutive VP–AS events above PMT detection rate. PMT is confirmed if VP–AS interval remains stable (within 16 ms of prior eight VP–AS intervals) despite shortening or increasing AVI by 31 ms if AS–VP interval is greater or shorter than 100 ms, respectively	Suspends VP event and delivers atrial pulse at 330 ms after detected retrograde P-wave	No	Yes

AS, atrial-sensed event; AV, atrioventricular; AVI, AV interval; BS, Boston Scientific; SJM, BTK, Biotronik; GDT, Guidant; St. Jude Medical; PVC, premature ventricular contraction; SIR, sensor-indicated rate; VIP, ventricular intrinsic preference; VP, ventricular paced event; for other acronyms, see Table 6.3.

PMT could also initiate despite PVARP extension after a PVC, due to ineffective atrial pacing soon after retrograde P wave (during the ARP), followed by ventricular pacing with retrograde VA conduction, initiating PMT (Figure 6.43A).

Commonly, PMT is prevented by programming the PVARP longer than VA conduction during ventricular pacing, as it will no longer track P waves falling within the PVARP. Nevertheless, VA conduction can change based on ventricular rate (decremental conduction), as well as vagal and adrenergic tone. Thus, the PVARP should be programmed based on VA conduction at the MTR in order to assess the longest VA conduction time.

Paradoxically, a similar form of VA dysynchrony (distinct from PMT) may occur when PVARP is significantly extended. After a PVC with retrograde P wave (VA conduction), a long PVARP avoids initiation of PMT. Since resetting of the VAI does not occur, ineffective atrial pacing (during atrial refractoriness) is followed by ventricular pacing (AV sequential pacing). After ventricular pacing takes place, a retrograde P wave will occur once again within the PVARP (without terminating the VAI). Thus, recurrent refractory atrial pacing followed by ventricular pacing will continue.[27] If the patient can sustain VA conduction (retrograde P wave within the PVARP), this sequence of events can perpetuate ineffective atrial pacing, resulting in a paced rhythm named "repetitive non–re-entrant VA synchrony (RNRVAS)," also known as "AV desynchronization arrhythmia" or "VA synchrony non–re-entrant arrhythmia" (Figure 6.43B). Under certain circumstances, RNRVAS may convert spontaneously to PMT and *vice versa*. This rhythm is more common with high LRL or rate-modulated pacing mode (DDDR) since the sensor-driven increase in VAI will increase the probability of a non-captured atrial-paced event allowing retrograde VA conduction after ventricular pacing. PVARP shortening could prevent RNRVAS at the expense of an increasing probability of PMT. Thus, decreasing sensor-driven response or MSR and shortening the AVI could decrease the probability of recurrence of this undesired rhythm and yet still prevent PMT.

Nowadays, various algorithms are available to diagnose and terminate PMT if it cannot be prevented (Table 6.11). The simplest algorithm assumes that atrial-sensed ventricular pacing occurring at the MTR is a PMT and, after a preset number of cycles, either withholds ventricular pacing or extends the PVARP. Withholding ventricular pacing will terminate retrograde VA conduction, whereas extending the PVARP will render the retrograde P wave "refractory" and terminate inappropriate tracking. Thus, true PMT will terminate after one of these interventions, whereas atrial arrhythmias will continue. A further refinement to these algorithms allows the clinician to select a PMT rate that is below the MTR, in an attempt to adjust for PMT at slower rates based on slow retrograde VA conduction. The limitation of these algorithms is that they are activated regardless of whether the rhythm is PMT or an intrinsic atrial rhythm with appropriate ventricular tracking. For a native atrial rhythm, repeated pauses are caused by the activation of the PMT termination algorithm, which may be symptomatic or could result in intermittent loss of tracking in biventricular devices.

More sophisticated algorithms attempt to confirm PMT before PMT intervention is deployed. These algorithms suspect PMT if retrograde VAI is stable within a predetermined number of cycles. Furthermore, PMT is confirmed if stability of retrograde VA conduction is preserved despite changing AVI or decreasing MTR. If the mechanism is *not dependent* on the ventricular-paced event (atrial or sinus tachycardia), the VP interval (VA conduction) on the next cycle is either lengthened or shortened by the same degree by which the AVI was changed. If atrial arrhythmia is confirmed, the pacemaker will continue to track atrial-sensed events. If PMT is confirmed, the device will intervene by withholding ventricular pacing, followed by atrial pacing at 330 ms if no intrinsic P wave is sensed. Successful atrial capture breaks the cycle and prevents retrograde conduction after the next ventricular-paced complex. This algorithm also prevents pauses occurring with some of the earlier generation PMT algorithms (Figure 6.44).

Biventricular pacing

Cardiac resynchronization therapy (CRT) has been shown to improve heart failure symptoms and LV function by restoring ventricular coordination

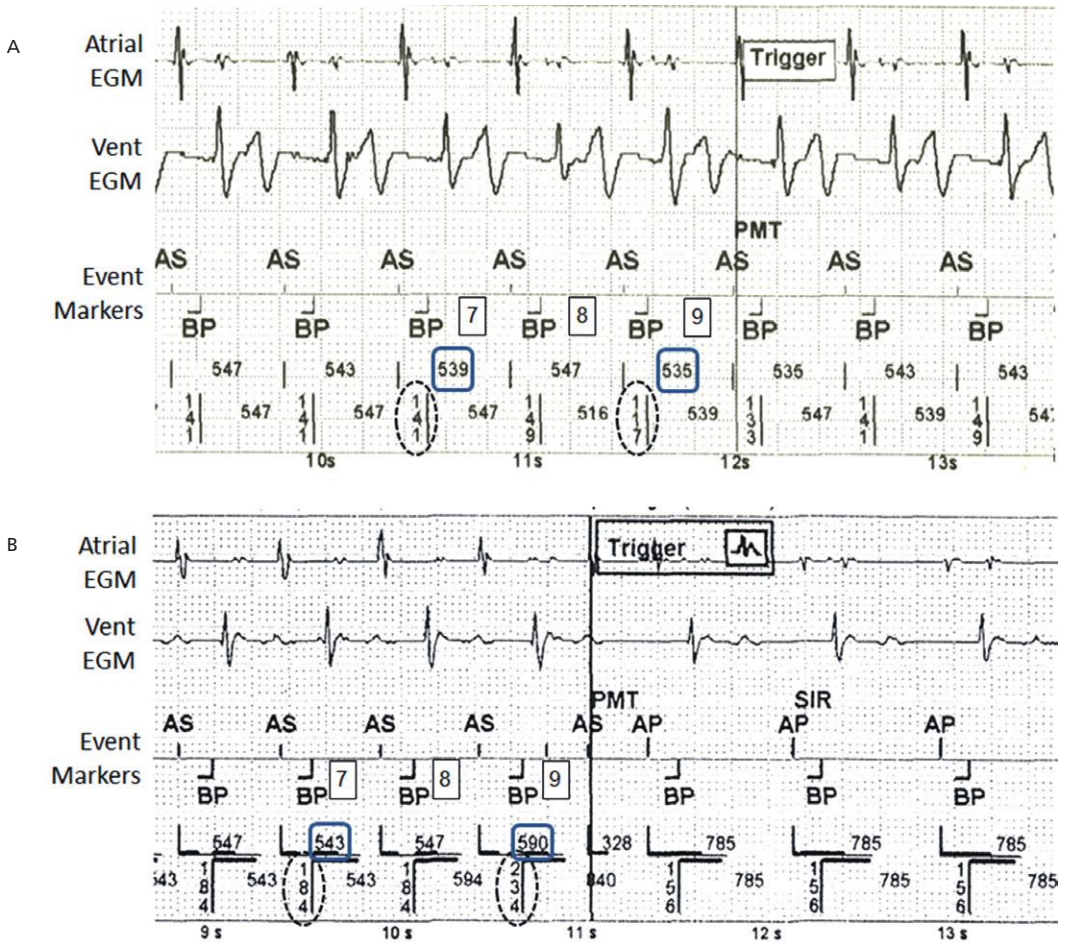


Figure 6.44 Pacemaker-mediated tachycardia (PMT) algorithm in a cardiac resynchronization therapy (CRT) device. (A) PMT response algorithm suspects PMT after eight consecutive VP–AS events. PMT is excluded since the ventriculoatrial interval (VAI) in beat "9" (VAI or BP–AS interval, 535–117 = 418 ms) changes more than 16 ms when compared to beat "7" (VAI, 539–141 = 398 ms) after decreasing the atrioventricular interval (AVI) from 141 to 117 ms (dashed oval). Thus, P-synchronous pacing continues as atrial arrhythmia was confirmed. (B) PMT is confirmed since the VAI (BP–AS interval) remains stable (<16 ms) between beat "9" (VAI, 590–234 = 356 ms) and beat "7" (VAI 547–184 = 359 ms) despite increasing AVI from 184 to 234 ms. PMT is terminated after ventricular pacing (VP) is withheld, restoring AV synchrony with atrial pacing (AP) 330 ms after the last atrial-sensed event (AS). (Source: PMT response, St. Jude Medical, Inc. Reproduced with permission of St. Jude Medical, Inc.)

(biventricular pacing) primarily in patients with wide QRS (>150 ms) and left bundle branch block.[2,3] In order to achieve this effect, biventricular pacing must be maintained and intrinsic conduction limited. In patients with chronic AF, the VVIR mode is frequently used. Although initial clinical trials utilized the VDDOV pacing mode, most patients in sinus rhythm are programmed to DDDOV or DDDRV pacing mode.

Timing cycles

Overall, the timing cycles for biventricular pacing are similar to those in dual chamber pacemakers. However, timing cycles in CRT can have numerous potential variations based on LV sensing.[28] Most of contemporary CRT devices use RV sensing for timing cycles, including base-rate behavior (Figure 6.45). One important distinction of CRT devices is the presence of two distinct PAVBs, one in the

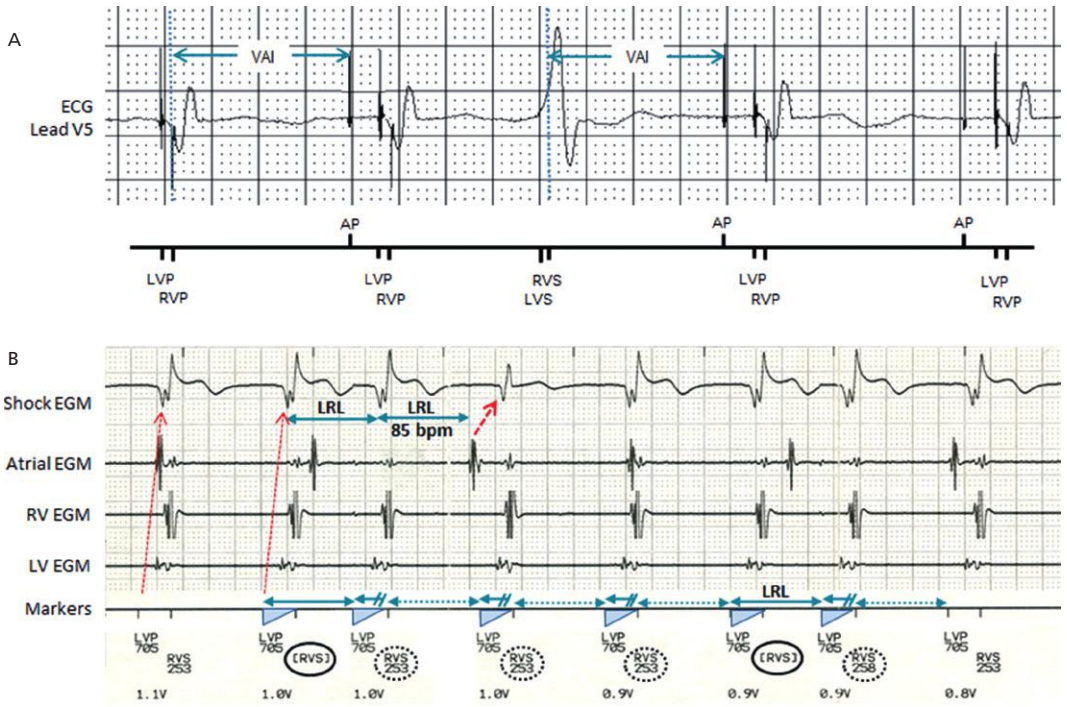


Figure 6.45 Role of right ventricular (RV) sensing for cardiac resynchronization therapy (CRT) timing cycles. (A) The device is programmed with an interventricular delay of 40 ms [left ventricular pacing (LVP) precedes RV pacing (RVP) by 40 ms]. During a premature ventricular contraction (LVS–RVS), the pacemaker uses RV sensing (RVS) as its reference to initiate a ventriculoatrial interval (VAI) even though this extrasystole was originated from the LV (LVS occurs prior to RVS). (B) Intermittent RV sensing beyond the RV refractory period (RVRP) causes resetting of the lower rate limit (LRL) with subsequent variability on LV pacing rate during LV threshold testing. Arrows on left side of the panel demonstrate LV capture after LVP. Despite LV threshold testing programmed with an LRL of 85 bpm (VVI 795 ms), variability on LV pacing rate (RR interval 958 and 705 ms or 63 and 85 bpm, respectively) is noted due to intermittent sensing of RV (RVS) within (solid circles) and beyond (dotted circles) the RVRP (designated by blue triangles), resetting the lower rate limit (bold dashed arrow, RR 958 ms). Note that RV sensing occurs way beyond RVRP due to a significant latency (160 ms) between the LVP stimulus and deflection of QRS in the shock ECG, which could be explained by a scar.

RV-sensing channel ($PAVB_{RV}$; similar to dual chamber pacemakers) and one in the LV-sensing channel ($PAVB_{LV}$), in order to prevent inappropriate inhibition of LV pacing due to far-field atrial pace oversensing (Figure 6.46). The PVAB on CRT devices will also inhibit atrial sensing after a RV- or LV-paced event, which can be particularly important if a significant interventricular delay is programmed between LV and RV pacing (see "Interventricular delay or LV offset").

It is particularly important to understand some unique timing cycles present in CRT devices (Table 6.3) as these optimize appropriate biventricular pacing.

Left ventricular refractory period (LVRP)

This period is a programmable interval in which a LV-sensed event after a LV-paced (LVP) or LV-sensed (LVS) event will not affect or reset timing cycles. This period is intended to prevent oversensing of QRS or T wave following a sensed or paced event, preventing inappropriate loss of CRT (seen more commonly with unipolar LV leads). A long LVRP shortens the LV-sensing window that could affect timing cycles.

Left ventricular protection period (LVPP)

Even though biventricular pacing should be delivered continuously to maximize CRT benefits, there

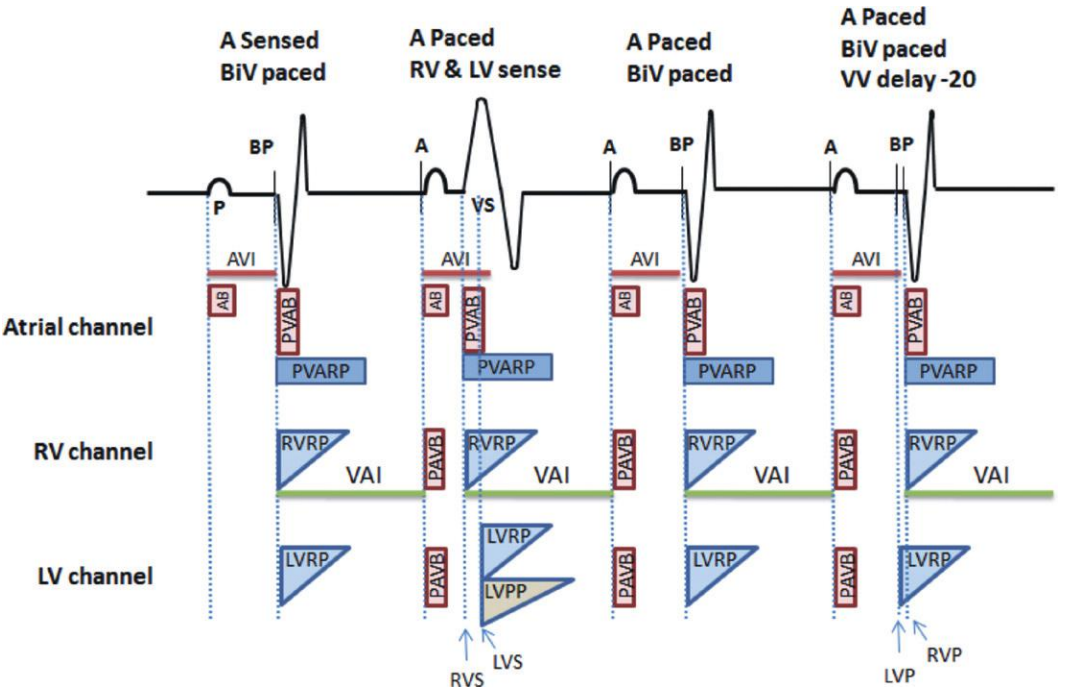


Figure 6.46 Blanking (red) and refractory (blue) periods in a biventricular pacemaker. The different blanking and refractory periods are demonstrated for different possible scenarios [atrial sense-BiV paced, atrial paced-RV&LV sensed, atrial paced-BiV paced, atrial paced-BiV paced with LV offset of −20 ms]. A, atrial; AB, atrial blanking; AVI, atrioventricular interval; BiV, biventricular; LVRP, left ventricular refractory period; LVP, LV-paced event; LVPP, LV protection period; LVS, LV-sensed event; PAVB, post-atrial ventricular blanking; PVAB, post-ventricular atrial blanking period; PVARP, post-ventricular atrial refractory period; RVP, RV-paced event; RVRP, right ventricular refractory period; RVS, RV-sensed event; VAI, ventriculoatrial interval; VV delay, interventricular delay.

are some circumstances in which it is appropriate to inhibit therapy (e.g. left-sided PVCs). The LVPP prevents the pulse generator from inadvertently delivering a pacing stimulus during the LV vulnerable period after an LV-sensed event, such as when a left-sided PVC occurs. However, if the LVPP inhibits LV pacing, the device will still deliver RV pacing. Proper programming of this feature will help maximize CRT delivery while reducing the risk of accelerating the patient's rhythm to a ventricular tachyarrhythmia. However, programming a long LVPP will reduce the MTR and inhibit biventricular pacing at higher rates.

Interventricular delay or left ventricular offset

Most contemporary biventricular pacemakers allow programming of different timing between the RV- and LV-paced events, referred to as "interventricular delay" or "LV offset" (RV–LV delay). For the most part, RV–LV delay can be programmed positive, negative, or zero in an attempt to optimize biventricular pacing and maximize clinical response. However, programming an interventricular delay can affect the programmed AVI depending upon the CRT manufacturer. For instance, a programmed sensed or paced AVI of 180 ms and 160 ms, respectively, will demonstrate a true AVI of 140 ms and 120 ms if LV pacing is programmed to occur 40 ms earlier than RV pacing (LV offset −40 ms; Figure 6.47).

Loss of biventricular pacing

There are a number of circumstances that may cause loss of biventricular pacing (inhibition or fusion), with the possible negative hemodynamic

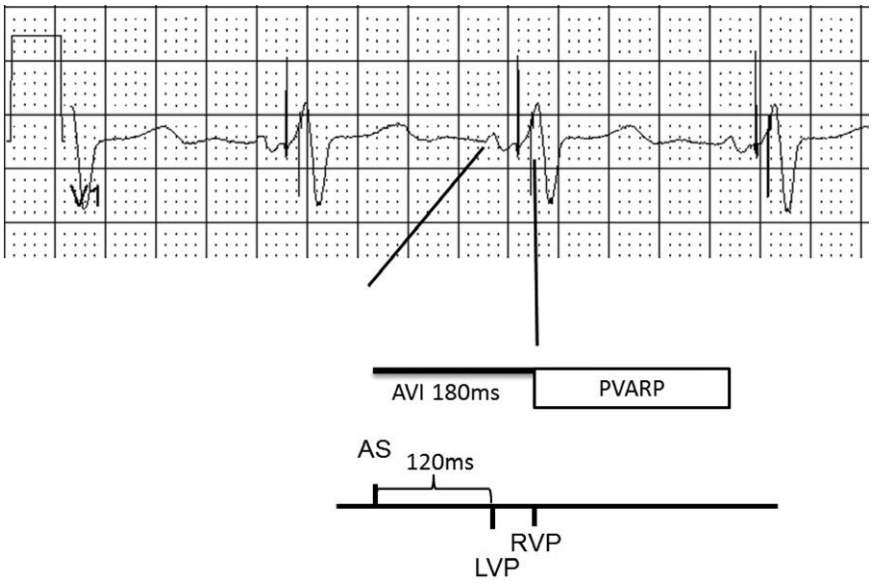


Figure 6.47 Left ventricular (LV) offset affecting atrioventricular interval (AVI) (Boston Scientific Corp.). Cardiac resynchronization therapy (CRT) has a programmed paced and sensed AV interval of 180 ms and 160 ms, respectively, with an LV offset of −40 ms. While right ventricular (RV) pacing will occur at a programmed AVI, LV pacing will occur at 140 and 120 ms after a paced or sensed P wave, respectively. AS, atrial-sensed event; AVI, AV interval; LVP, LV-paced event; PVARP, post-ventricular atrial refractory period; RVP, RV-paced event.

consequences. Fusion of biventricular pacing with intrinsic conduction can be easily overlooked if we only depend on device interrogation, since the counters may show a high biventricular pacing percentage. Thus, true biventricular pacing capture may need to be confirmed by a 12-lead ECG or Holter monitor.[29]

Common examples of loss of biventricular pacing include: (1) rapid sinus or atrial rates above the MTR; (2) short and dynamic PR intervals; (3) PACs; (4) frequent PVCs; and (5) AF with ventricular response above the LRL or SIR. Fortunately, several device features and alternatives are available to assist in improving biventricular pacing.

Rapid sinus or atrial rates above the MTR

If an atrial rhythm including sinus tachycardia occurs above the MTR, biventricular pacing will not occur even with a short programmed AVI. Furthermore, Wenckebach-pacemaker behavior will not be seen unless the patient is pacemaker dependent. In this circumstance, it is important to consider reprogramming the MTR (if appropriate) or to treat the atrial dysrhythmia in order to allow resumption of biventricular pacing.

Short and dynamic PR intervals

The basic timing cycle for biventricular pacing is based on RV-based timing with a sensed or paced ventricular event initiating a VAI (Figure 6.45 and Figure 6.46). The AVI must be sufficiently short to result in constant ventricular capture rather than intrinsic conduction. AV hysteresis (see "Atrioventricular interval hysteresis") may be used to promote ventricular capture in biventricular pacing. Furthermore, a rate-adaptive or dynamic AVI may be programmed in order to decrease the AVI during exercise or elevated heart rates. Finally, a feature called *"ventricular-sensed response"* or *"biventricular trigger"* allows LV pacing immediately after an intrinsic conduction or RV-sensed event occurs. This feature promotes synchronized RV and LV contractions (fusion between intrinsic activation and LV pacing) only if an RV-sensed event occurs between the LRL and MTR, although

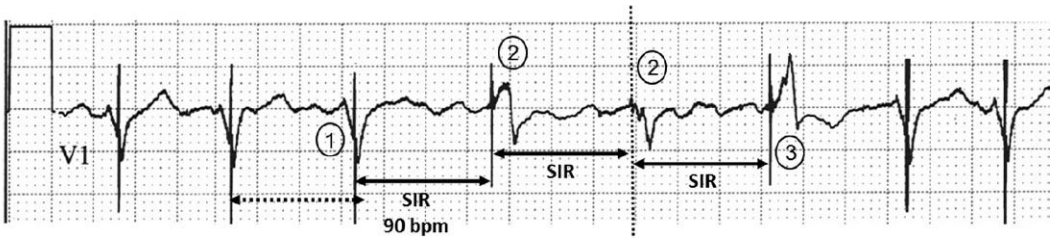


Figure 6.48 Biventricular trigger feature. Atrial fibrillation with a rapid ventricular response of 110 bpm (VVIR pacing mode) prevents appropriate biventricular pacing (first three beats, labeled "1") since the sensor-indicator rate (SIR) is 90 bpm. However, the biventricular trigger delivers left ventricular (LV) pacing immediately after right ventricular (RV) sensing in an attempt to maintain LV pacing even when rates are higher than the SIR. The tracing also demonstrates fusion beats (labeled "2") and full biventricular paced beats (labeled "3") when the heart rate is close to or below 90 bpm, respectively.

some devices will allow a distinct programmable maximum biventricular trigger rate (Figure 6.48).

Premature atrial contractions

A common phenomenon is an atrial event occurring during the PVARP, resulting in failure to track the atrial event with subsequent intrinsic AV conduction and biventricular pacing inhibition. Because the PR interval may be relatively long compared with the sinus cycle length, the P wave may fall in the PVARP of the preceding R wave interval. With a specific set of relationships between the AVI, PR interval, and PVARP, biventricular pacing may continue to be inhibited. As the atrial rhythm reaches rates faster than the total ARP (PVARP + AVI), biventricular pacing will stop. When the atrial rate falls, biventricular pacing will continue to be inhibited until the atrial rate is below the total intrinsic ARP (PVARP + PR interval). For instance, if the PR interval is 240 ms, the AVI is 150 ms and the PVARP is 300 ms (TARP 450 ms), at a sinus cycle length of 450 ms or 133 bpm, biventricular pacing will cease. As the rate slows, biventricular pacing will continue to be inhibited until the sinus cycle length increases to 540 ms (PVARP + PR interval) or 111 bpm.

Premature ventricular contractions

Frequent PVCs are commonly responsible for loss of biventricular pacing due to inhibition. A PVC trigger algorithm is frequently available in CRT devices (biventricular trigger or ventricular-sensed response, described above), by which the device will immediately deliver LV pacing after an RV-sensed event (Figure 6.48). However, this response will commonly result in a fusion beat rather than true biventricular pacing with unclear hemodynamic effects. Even occasional PVCs can result in loss of biventricular pacing, since they will reset the VAI and create a new PVARP. Biventricular pacing is inhibited after a PVC if the following sinus P wave falls within the PVARP (lack of ventricular tracking). It is important to understand that PVC response algorithms (PVARP extension) likely will exacerbate loss of biventricular pacing and should be disabled if thought to be the main cause of loss of biventricular pacing. Because the PVARP may be markedly extended, e.g. to 600 ms, perpetuation of loss of biventricular pacing can occur even at slower rates. For example, a PVARP extended to 600 ms combined with an AVI of 140 ms would result in continued loss of pacing until the sinus cycle length dropped to 740 ms or 81 bpm. Algorithms that reduce the PVARP when a sensed ventricular event occurs may prevent perpetuation of loss of biventricular pacing. Finally, elimination of PVCs with either medical (e.g. amiodarone) or invasive therapies (e.g. radiofrequency catheter ablation) should be considered in order to optimize biventricular pacing.

Atrial fibrillation with ventricular response above the LRL or SIR

Biventricular pacing in patients with chronic AF with rapid ventricular response is a common challenge. However, even subjects with a relatively

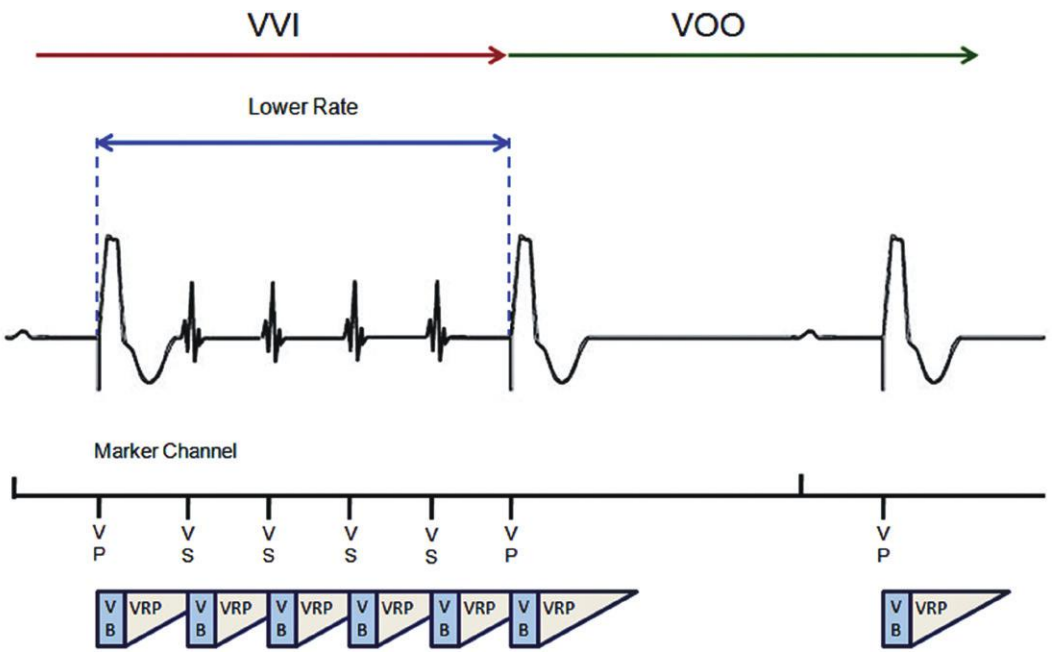


Figure 6.49 Noise reversion response. After a ventricular-sensed (VS) event occurs during the ventricular refractory period (VRP), this period will be re-initiated. Recurrent VS at non-physiological rates will be labeled as "noise" and switch to an asynchronous (VOO) pacing mode. (Source: Modified from Huizar JF, Kaszala K, Ellenbogen KA. Cardiac pacing modes and terminology. In: Sakena S, Camm AJ, eds. *Electrophysiological Disorders of the Heart*, 2nd Ed. Philadelphia, PA: Elsevier Saunders, 2012: 441–456. Reproduced with permission of Elsevier.)

good rate control may have fusion or lack of biventricular pacing (mode switch to non-tracking pacing mode) if ventricular response occurs above LRL or SIR. This can be dealt with by increasing LRL or sensor response, enabling ventricular rate regularization (see "*Rate enhancements*"), or ventricular sense response (biventricular trigger), as discussed above. Other possible therapies are detailed in Chapter 9.

Noise reversion

All manufactures have a noise reversion algorithm to prevent asystole or inappropriate bradycardia if a patient is exposed to an external source that can generate inappropriate sensing, such as electromagnetic interference (EMI). A ventricular-sensed event initiates a ventricular refractory period (non-programmable "noise window" in some devices), which will be reset if a ventricular-sensed event is noted within this period. Most algorithms will label these signals as electrical "noise" if they exceed physiological rates (400–600 bpm). Once the counter of the noise reversion algorithm is met, the device will adopt an asynchronous pacing mode, termed noise mode response, noise reversion mode, bradycardia noise mode, or noise rejection, depending on the device manufacturer (Figure 6.49).

Magnet response

Traditionally, magnet application has been used in special circumstances, such as: (1) temporary asynchronous pacing (such as in a pacemaker-dependent individual who will undergo a procedure where pacing inhibition is likely due to electromagnetic interference) and (2) assessment of pacing and battery status (latter determined by base pacing rate).

The response of a pacemaker to magnet application depends on the manufacturer as well as the

device programming. Overall, single and dual chamber pacemakers will *almost* always result in asynchronous pacing (AOO, VOO, DOO). Some pacemakers continue to pace asynchronously for a number of beats after magnet removal and most have a variable pacing rate with magnet application, determined by battery status. In "reset mode," some devices do not exhibit asynchronous pacing. Some pacemakers have a programmable "off" magnet response, while others may be programmed to store electrogram diagnostics when the magnet is applied. In contrast to pacemakers, defibrillators *will not* display asynchronous pacing mode, but will inhibit detection of ventricular arrhythmia (disabling therapies) and therefore patients should be monitored until the magnet is removed.

Summary

A clear understanding of pacing modes, timing cycles, and special pacemaker features is crucial to differentiate between appropriate and inappropriate pacemaker function, particularly when elucidating an ECG with an unusual pacing behavior.

Overall, all pacemakers follow the basic principles of timing cycles reviewed in this chapter. However, different pacemaker manufacturers and models have significant differences in their special pacemaker features, even when the goal is the same. When troubleshooting these cardiac devices, it is paramount to (1) interrogate the device to understand baseline programmed pacemaker settings; (2) understand in depth the different algorithms or pacing features; and (3) attempt to reproduce these episodes if possible, since both atrial and ventricular event markers (a pacemaker's interpretation of cardiac events) can assist us to further differentiate between appropriate and inappropriate pacemaker behavior response. Pacemaker manufacturers provide manuals and technical service experts around the clock to corroborate appropriate or inappropriate device function.

References

1 Bernstein AD, Daubert JC, Fletcher RD, *et al*. The revised NASPE/BPEG generic code for antibradycardia, adaptive-rate, and multisite pacing. North American Society of Pacing and Electrophysiology/British Pacing and Electrophysiology Group. *Pacing Clin Electrophysiol* 2002; 25(2): 260–264.

2 Ellenbogen KA, Kay GN, Lau C-P. *Clinical Cardiac Pacing, Defibrillation, and Resynchronization Therapy*, 3rd edn. Philadelphia: Saunders, Elsevier, 2007.

3 Kaszala K, Huizar JF, Ellenbogen KA. Contemporary pacemakers: what the primary care physician needs to know. *Mayo Clin Proc* 2008; 83(10): 1170–1186.

4 Cleland JG, Coletta AP, Abdellah AT, Witte KK, Hobson N, Clark AL. Clinical trials update from Heart Rhythm 2007 and Heart Failure 2007: CARISMA, PREPARE, DAVID II, SAVE-PACE, PROTECT and AREA-IN-CHF. *Eur J Heart Fail* 2007; 9(8): 850–853.

5 Biotronik I. *Cyclos Pacemaker Feature Handbook*. Lake Oswego, OR: Biotronik, Inc, 2006.

6 Higano ST, Hayes DL. P wave tracking above the maximum tracking rate in a DDDR pacemaker. *Pacing Clin Electrophysiol* 1989; 12(7 Pt 1): 1044–1048.

7 Boston Scientific, Corp. *Cognis TM 100-D System Guide*. St. Paul, MN: Boston Scientific, Corp., 2008.

8 Boston Scientific, Corp. *Altrua 20 and Altrua 40—Multiprogrammable Pacemakers*. St. Paul, MN: Boston Scientific, Corp., 2008.

9 St. Jude Medical, Inc. *Bradycardia Devices—Help Manual*. Sylmar, CA: St. Jude Medical, Inc, 2008.

10 Medtronic, Inc. *Adapta/Versa/Sensia Pacemaker Reference Guide*. Minneapolis, MN: Medtronic, Inc, 2006.

11 Connolly SJ, Sheldon R, Roberts RS, Gent M. The North American Vasovagal Pacemaker Study (VPS). A randomized trial of permanent cardiac pacing for the prevention of vasovagal syncope. *J Am Coll Cardiol* 1999; 33(1): 16–20.

12 Palmisano P, Zaccaria M, Luzzi G, Nacci F, Anaclerio M, Favale S. Closed-loop cardiac pacing vs. conventional dual-chamber pacing with specialized sensing and pacing algorithms for syncope prevention in patients with refractory vasovagal syncope: results of a long-term follow-up. *Europace* 2012; 14(7): 1038–1043.

13 Connolly SJ, Sheldon R, Thorpe KE, *et al*. Pacemaker therapy for prevention of syncope in patients with recurrent severe vasovagal syncope: Second Vasovagal Pacemaker Study (VPS II): a randomized trial. *JAMA* 2003; 289(17): 2224–2229.

14 Lau CP, Leung SK, Tse HF, Barold SS. Automatic mode switching of implantable pacemakers: II. Clinical performance of current algorithms and their programming. *Pacing Clin Electrophysiol* 2002; 25(7): 1094–1113.

15 Lau CP, Leung SK, Tse HF, Barold SS. Automatic mode switching of implantable pacemakers: I. Principles of instrumentation, clinical, and hemodynamic considerations. *Pacing Clin Electrophysiol* 2002; 25(6): 967–983.

16 Medtronic, Inc. *Entrust Implantable Cardioverter Defibrillator systems—Reference Manual*. Minneapolis, MN: Medtronic, Inc, 2005.

17 Mitchell AR, Sulke N. How do atrial pacing algorithms prevent atrial arrhythmias? *Europace* 2004; 6(4): 351–362.
18 Carlson MD, Ip J, Messenger J, *et al*. A new pacemaker algorithm for the treatment of atrial fibrillation: results of the Atrial Dynamic Overdrive Pacing Trial (ADOPT). *J Am Coll Cardiol* 2003; 42(4): 627–633.
19 Israel CW, Lawo T, Lemke B, Gronefeld G, Hohnloser SH. Atrial pacing in the prevention of paroxysmal atrial fibrillation: first results of a new combined algorithm. *Pacing Clin Electrophysiol* 2000; 23(11 Pt 2): 1888–1890.
20 Ellenbogen KA. Pacing therapy for prevention of atrial fibrillation. *Heart Rhythm* 2007; 4(3 Suppl): S84–87.
21 Israel CW, Hugl B, Unterberg C, *et al*. Pace-termination and pacing for prevention of atrial tachyarrhythmias: results from a multicenter study with an implantable device for atrial therapy. *J Cardiovasc Electrophysiol* 2001; 12(10): 1121–1128.
22 Lee MA, Weachter R, Pollak S, *et al*. The effect of atrial pacing therapies on atrial tachyarrhythmia burden and frequency: results of a randomized trial in patients with bradycardia and atrial tachyarrhythmias. *J Am Coll Cardiol* 2003; 41(11): 1926–1932.
23 Padeletti L, Purerfellner H, Adler SW, *et al*. Combined efficacy of atrial septal lead placement and atrial pacing algorithms for prevention of paroxysmal atrial tachyarrhythmia. *J Cardiovasc Electrophysiol* 2003; 14(11): 1189–1195.
24 Gold MR, Adler S, Fauchier L, *et al*. Impact of atrial prevention pacing on atrial fibrillation burden: primary results of the Study of Atrial Fibrillation Reduction (SAFARI) trial. *Heart Rhythm* 2009; 6(3): 295–301.
25 Savoure A, Frohlig G, Galley D, *et al*. A new dual-chamber pacing mode to minimize ventricular pacing. *Pacing Clin Electrophysiol* 2005; 28(Suppl 1): S43–46.
26 Sweeney MO, Bank AJ, Nsah E, *et al*. Minimizing ventricular pacing to reduce atrial fibrillation in sinus-node disease. *N Engl J Med* 2007; 357(10): 1000–1008.
27 Barold SS. Repetitive reentrant and non-reentrant ventriculoatrial synchrony in dual chamber pacing. *Clin Cardiol* 1991; 14(9): 754–763.
28 Wang P, Kramer A, Estes NA, 3rd, Hayes DL. Timing cycles for biventricular pacing. *Pacing Clin Electrophysiol* 2002; 25(1): 62–75.
29 Kamath GS, Cotiga D, Koneru JN, *et al*. The utility of 12-lead Holter monitoring in patients with permanent atrial fibrillation for the identification of nonresponders after cardiac resynchronization therapy. *J Am Coll Cardiol* 2009; 53(12): 1050–1055.
30 Sweeney MO, Hellkamp AS, Ellenbogen KA, *et al*. Adverse effect of ventricular pacing on heart failure and atrial fibrillation among patients with normal baseline QRS duration in a clinical trial of pacemaker therapy for sinus node dysfunction. *Circulation* 2003; 107(23): 2932–2937.

7

CHAPTER 7

Evaluation, troubleshooting, and management of pacing system malfunctions

Karoly Kaszala

Hunter Holmes McGuire VA Medical Center *and* Medical College of Virginia/VCU School of Medicine, Richmond, VA, USA

Introduction

The advanced functionality and programmability of modern pacemaker systems allow specific options to manage cardiac arrhythmias. Increasing complexity of both the mechanical (as in dual and multi-chamber devices) and software features (such as complex algorithms and pacemaker behaviors) creates a potential for increased component or software malfunction and appearance of unusual device behavior (pseudo-malfunction) that may challenge the providers. Over the last two decades, while challenges continue, technological advances have also improved the reliability and diagnostic capabilities of cardiac pacemakers and implantable cardioverter–defibrillators (ICDs). Miniaturization has allowed incorporation of increasing memory function and automatization in devices, which supports simpler device follow-up and advanced troubleshooting. In this chapter, commonly encountered problems relating to pacing in pacemakers and ICDs will be discussed.

General considerations; approach to evaluate pacemaker function and malfunction

Proper device evaluation and troubleshooting require the review of clinical and device history, a comprehensive, systematic clinical assessment of the patient, interrogation of the device, and review of the ancillary data. Intraoperative evaluation for diagnostic purposes is very rarely required, but is important for final confirmation of hardware abnormalities. The order of the diagnostic steps should be directed by the clinical circumstances and urgency of the problem, but in general, evaluation should start with non-invasive assessment and tests. During initial clinical encounters, some of the historical information may not be readily available and in these cases the ancillary data become even more important. Obtaining a focused medical history may help to clarify the indication of device therapy and identify prior system problems until other records become available. Co-morbidities may have significant implications

Cardiac Pacing and ICDs, Sixth Edition. Edited by Kenneth A. Ellenbogen and Karoly Kaszala.
© 2014 John Wiley & Sons, Ltd. Published 2014 by John Wiley & Sons, Ltd.

Table 7.1 Baseline data needed for pacemaker troubleshooting

Pacemaker system	Pacemaker generator Manufacturer Model and serial numbers Current programming Date of implant Alert or recalls Header type Special features
Lead system	Manufacturer Model and serial numbers Polarity and fixation mechanism Pin type Insulation material Date of implant Alert or recalls
Patient	Indication for pacemaker Implant operative report Medical and cardiac diagnosis Medications History of recent medical procedures (cardioversion, defibrillation, magnetic resonance imaging, electrocautery, etc.) History of electrical current exposure, trauma

Table 7.2 Symptoms suggestive of pacemaker abnormality

*Symptom**	*Cause*
Fatigue Confusion Dyspnea Orthopnea Chest pain Palpitations Presyncope Syncope	Pacemaker syndrome: Hemodynamic and neurohormonal abnormality related to ventricular pacing and/or loss of AV synchrony Loss of capture or pacing output Sensing abnormality Special algorithms Suboptimal rate-modulated pacing Arrhythmias: With or without suboptimal pacemaker programming
Hiccups (due to diaphragmatic stimulation)	LV pacing close to the phrenic nerve RA pacing close to the phrenic nerve RA lead dislodgement to the SVC Lead perforation
Chest wall/pectoral muscle contractions (due to pectoral muscle or intercostal muscle capture)	Unipolar pacing Loose set-screw Lead insulation damage Lead perforation

*Many of the above symptoms are not specific for a pacemaker abnormality. Correlation with additional clinical and ancillary data is required to make the diagnosis.
AV, atrioventricular; LV, left ventricular; RA, right atrial; SVC, superior vena cava.

regarding pacemaker programming, appropriate device selection, and risk of complications. The surgical implantation note should be carefully reviewed. The operative report should describe the indication for device therapy, vascular access site, lead type and position, device position, as well as any procedural difficulties. Device and lead parameters, including lead polarity, lead connection type, lead fixation mechanism, product manufacturer, and serial numbers should also be listed. Baseline programming parameters as well as post-implant electrocardiography (ECG) and chest X-ray are also important references. Any advisories related to the leads and device should be noted (Table 7.1). The next step is evaluation for the presence of any symptoms. While certain symptoms, such as syncope, are commonly linked to pacemaker malfunction, other less common signs may also indicate malfunction and should be looked for under appropriate clinical circumstances (Table 7.2). A focused physical exam may identify signs of heart failure and valvular abnormalities. Inspection of the jugular venous pressure may reveal the presence of cannon A waves, suggesting a loss of atrioventricular (AV) synchrony as atrial contraction takes place against a closed tricuspid valve. Presence of pectoral or intercostal muscle stimulation or diaphragmatic capture may point to mechanical malfunction. If lead integrity failure or skeletal muscle oversensing is suspected, provocative maneuvers, such as isometric arm exercise, hyperventilation, or Valsalva maneuver, may be useful to trigger abnormal function. Inspection

should also extend to the device pocket to assure proper healing and look for postoperative complications such as infection or erosion. A current ECG is important to confirm the heart rhythm and presence or absence of pacing. The ECG may identify atrial and ventricular sensing or pacing abnormality, and morphology of paced atrial and ventricular complexes provides rough information on the pacing site. Review of a baseline ECG before device implantation may also be useful. Pacemaker lead position and gross lead integrity may be further evaluated by anteroposterior (AP) and lateral chest X-ray images. While analysis of the ancillary information rarely reveals all details of an abnormality, it is helpful with triaging until a device-specific programmer becomes available for further analysis.

The programmer is required to retrieve information from the device memory and test the pacing system. It is therefore essential to know the manufacturer of the device in order to perform a full evaluation. A manufacturer's information may be retrieved from the operative report or from the device identification card that is mailed to the patient following an implant. If these are not available, the radiographic identifier of the pulse generator (Figure 7.1) on a chest radiograph or pacing response to magnet application over the pacemaker (magnet response) may help to narrow down the device manufacturer. An X-ray image showing the profile of the device may also provide additional clues.[1] If all these efforts fail, technical service representatives of the device companies (current major device manufacturers in the US include Biotronik, Boston Scientific, Medtronic, Sorin, and St. Jude Medical) may be able to retrieve the patient information from their implant database. Technical services may also assist with interpretation of the device interrogation and provide additional information about the leads, pulse generator, and certain device- and manufacturer-specific algorithms.

Differential diagnosis of device malfunction

Pacing system malfunctions may be categorized according to ECG manifestations, including abnormal sensing, lack of pacing or of capture, and abnormal or unexpected rate of pacing. In broader terms, pacemaker malfunction also includes symptoms associated with the pacing or pacemaker programming, or complications from the pacemaker system. Malfunctions may also be divided according to the particular cause, which includes mechanical abnormalities, programming abnormalities, and extrinsic/external causes. In clinical practice, malfunction is usually suspected based on abnormal ECG or symptoms. Latent abnormalities may also be diagnosed from stored device data and proper action may halt an impending clinical problem. Ultimately, the particular cause is

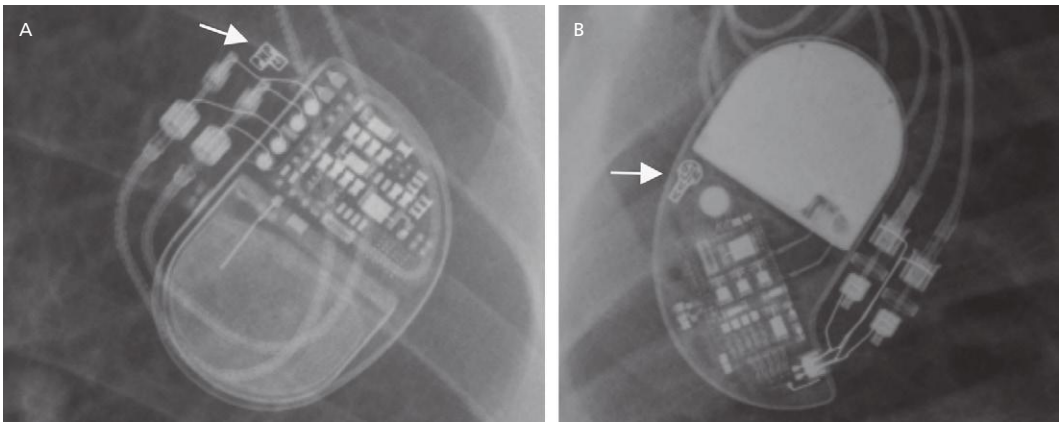


Figure 7.1 Examples of radiographic device identifiers. (A) An Enrhythm device with Medtronic logo and PNP device identifier (arrow). (B) Logo of a St. Jude Medical Identity pacemaker (arrow). Bipolar leads are identified based on two pin electrodes for each lead.

determined following correlation of all ancillary information with the interrogated device data.

Abnormalities in the mechanical components of a pacing system

A pacing system is comprised of a pulse generator and the pacemaker lead(s). The pulse generator, which houses the battery and electrical circuitry, is hermetically sealed and connected to the pacemaker leads through the header. The pacemaker lead pins are secured in the header with one or two set-screws during the implant procedure. The leads maintain a connection to the cardiac tissue by either an active screw mechanism or passive fixation. The pacemaker leads consist of one or more conductors surrounded by insulation material. In a bipolar lead, the conductors connect the tip and ring electrodes to the terminal pin, whereas in a unipolar lead only a tip electrode is present and the can serves as the anode (Figure 7.1 and Figure 7.2). The ICD leads are more complex structures incorporating, in addition, one or two coils for high-voltage defibrillation. These additional components make lead engineering more difficult and are likely major contributors to a poorer long-term lead survival compared to that for pacemaker leads. The electrical circuit of a pacer system is completed by the tissue between the anode and cathode. The distance between the anode and cathode is the major difference between a unipolar and bipolar system in terms of sensing characteristics and current and energy requirement to capture the myocardium. A larger distance in a unipolar system predisposes to sensing far-field signals from cardiac or non-cardiac sources. Pacing impedance is lower during unipolar pacing compared to bipolar pacing in the same system. Any defect in the integrity of the lead and pacemaker header assembly may result in the introduction of noise and cause sensing abnormality or divert pacing current away from the myocardium with resultant capture failure.

Pulse generator hardware and software

A predictable failure of any current pacer or ICD system is related to battery depletion, which is the most common reason for device explantation.[2]

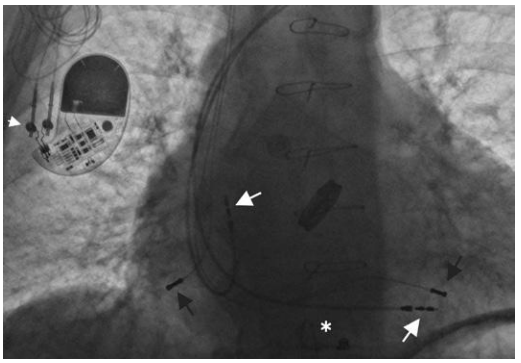


Figure 7.2 PA radiographic image of a unipolar pacemaker system. Note the single pin electrode on each lead and header (small white arrow). Lead integrity failure occurred in the system and the patient underwent implantation of two new bipolar leads. Due to venous occlusion, a completely new system was implanted from the left subclavian system. Black arrows point to the passive fixation unipolar lead tips and large white arrows to the new bipolar active fixation pacemaker leads. A mechanical aortic valve is also present. A broken old epicardial pacer wire is marked (*). The unipolar system was over 30 years old and it required a special header to accommodate 5-mm lead pins. Special consideration is required when plans are made for pulse generator change in such a patient as a standard header would not accommodate the lead. In addition, the pacemaker generator serves an active part in the pacing circuit and capture would not take place once the device is removed from the body (in contrast to a bipolar pacing system). Another implication of a unipolar system is that there is an increased chance of noise oversensing, and special attention to this is required, especially in the hospital environment. Note that the electrodes of the second set of leads (large white arrows, new implant) are >1 cm away from the other lead components, minimizing the risk of lead chatter.

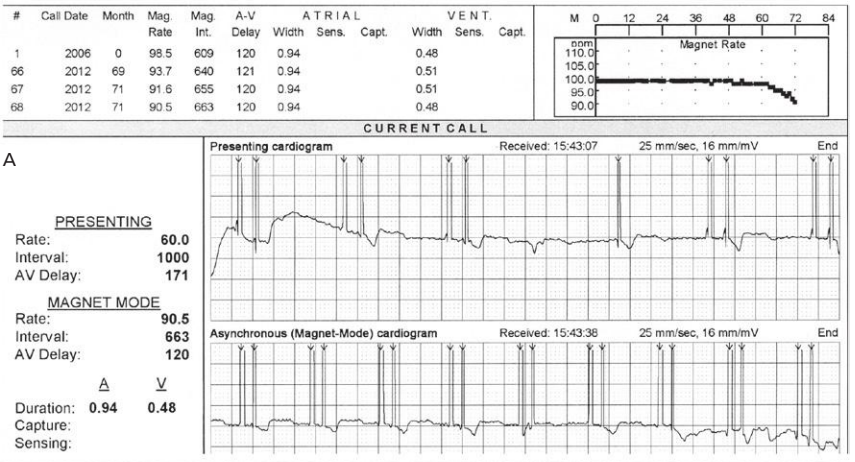
One of the goals of regular device follow-up is to ascertain that there is adequate battery capacity to maintain appropriate device function. Among the several challenges of battery engineering are the constant efforts to minimize device (and battery) size, yet maximize longevity in a very reliable manner. In addition, in order to allow adequate time to diagnose battery depletion and schedule generator replacement, battery depletion has to follow a very predictable pattern. For the purpose of cardiac pacing, the characteristics of lithium–iodine batteries have been optimal and have been utilized for decades with great reliability. Battery

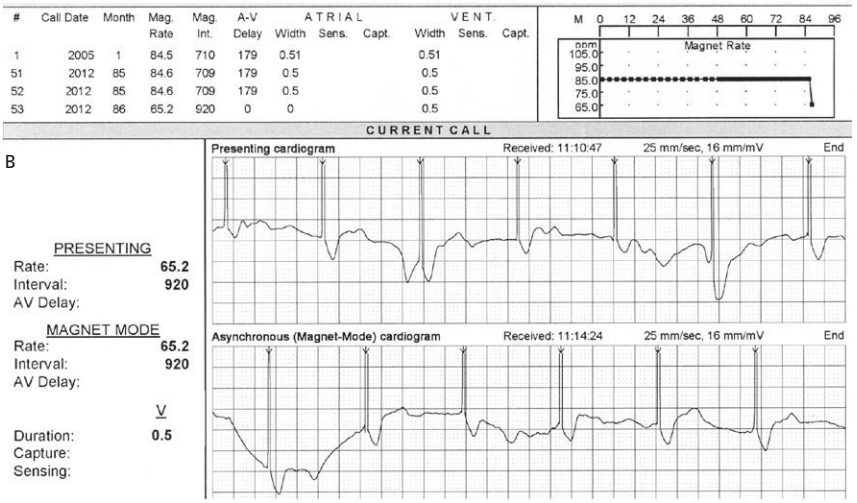
voltage remains relatively flat during much of the device's lifetime, with decline only close to end of service. Battery impedance on the other hand increases continuously, with a very rapid rise as battery depletion approaches. Impedance is therefore a better overall predictor of battery longevity at any given time point. Manufacturers differ in whether they express battery parameters in numerical or graphical fashion, but battery status is one of the key parameters that is followed in the clinic. Application of a magnetic field over a pacemaker (clinically by placing a special donut-shaped magnet) results in a device-specific magnet response. This response may be observed during clinic follow-up or during trans-telephonic monitoring (TTM). In most pacemakers, magnet application results in asynchronous pacing at a certain rate (except for rare circumstances when a different special magnet function is programmed "on"). As the battery approaches end of service, the magnet-activated pacing rate gradually decreases or remains stable in some generators until the battery reaches elective replacement indicator (ERI) status. At this point, a specific model or company-specific magnet rate indicates that the device is nearing end of service (Figure 7.3). At ERI there is an additional 3 months' battery support before the device reaches end of life (EOL). At EOL, device reliability is not guaranteed and erratic behavior may be observed (Figure 7.4). As ERI may also trigger a change in pacing mode (rate response turned "off," switch to single chamber VVI mode); in rare patients, clinical decompensation may occur even as ERI is reached (Figure 7.5). Increasing availability of Web-based remote home monitoring has revolutionized patient follow-up and this technology will likely completely replace TTM in the near future.[3]

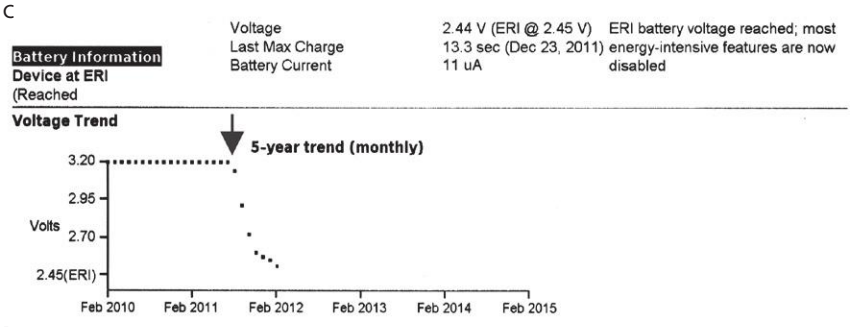
ICD batteries are designed differently from pacemaker batteries in order to support standard pacing requirements (1–20 μJ per pacing pulse) and deliver rapid charge to high-voltage capacitors (up to 30–40 J) for defibrillation or cardioversion therapy of tachyarrhythmias. These tasks are achieved more efficiently with currently used lithium–silver vanadium oxide- or lithium–manganese dioxide-based batteries. The discharge curves of these batteries vary based on the composition material and also differ from those of pacemaker batteries. It is important to understand the individual variations in order to make informed decisions during follow-up. Assistance from the technical service at the device company may be helpful in unclear situations. In ICD generators, battery voltage and capacitor charge time is used most commonly to follow the battery status.

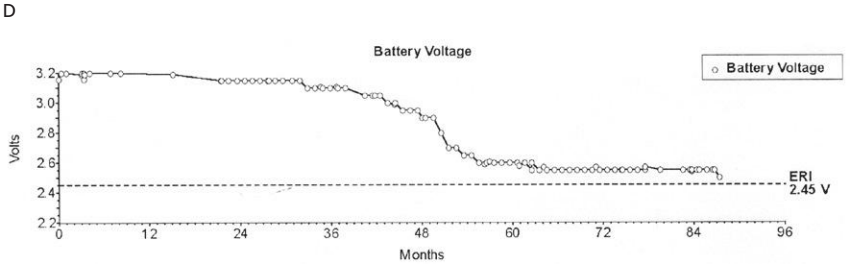
While reliability of pacemaker and ICD generators continues to improve, random system failure or mechanical (such as battery, circuitry, header, wiring, etc.) or software design flaws continue to occur, as has been seen in recent advisories.[4] Depending on which particular component is affected, inappropriate pacing behavior, battery or wiring short with lack of pacing or defibrillation, or accelerated battery depletion may result (Figure 7.3C). Early battery depletion may be caused by suboptimal device programming or lead/patient-related events (exit block, high pacing threshold, frequent defibrillation therapy in ICDs). Other causes of generator failure or malfunction may be suspected based on clinical circumstances, such as recent mechanical trauma to the device site, exposure to significant electromagnetic interference (EMI; especially in hospital settings, such as electrocautery, MRI scan, TENS), or radiation (diagnostic or therapeutic). While EMI has caused system failures in early devices, these types of serious events are much less common with modern pacemakers and ICDs due to advanced filtering and shielding, and increased awareness of these

Figure 7.3 Pacemaker trans-telephonic transmission (TTM) summaries:(A) St. Jude Medical and (B) Medtronic. A typical, gradual decline in magnet response rate is seen in the St. Jude device (model: Identity Adx), whereas there is sudden drop to VVI 65 bpm in the Medtronic pacemaker (model: EnRhythm). Electrogram strips show current presenting rhythm as well as current magnet rate. (C) Battery voltage trend from an ICD. This device was found with an abnormal, sudden battery depletion (arrow) 2 years after implant. The abnormality was recognized during remote device monitoring. This was a random component failure and no specific cause was identified. (D) Normal ICD battery depletion curve of a St. Jude Atlas device with two plateau phases, one at the beginning of life and one before ERI.


#
Call Date
Month
Mag. Rate
Mag. Int.
A-V Delay
ATRIAL Width
ATRIAL Sens.
ATRIAL Capt.
VENT. Width
VENT. Sens.
VENT. Capt.
1 2006 0 98.5 609 120 0.94 0.48
66 2012 69 93.7 640 121 0.94 0.51
67 2012 71 91.6 655 120 0.94 0.51
68 2012 71 90.5 663 120 0.94 0.48
M 0 12 24 36 48 60 72 84
Magnet Rate
110.0
105.0
100.0
95.0
90.0
CURRENT CALL
A
PRESENTING
Rate: 60.0
Interval: 1000
AV Delay: 171
MAGNET MODE
Rate: 90.5
Interval: 663
AV Delay: 120
A V
Duration: 0.94 0.48
Capture:
Sensing:
Presenting cardiogram
Received: 15:43:07
25 mm/sec, 16 mm/mV
End
Asynchronous (Magnet-Mode) cardiogram
Received: 15:43:38
25 mm/sec, 16 mm/mV
End


#
Call Date
Month
Mag. Rate
Mag. Int.
A-V Delay
ATRIAL Width
ATRIAL Sens.
ATRIAL Capt.
VENT. Width
VENT. Sens.
VENT. Capt.
1 2005 1 84.5 710 179 0.51 0.51
51 2012 85 84.6 709 179 0.5 0.5
52 2012 85 84.6 709 179 0.5 0.5
53 2012 86 65.2 920 0 0 0.5
M 0 12 24 36 48 60 72 84 96
Magnet Rate
105.0
95.0
85.0
75.0
65.0
CURRENT CALL
B
PRESENTING
Rate: 65.2
Interval: 920
AV Delay:
MAGNET MODE
Rate: 65.2
Interval: 920
AV Delay:
V
Duration: 0.5
Capture:
Sensing:
Presenting cardiogram
Received: 11:10:47
25 mm/sec, 16 mm/mV
End
Asynchronous (Magnet-Mode) cardiogram
Received: 11:14:24
25 mm/sec, 16 mm/mV
End


C
Battery Information
Device at ERI
(Reached
Voltage
Last Max Charge
Battery Current
2.44 V (ERI @ 2.45 V)
13.3 sec (Dec 23, 2011)
11 uA
ERI battery voltage reached; most energy-intensive features are now disabled
Voltage Trend
5-year trend (monthly)
3.20
2.95
2.70
2.45(ERI)
Volts
Feb 2010
Feb 2011
Feb 2012
Feb 2013
Feb 2014
Feb 2015


D
Battery Voltage
Battery Voltage
3.2
3.0
2.8
2.6
2.4
2.2
Volts
ERI
2.45 V
0
12
24
36
48
60
72
84
96
Months

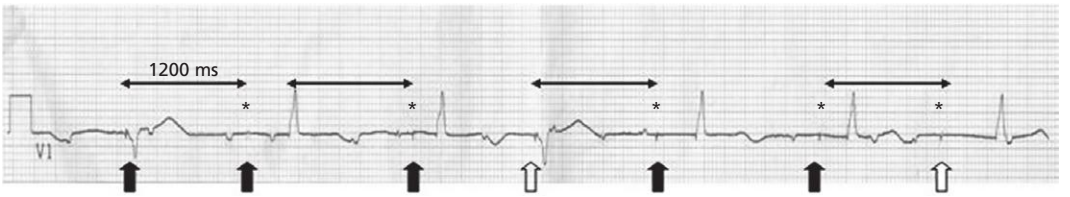


Figure 7.4 Pacemaker battery depletion. The rhythm strip (lead V1) from a patient who had undergone VVI pacemaker implantation 14 years earlier and had subsequently not obtained any further pacemaker follow-up. Pacing stimuli are denoted by the vertical closed arrows; pacing is occurring at a cycle length of 1200 ms (horizontal arrows). There is both intermittent failure to capture (*) and failure to sense (vertical open arrows). The combination of sensing and capture problems suggested a problem intrinsic to the lead; however, at pacemaker generator change, the lead demonstrated no abnormality. The erratic pacing behavior is best explained by near-complete depletion of the pacemaker's battery.

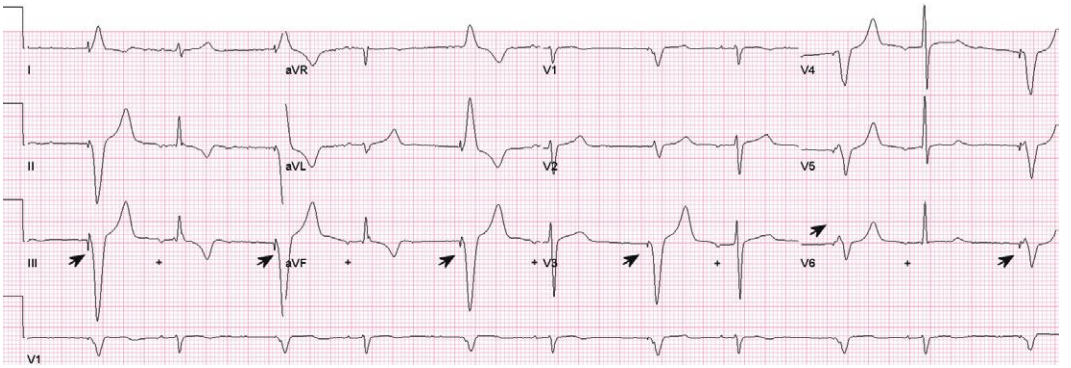
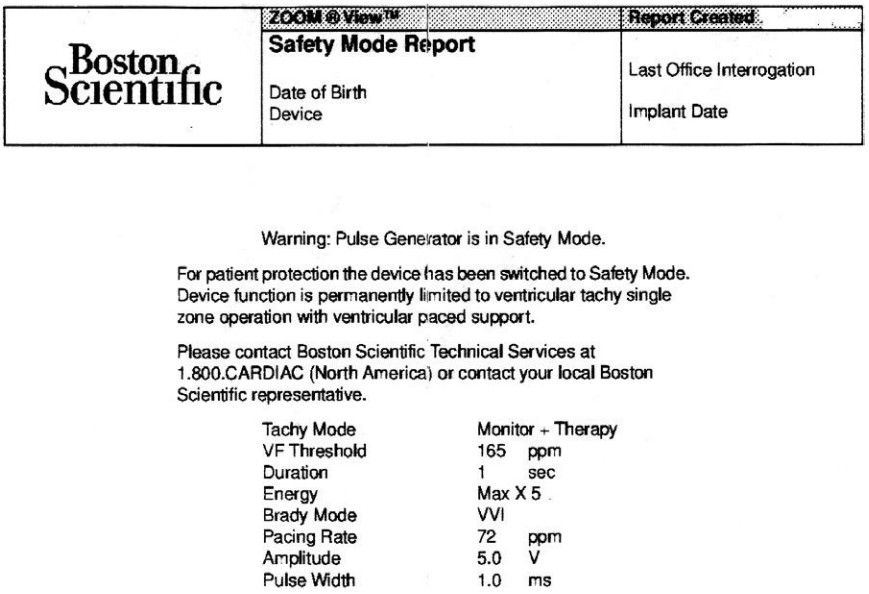


Figure 7.5 A patient with sinus node dysfunction presented with shortness of breath. The Medtronic device had reached elective replacement indicator (ERI) and this ECG shows VVI pacing at 65 bpm with appropriate sensing and capture [pacing artifact (arrows) is followed by ventricular depolarization]. There is slow retrograde conduction with echo beats (+). The ninth beat is a fusion beat between a ventricular ectopic beat and paced beat. This presentation with acute loss of atrioventricular synchrony due to pacing mode change is consistent with pacemaker syndrome. His symptoms resolved after pacemaker generator change.

potential interactions.[5] EMI may cause temporary changes in pacemaker or ICD behavior and trigger a reset or a partial reset of the device. These are fallback safety settings that are activated in the event of suspected software or hardware malfunction. Most commonly, a change in bradycardia programming (and/or tachycardia programming in ICDs) or loss of stored data occurs. The programming changes are usually reversible, but a generator change may be required in rare instances when changes are non-programmable (Figure 7.6). Direct or scattered radiation may affect the device circuitry and cause various levels of reset. Direct radiation over the device may cause permanent damage to the circuitry. If the device-specific safety dose is exceeded, the reliability of the device may be impaired and the generator has to be replaced. The radiation exposure for the device needs to be calculated, especially when therapeutic radiation is applied close to the device site. The maximum tolerated radiation dose for a particular device is available from the manufacturer. If the planned radiation path is close to or over the device, the generator may need to be repositioned before treatment, particularly in pacemaker-dependent patients. The mechanism of radiation-induced changes is multifactorial. Modern devices utilize complementary metal oxide semiconductor



Boston Scientific

ZOOM ® View™

Safety Mode Report

Report Created

Last Office Interrogation

Date of Birth

Device

Implant Date

Warning: Pulse Generator is in Safety Mode.

For patient protection the device has been switched to Safety Mode. Device function is permanently limited to ventricular tachy single zone operation with ventricular paced support.

Please contact Boston Scientific Technical Services at 1.800.CARDIAC (North America) or contact your local Boston Scientific representative.

Tachy Mode	Monitor + Therapy
VF Threshold	165 ppm
Duration	1 sec
Energy	Max X 5
Brady Mode	VVI
Pacing Rate	72 ppm
Amplitude	5.0 V
Pulse Width	1.0 ms

Figure 7.6 Biventricular ICD generator switched to non-programmable safety mode due to exposure to electromagnetic interference (EMI) in the hospital environment. The patient had undergone open heart surgery and electrocautery was used very close to or over the coronary sinus lead; this was the likely cause of the problem. A new generator was implanted after the patient had recuperated from surgery.

circuitry (CMOS). Radiation may induce ionization in CMOS with build-up of a charge.[6] The time course of these changes and possible consequences are variable, and include increased current drain and shortened battery life or changes in sensing. Scattered radiation may also affect the random access memory (RAM) and result in errors in device function or data storage. RAM is increasingly used in more complex ICDs, but also in newer generation pacemakers.

Software abnormalities had been common reasons for device advisories in the past. The increasing sophistication of the device circuitry and memory have increasingly allowed non-invasive postoperative software upgrades via the programmer, and the clinical consequences of software anomalies in recent years have been less significant. An example of software upload includes the update of Medtronic ICDs with the Lead Integrity Alert™ algorithm in order to minimize the risk of inappropriate ICD therapies in the event of a lead fracture. This software was retro-fitted to several earlier classes of Medtronic devices.[7] As software-specific information is proprietary, providers need to rely on information from the manufacturers about any updates or to confirm abnormalities.

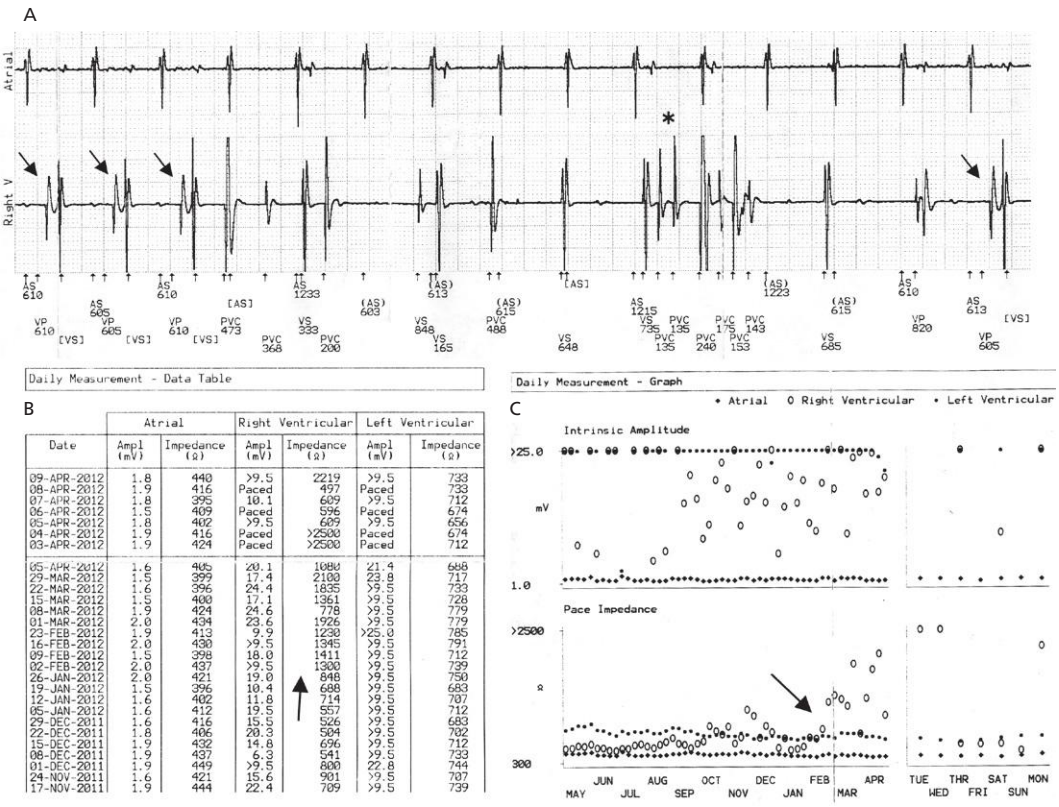
Failure of pacemaker circuitry or complete depletion of the battery results in system failure and inability to interrogate the device. If communication with the device cannot be established, several possible confounders need to be ruled out before a generator change is contemplated. First, an environmental factor that may affect the communication with the device, such as EMI [as may be seen in a patient with a left ventricular (LV) assist device], or a malfunctioning programmer has to be excluded. As part of the evaluation process, the manufacturer of the device has to be ascertained, as discussed above, to make ensure that the proper programmer is used for interrogation. This is critical for assessing a new patient, but may also be an embarrassing oversight in a patient who is normally followed in the device clinic but had a device exchange or upgrade performed in another facility between visits.

Leads

Pacemaker and ICD leads are commonly referred to as the Achilles heel of the pacer/ICD system as they remain the main source of mechanical failure. Starting at the implantation procedure and over the lifetime of the system, leads are exposed to significant chemical and mechanical stress in the hostile intravascular environment. The restricted space at the intersection of the first rib and clavicle may cause additional stress, and this is the site where subclavian crush injuries develop. Lead-to-lead and lead-to-can interaction as well as tight anchoring sutures are other common mechanical points for potential lead failure. Lead-to-lead interactions may also occur between the leads as they make their way to the heart in the vascular system. Repetitive stress due to friction, pressure, and cyclical repetitive movement may result in lead insulation defect or fracture of the conductors. Certain pacemaker or ICD leads are more prone to develop structural failure for various reasons, such as defects in the design or manufacturing of insulation material, type of insulation material, or other parts of the lead assembly. Long-term survival data for individual leads are available from the performance report of the manufacturers. Lead failures are notoriously underreported and it is difficult to know the true incidence of this problem. In case there are concerns about lead reliability, advisories are initiated by the manufacturer or Food and Drug Administration (FDA) to inform clinicians and assist with clinical decision-making. While the reliability of pacemaker leads has improved over the last decades, two major advisories drew attention to design failures and risk of premature lead degradation in certain ICD leads, affecting tens of thousands of patients (Sprint Fidelis™, Medtronic in 2007; and Riata™, St. Jude Medical ICD leads as well as LV leads from St. Jude Medical, 2011).[8] Review of recommendations about the management of these advisories is beyond the scope of this chapter but in general, an individualized approach is recommended with enhanced surveillance. Routine invasive interventions are rarely beneficial or advised for prophylactic purposes.

In general, abnormalities in lead insulation manifest as decreased lead impedance, whereas conductor fracture is associated with increased lead impedance (Figure 7.7 and Figure 7.8). Insulation or conductor failure may cause noise, oversensing, or failure to capture. The normal lead impedance values usually vary between 300 and 1800 Ω depending on the particular lead characteristics, but remain relatively stable following the lead maturation period. Out of range values would not necessarily mean abnormal lead function (Figure 7.9). On the other hand, significant variation in lead impedance, even if it is within the range of "normal values," should raise concerns about possible lead failure.[9] Subclinical mechanical abnormality may present with sudden, erratic change in lead impedance in the lead trend data or non-physiological noise may be recorded as an arrhythmia event (Figure 7.7). Web-based remote or *in-situ* alert notifications are increasingly used to warn patients and providers if lead impedance parameters fall outside of a programmable, predetermined range. Lead failure in a pacemaker system may result in oversensing and lack of or inappropriate pacing or lack of capture. In certain pacemakers, automatic polarity switch (from bipolar to unipolar) takes place if lead impedance values reach an out of range value. This safety feature may help to re-establish pacing if only the ring electrode circuit is damaged (Figure 7.10).

In ICD patients, noise and oversensing may present with inappropriate ICD therapies or dizziness and syncope due to oversensing and pauses. In some newer generation ICDs, a near-field or sensed intracardiac electrogram (EGM) is correlated with a far-field EGM to rule out oversensing of non-physiological signals (Securesense™, St. Jude Medical; Smartshock™, Medtronic). A special algorithm, developed by Medtronic, monitors lead impedance change, VT episodes in the non-physiological range, and non-physiological ventricular-sensed events (VV intervals in the range of 120–130 ms that are too closely coupled to represent physiological ventricular depolarization), and this technology has been helpful to identify impending lead integrity failure before any clinical event and reduce the risk of inappropriate ICD therapies.[7] Any suggestion of lead integrity failure has to be taken very seriously, especially in ICD leads or in pacemaker-dependent patients, as the functionality of the lead may change very



Date	Atrial Ampl (mV)	Atrial Impedance (Ω)	Right Ventricular Ampl (mV)	Right Ventricular Impedance (Ω)	Left Ventricular Ampl (mV)	Left Ventricular Impedance (Ω)
09-APR-2012	1.8	440	>9.5	2219	>9.5	733
08-APR-2012	1.9	416	Paced	497	Paced	733
07-APR-2012	1.8	395	10.1	609	>9.5	712
06-APR-2012	1.5	409	Paced	596	Paced	674
05-APR-2012	1.8	402	>9.5	609	>9.5	656
04-APR-2012	1.9	416	Paced	>2500	Paced	674
03-APR-2012	1.9	424	Paced	>2500	Paced	712
05-APR-2012	1.6	405	20.1	1080	21.4	688
29-MAR-2012	1.5	399	17.4	2100	23.8	717
22-MAR-2012	1.6	396	24.4	1835	>9.5	733
15-MAR-2012	1.5	400	17.1	1361	>9.5	726
08-MAR-2012	1.9	424	24.6	778	>9.5	779
01-MAR-2012	2.0	434	23.6	1926	>9.5	779
23-FEB-2012	1.9	413	9.9	1230	>25.0	785
16-FEB-2012	2.0	430	>9.5	1345	>9.5	791
09-FEB-2012	1.5	398	18.0	1411	>9.5	712
02-FEB-2012	2.0	437	>9.5	1300	>9.5	739
26-JAN-2012	2.0	421	19.0	848	>9.5	750
19-JAN-2012	1.5	396	10.4	688	>9.5	683
12-JAN-2012	1.6	402	11.8	714	>9.5	707
05-JAN-2012	1.6	412	19.5	557	>9.5	712
29-DEC-2011	1.6	416	15.5	526	>9.5	683
22-DEC-2011	1.8	406	20.3	504	>9.5	702
15-DEC-2011	1.9	432	14.8	696	>9.5	712
08-DEC-2011	1.9	437	6.3	541	>9.5	733
01-DEC-2011	1.9	449	>9.5	800	22.8	744
24-NOV-2011	1.6	421	15.6	901	>9.5	707
17-NOV-2011	1.9	444	22.4	709	>9.5	739

Figure 7.7 (A) Atrial and right ventricular (RV) electrogram recording from a biventricular pacemaker. At the beginning of the tracing, there is atrial–synchronous biventricular pacing but only the left ventricular lead captures (arrows). A subsequently delayed RV signal (marked as VS) represents loss of capture at the RV pacing site. There are make-or-break signals consistent with noise (*) and suggestive of lead integrity failure. Lead fracture was confirmed by the sudden increase and erratic changes in RV lead impedance (B,C, arrows). This example shows that while the biventricular pacemaker provides some safety advantage in the case of a lead fracture, significant noise in the RV lead would result in inhibition of pacing (A, *) and cause asystole.

rapidly and failure to act on it in a timely manner may have catastrophic consequences.

In broader terms, lead failure may be seen with mechanically intact leads when fixation to the heart is suboptimal, such as in the case of micro- and macro-dislodgement or lead perforation. Macro- dislodgement is suspected based on alterations in pacing parameters and change in lead position seen on imaging studies (mainly chest X-ray). A change in the paced ECG morphology may also be evident following significant ventricular lead migration. Atrial lead dislodgement to the ventricle may mimic switched lead pins in the header. Micro-dislodgement is suspected when pacing parameters change (decreased sensing, increased pacing threshold, change in lead impedance, or a combination of these) within the first days to weeks following implantation, but without a noticeable change in lead position based on X-ray appearance. It is important to remember that during normal lead maturation, an inflammatory reaction takes place in the myocardium near the lead tip. This may result in an increase in capture threshold and decrease in sensing, and can be expected to resolve within several weeks. Almost all contemporary transvenous leads now have steroid-eluting tips, which have markedly reduced the incidence of significant tissue reaction. Once the healing process is complete, some degree of fibrosis develops at the lead tip contact site and

A

Daily Measurement - Data Table

Date	Atrial Amplitude (mV)	Atrial Impedance (Ω)	Ventricular Amplitude (mV)	Ventricular Impedance (Ω)	Threshold (V)
11-JUL-2012	N.R.	240	7.6	380	1.1
10-JUL-2012	N.R.	<100	7.4	380	1.0
09-JUL-2012	N.R.	<100	7.0	380	1.0
08-JUL-2012	N.R.	230	7.8	380	1.1
07-JUL-2012	N.R.	240	9.3	380	1.0
06-JUL-2012	N.R.	240	N.R.	380	1.1
05-JUL-2012	N.R.	230	N.R.	370	1.1
02-JUL-2012	N.R.	200	7.8	370	1.1
25-JUN-2012	N.R.	200	9.1	370	1.1
18-JUN-2012	N.R.	190	7.6	370	1.1
11-JUN-2012	N.R.	200	8.7	370	1.1
04-JUN-2012	N.R.	240	9.9	370	1.1
28-MAY-2012	N.R.	190	9.2	370	1.1
20-FEB-2012	N.R.	190	9.0	380	1.0
13-FEB-2012	N.R.	200	N.R.	400	1.0
06-FEB-2012	N.R.	230	9.1	400	0.9
30-JAN-2012	N.R.	230	7.5	400	0.9
23-JAN-2012	N.R.	260	5.4	400	0.9
16-JAN-2012	N.R.	310	6.5	400	0.9
09-JAN-2012	N.R.	360	6.6	400	0.8
02-JAN-2012	N.R.	340	5.7	400	0.8
26-DEC-2011	N.R.	350	4.6	410	0.9
19-DEC-2011	N.R.	360	5.4	410	0.9
12-DEC-2011	N.R.	370	3.9	410	0.9
05-DEC-2011	N.R.	380	3.2	410	0.8
28-NOV-2011	N.R.	380	5.4	410	0.8
21-NOV-2011	N.R.	400	3.3	410	0.8
14-NOV-2011	N.R.	400	4.6	410	0.7
07-NOV-2011	N.R.	410	8.6	420	0.7
31-OCT-2011	N.R.	410	9.2	420	0.7
24-OCT-2011	N.R.	410	8.2	410	0.7
17-OCT-2011	N.R.	410	N.R.	410	0.7
10-OCT-2011	N.R.	410	3.6	420	0.7
03-OCT-2011	N.R.	420	4.7	410	0.7
26-SEP-2011	N.R.	420	9.7	420	0.6

B

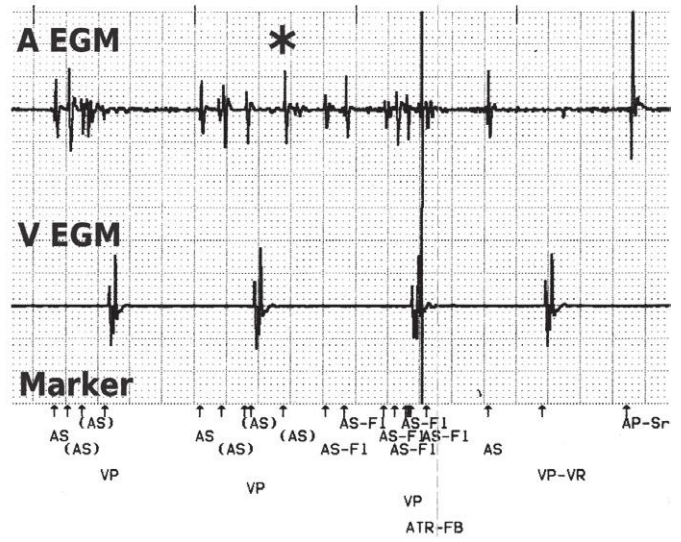


Figure 7.8 Example of lead abnormality due to insulation failure. (A) Long-term lead trends. There is gradual decline in lead impedance and subsequent variability (arrow) with minimum impedance recorded as $<100\,\Omega$. (B) Noise with oversensing was recorded in the device memory as a mode switch episode. Following mode switch (ATR–FB), DDI pacing is initiated with ventricular rate regularization (VP–VR).

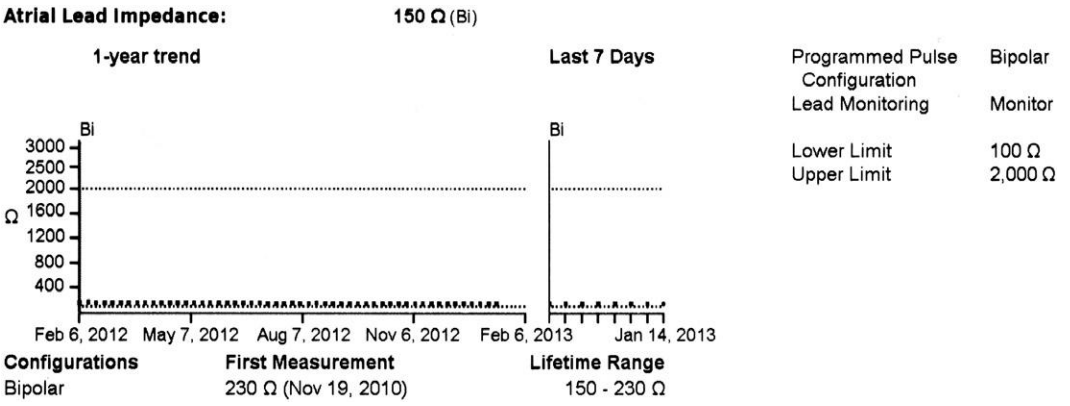


Figure 7.9 Chronic low impedance trend of a bipolar atrial lead. Note the long-term stable impedance value in this lead with normal function.

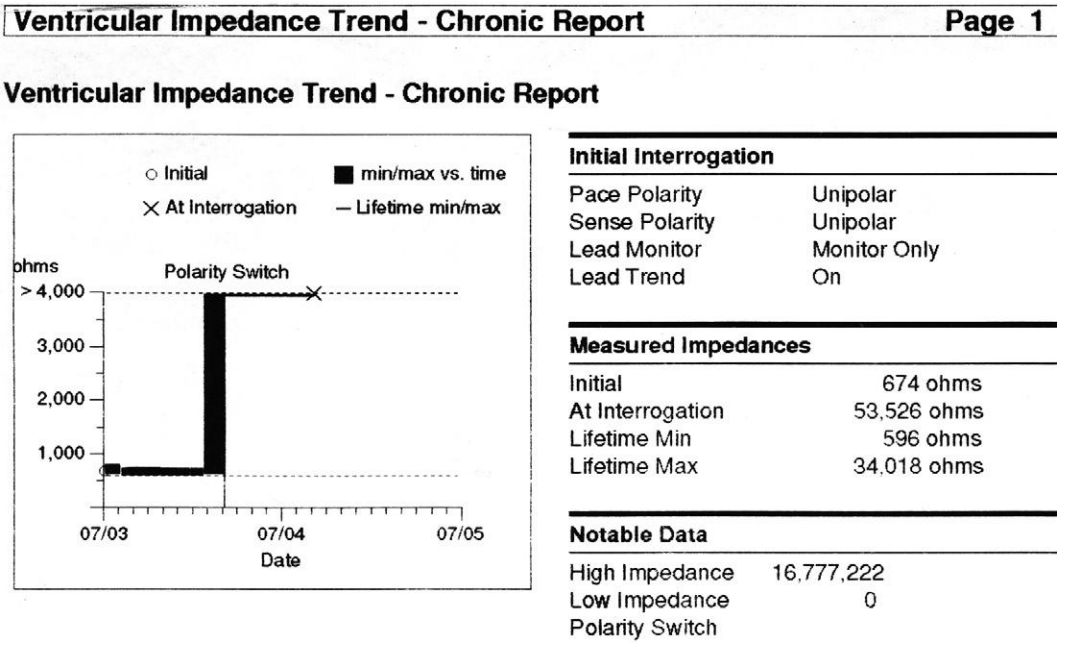


Figure 7.10 Polarity change from bipolar to unipolar pacing due to sudden marked elevation in lead impedance. In this case, the impedance remained abnormal even in unipolar mode, suggesting that the lead fracture involved the tip electrode or both tip and ring electrodes.

when this process is excessive, permanent exit block and sensing abnormality may develop. Exit block usually develops in the chronic stage, weeks to months after implant. Differentiation between exit block and micro-dislodgement is difficult, especially if the abnormality is identified weeks to months after implant. Lead dislodgement may be due to inadequate fixation to the cardiac tissue, inadequate lead redundancy, loose fixation of the lead in the suture sleeves, or patient-related causes (such as non-compliance with activity or Twiddler's syndrome). It is important to identify the

mechanism of failure (if possible) in order to minimize the chance of the same problem occurring over again. Lead repositioning would resolve the problem with dislodgement, but exit block is related to tissue reaction and a similar response may develop at the new implant site. The decision to manage lead abnormalities invasively or non-invasively is dependent on the clinical circumstances, such as the lead affected, urgency of need for pacing, and degree of change in parameters.

Acute lead perforation usually presents as a hemodynamic catastrophe in the perioperative period and usually requires emergency pericardiocentesis and lead repositioning. Subacute and chronic lead perforation may cause pericarditis, pericardial effusion, pneumothorax (may be seen with right atrial lead perforation), and pectoral muscle stimulation, and are associated with changes in pacing, sensing, and impedance values. In the case of gross lead perforation, chest X-ray is very helpful (Figure 7.11). In these cases, complete loss of capture and sensing may be seen. Micro-perforation may be suspected if the unipolar tip pacing threshold is significantly higher than the ring threshold in appropriate clinical settings. If high output pacing causes pectoral muscle stimulation, the possibility of perforation should be considered. Advanced imaging studies with computed tomography (CT) scan or echocardiography are of limited value in evaluating micro-perforation because of streaming artifact from the lead tip, but may be of diagnostic value.[10] In most cases, lead revision is required to correct the problem.

Lead-to-lead interaction may cause chatter and oversensing when the tip or ring electrode collides with other intracardiac leads during the cardiac cycle. This is best avoided by paying meticulous attention to lead positioning when more than one lead is present in the cardiac chamber. X-rays in two orthogonal views should document that the lead tips and electrodes are ideally at least 1 cm apart (Figure 7.2).

Inadequate connection of the lead pins (from using devices with non-compatible headers, connecting to the wrong pinhole, or improper tightening of the set-screw) is a cause of a completely avoidable mechanical malfunction. Another usually reversible abnormality may be seen when an air bubble remains entrapped around the lead pin following securing of the lead in the header during implantation. Once the air evaporates from the chamber (generally within a few hours to days), the noise usually subsides. Rarely, re-operation may become necessary if sensing or pacing abnormality persists.[11] Careful implantation techniques may help to reduce the risk of future mechanical problems.

Radiographic imaging of pacer systems

Radiographic imaging is a routine part of the clinical assessment following a device implant and in chronic settings when clinical questions arise. As the left cardiac chambers are positioned in a posterolateral orientation relative to the right chambers, a PA projection alone is not sufficient to adequately assess lead position (Figure 7.12). Two commonly used perpendicular X-ray projections include posteroanterior (PA) and lateral projections during outpatient follow-up, and right and left anterior oblique views during implant. Inadvertent lead placement in the left chambers may easily be missed unless lateral projections are included in the evaluation. Besides providing information on lead position, chest X-ray also helps to identify the number and type of leads present (such as unipolar or bipolar, active or passive fixation, pacemaker or ICD lead; Figure 7.2). Company-specific radiographic markers of the pacemaker may be identified and adequate connection of the lead pins confirmed (Figure 7.1). Certain lead abnormalities, such as integrity failure or fracture, may also become apparent on an X-ray and X-rays are the primary screening tools for certain complications related to the pacing system (Figure 7.13).

Electrocardiographic manifestations of pacer malfunction

Interpretation of the electrocardiogram

Abnormal pacer function may be suggested by a telemetry strip or a 12-lead ECG and a consultation at pacemaker clinics is common for this

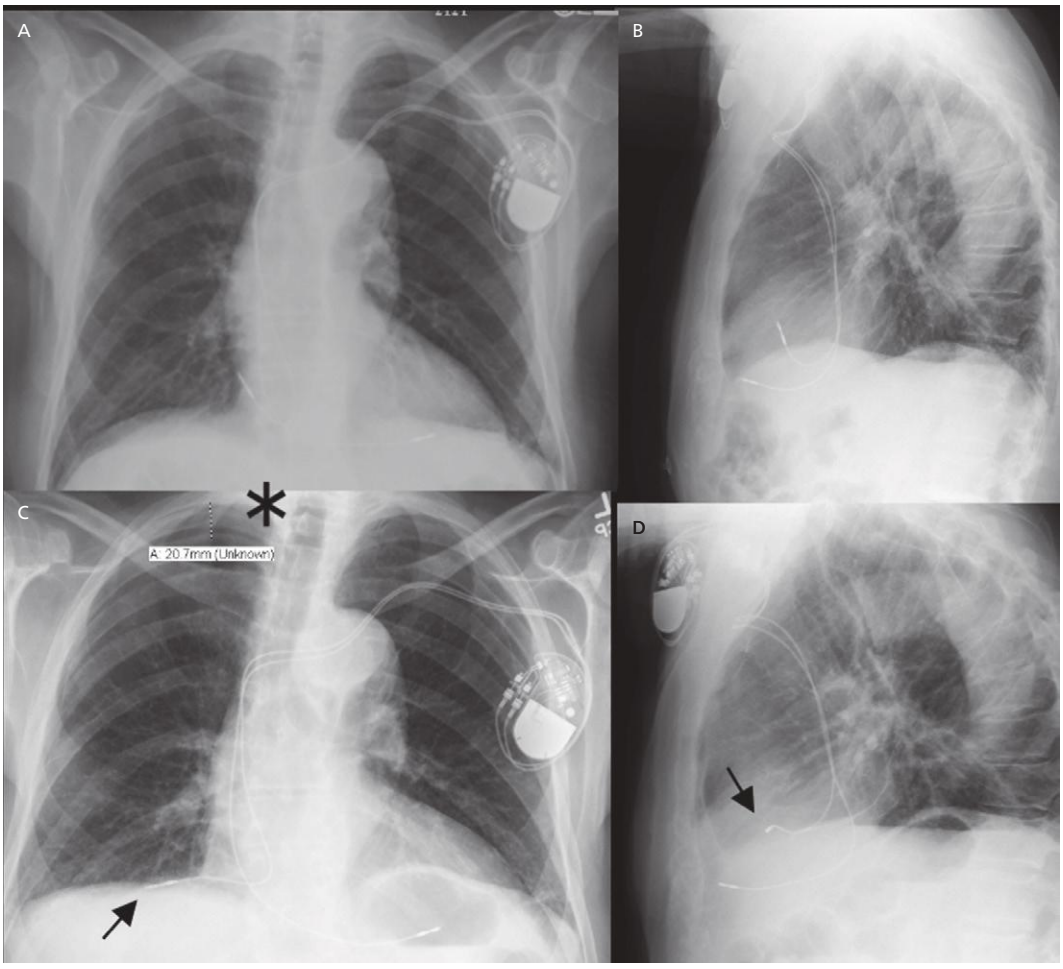


Figure 7.11 (A) Posteroanterior and (B) lateral chest X-rays 24 h after a pacemaker implantation using active fixation leads. The atrial lead is located in an anterolateral position in the right atrial appendage. The right ventricular lead is placed in the anterior free wall/apical area. The patient presented 3 weeks later with right-sided diaphragmatic stimulation. There was no sensing or pacing with the right atrial lead, but diaphragmatic capture was reproduced with high pacing output. This symptom commonly occurs when the right atrial lead pulls back to the superior vena cava and pacing results in phrenic nerve capture. In this case, the cause for diaphragmatic stimulation was right atrial perforation (C,D). Note the migration of the right atrial lead tip (arrows). The lead was found in the pleural space and there was evidence of a small, asymptomatic pneumothorax (*). The patient was receiving chronic high-dose oral steroid therapy at the time of the implant, which is a significant risk factor for lead perforation.

reason. When one faces a challenge in analyzing an ECG strip, the first task is to identify the intrinsic and paced cardiac complexes and the underlying atrial rhythm. It is often a challenge to identify P waves or pacing artifacts, and occasionally even QRS complexes may be hard to recognize, especially from a single-lead ECG. Multiple ECG leads should be examined if there is any uncertainty. It is important to look for clues such as the presence of a T wave despite a "missing" QRS complex, as may be the case when the QRS vector is small or relatively isoelectric in a particular lead (Figure 7.14). The isoelectric QRS vector is occasionally seen in TTM strips. The next task is to search for

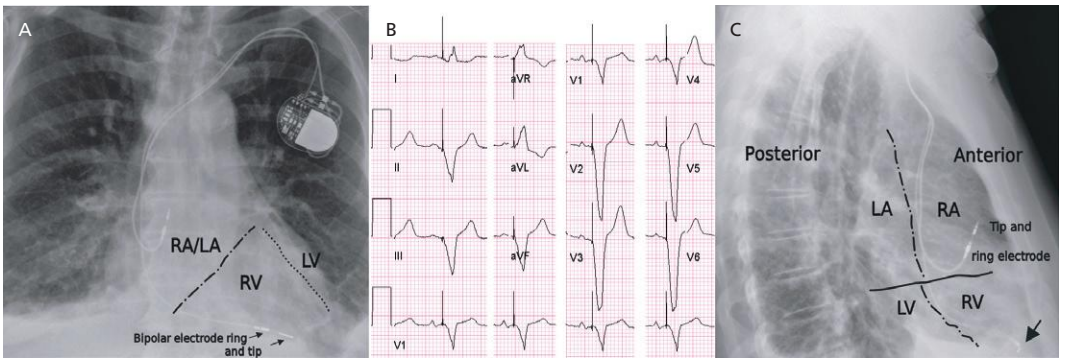


Figure 7.12 Chest X-ray and ECG features of a typical dual chamber pacing system. (A) Posteroanterior projection of a chest X-ray. The dash–-dot line delineates the approximate location of the atrioventricular (AV) groove and the dotted line approximates the septum between the right (RV) and left ventricle (LV). The right atrial lead is an active fixation bipolar lead (screw visible at the tip), whereas the RV lead is a passive fixation, bipolar lead. There is significant overlap between the RV and LV in this view. (B) ECG features of typical RV apical pacing. There is left axis deviation with purely negative, left bundle branch block-like QRS morphology in V1. (C) Lateral X-ray projection in the same patient. The dash–dot line illustrates the septum between the left and right chambers and the solid line indicates the AV groove. The arrow marks the RV lead tip. LA, left atrium; RA, right atrium.

pacing artifacts and establish their relationship and timing to intrinsic complexes (P wave, QRS). Once pacing artifacts are identified, electrical capture of the relevant cardiac chamber has to be evaluated (i.e. pacing artifact consistently followed by P wave or QRS complex; Figure 7.15). Based on the timing of the pacing spikes, the base rate, AV interval, ventriculoarterial (VA) interval, and AA interval should be determined if possible. Measurement of these basic pacing intervals on a 12-lead ECG and their correlation with intrinsic cardiac events often clarify a device behavior without further need of device testing. It is important to note that digital ECG recording systems may reduce or eliminate pacing artifacts due to filtering or assign pacing artifacts spuriously. Electrical artifacts may also be recorded as signals from non-cardiac devices; therefore just like in any other test, ECGs should be interpreted in the clinical context (Figure 7.16).

A standard 12-lead ECG with pacing is helpful to identify the pacing site by analyzing the QRS vector and morphology. An ECG with pacing should ideally be collected following the implantation of every device as a subsequent change in pacing morphology may indicate lead migration. In general, right ventricular (RV) apical pacing gives a left bundle branch block-type appearance and left superior axis (Figure 7.9). As the pacing site is moved up on the septum, the QRS axis gradually rotates to the right, reaching an inferior axis with pacing in the RV outflow tract. If there is a right bundle branch block appearance in the precordial leads, inadvertent LV placement (via the arterial system or a patent foramen ovale), perforation with LV pacing, or biventricular/coronary sinus pacing has to be considered. Mechanical lead complications may be further assessed with echocardiography, chest X-ray, or CT. During biventricular pacing, there is fusion between RV and LV pacing, and the QRS axis is mainly determined by the LV and RV lead location and presence and extent of scar. In typical cases, the axis is rightward with a prominent R wave in V_1 and Q wave in lead I.[12] A multi-lead ECG may help to identify intermittent loss of LV capture in a biventricular device that may otherwise be unnoticed in a single-lead tracing (Figure 7.17). Occasionally, right bundle branch morphology may be seen with RV pacing. In most cases, repeating the ECG with leads V_1 and V_2 repositioned one intercostal space below the standard position eliminates the right bundle

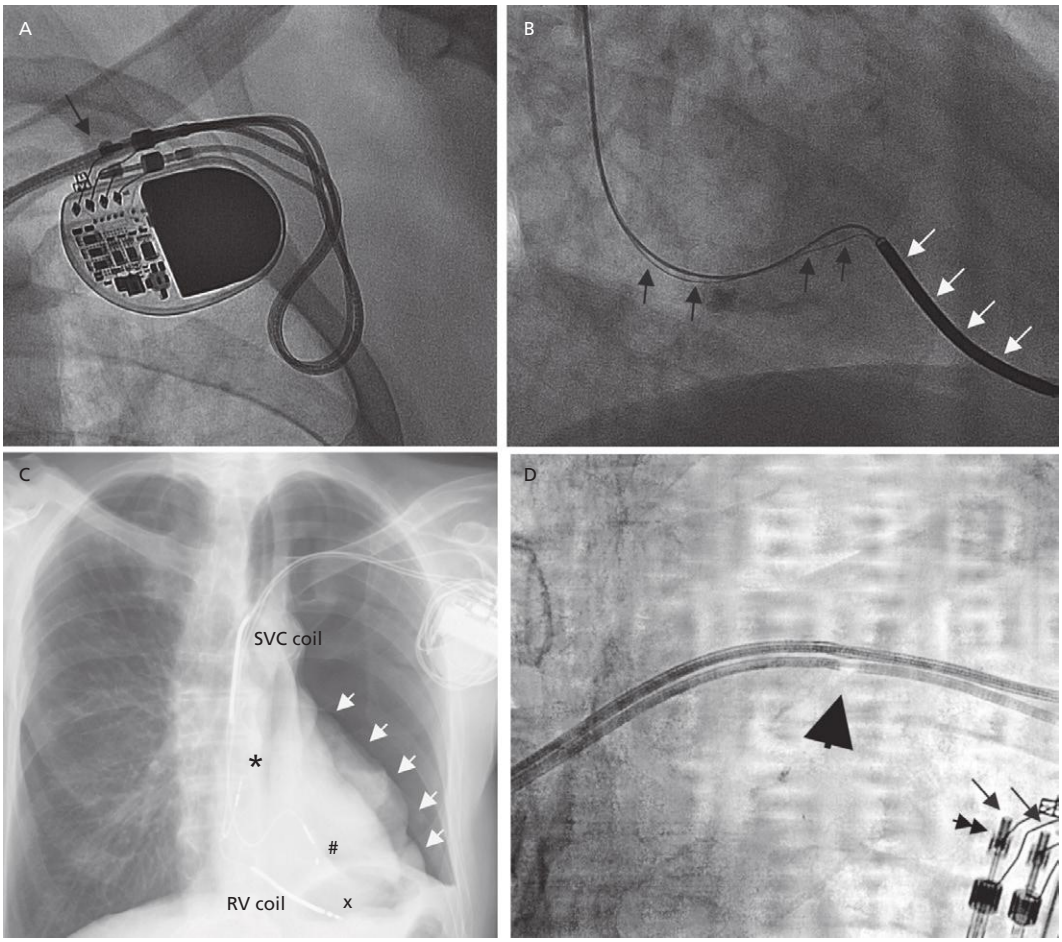


Figure 7.13 Examples of pacing system abnormalities seen on chest X-ray. (A) Loose pacemaker lead pin. The arrow points to a withdrawn lead pin, which now hardly reaches the distal screw location (atrial lead). Compare this to the correctly positioned ventricular lead pin. This patient was referred for lead revision due to noise, inappropriate mode switches, and pocket stimulation during pacing. During operative evaluation, the lead was easily pulled out of the header without loosening the screw and diagnosis was confirmed. The lead was functioning properly. (B) A typical fluoroscopy appearance of "inside–out" insulation failure of a St. Jude Medical Riata™ ICD lead. The black arrows point to the separation of the high-voltage (HV) cable from the remainder of the lead. Due to additional insulation around the HV cable, this finding is usually not associated with immediate electrical malfunction and currently the best long-term management for this lead abnormality is unclear. The white arrows point to the HV coil. This lead component is only present in ICD leads. (C) Chest X-ray 24 h following a biventricular ICD implant in a patient with severe chronic obstructive pulmonary disease. There is complete collapse of the left lung (arrows). This patient was asymptomatic. There was tympany and complete loss of air movement in the left lung during auscultation. The patient fully recovered following chest tube placement. The superior vena cava (SVC) and right ventricular (RV) coils of the ICD lead are marked: bipolar active fixation atrial lead tip (*); left ventricular bipolar pacing lead tip (#); ICD lead tip (x). (D) Magnified X-ray image of a lead fracture at the first rib/clavicle junction (large arrowhead). This is the typical site for subclavian crush injury. The small arrows point to the lead pins in the header. Both pins pass well beyond the distal header posts (double arrowhead).



Figure 7.14 While pacer spikes are clearly seen, assessment of proper capture in an ECG lead with isoelectric QRS complex is very difficult (V1). Analysis of a different ECG lead (aVF) reveals clear capture with each pacing stimulus.



Figure 7.15 Example of how to analyze a paced ECG. The underlying rhythm is atrial pacing with frequent premature atrial complexes. All P waves are marked as P. There is consistent ventricular capture and two premature ventricular contractions (#8 and #10 beats). A dual chamber pacemaker is present as evidenced by the short coupled (180-ms) pairs of pacing artifacts and tracking of p waves. This latter fact is confirmed by the irregularity in ventricular pacing which correlates with the p waves. Paced atrioventricular (AV) delay (PAV = 180 ms) and ventriculoatrial (VA) interval may be measured in the middle of the tracing (VAI = 820 ms). The pacemaker lower rate may be calculated as 1000 ms or 60 bpm. The last three atrial pacing spikes result in atrial capture. There are at least two p waves that are not sensed properly (marked as y). These are followed by close-coupled atrial pacing and functional non-capture (marked as x). The post-ventricular atrial refractory period (PVARP) is not known but P waves in the range of 400–440 ms following V pacing are tracked, suggesting that the PVARP is shorter. The second P wave may be in the refractory period or below the sensing threshold. There is no evidence of atrial or ventricular capture abnormality. The pacemaker was interrogated, P wave undersensing was confirmed and sensitivity adjusted.

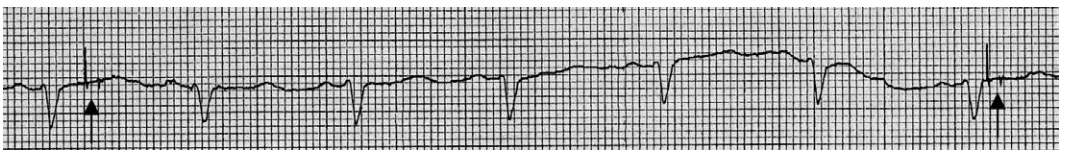


Figure 7.16 ECG recorded from a patient who received a gastric stimulator for gastric hypomotility. Pacing impulses (arrows) are unrelated to the cardiac cycle for obvious reasons.

branch pattern and confirms RV pacing.[13] A negative P wave morphology in lead I suggests left atrial pacing, and negative inferior P waves point to a pacing site near the coronary sinus. The duration of the paced P wave reflects intra-atrial conduction time and a shorter P wave duration is expected with septal lead position.

Interpretation of intracardiac electrograms

Current pacemakers and ICDs provide a wealth of information in real-time as well as in stored data summaries, statistics, and stored EGMs. Real-time EGMs of the atrial and ventricular channel, surface ECG, and marker channel are usually included in dual chamber pacemakers. Additional EGM configurations may be available in ICDs or biventricular pacemakers. Connection of a surface ECG during interrogation should be encouraged, especially in complex cases when a far-field EGM is not available or in pacemaker-dependent patients (Figure 7.18). The first step in the interpretation is analysis of the surface ECG and correlation with the intracardiac EGMs. After distinguishing the atrial and

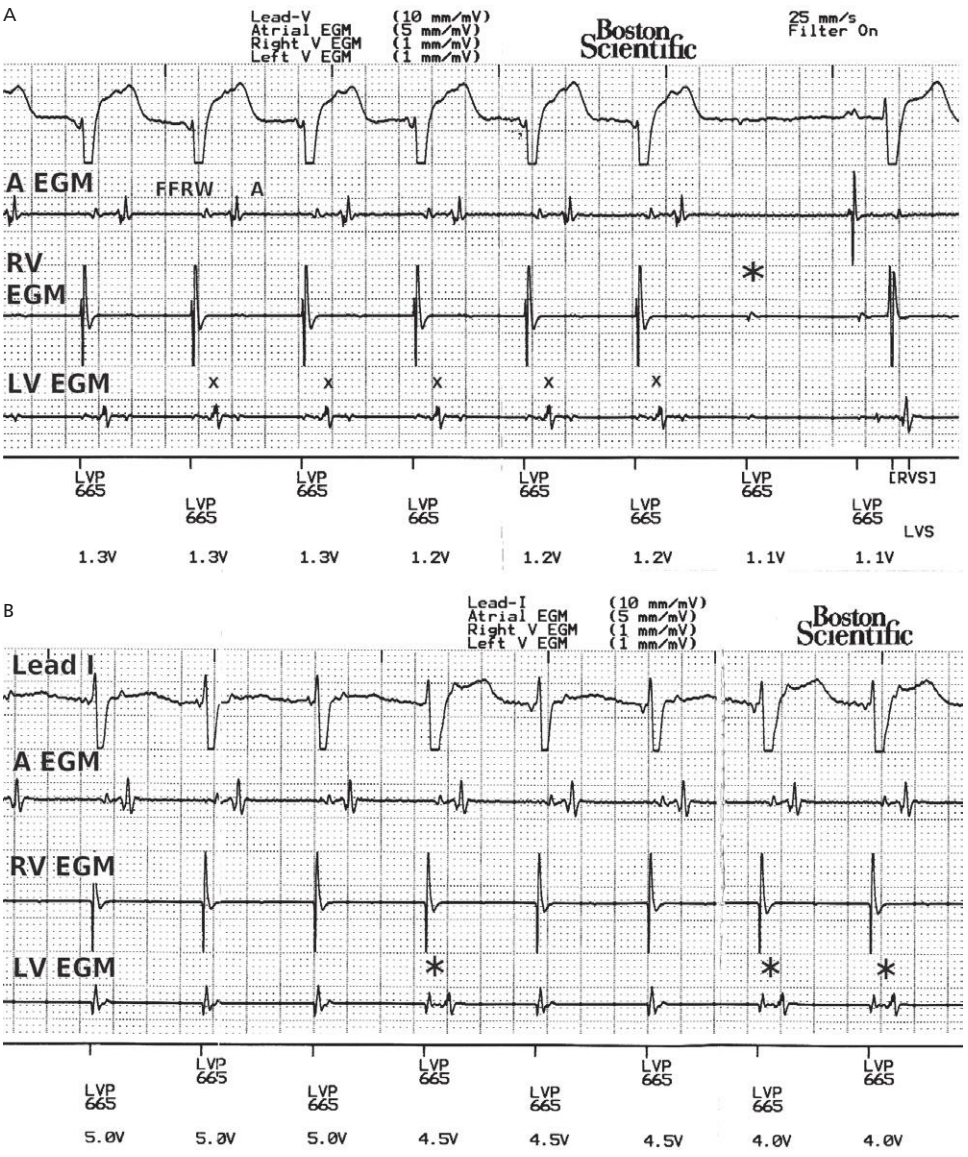


Figure 7.17 Left ventricular (LV) threshold assessment in a biventricular pacemaker. (A) The first threshold test showed a LV threshold of 1.2 V and loss of capture at 1.1 V (*). The last beat of the tracing is a sinus beat after loss of capture with A–RV–LV activation. A closer look at the tracing reveals that the LV electrogram (EGM) (x) follows the right ventricular (RV) EGM. This should not be the case during LV capture. These findings are most consistent with anodal capture at the RV ring electrode and loss of LV capture. When pacing takes place between the LV electrode (cathode) and a relatively small sized RV ring electrode (anode), occasionally capture threshold may be lower at the anodal site, which results in RV capture. (B) Anodal capture was proven by pacing at a higher output. There is now RV/LV capture at 5 V, with intermittent LV capture at 4.5 V and loss of capture at 4 V (*). Also note the subtle change in QRS morphology in lead I with the RV-only beats. Multiple ECG leads or another ECG lead configuration would be helpful in this case. Anodal capture may be associated with arrhythmias. Commonly available configurations in biventricular pacemakers include LV tip–LV ring, LV tip–RV ring, and LV ring–RV ring. Other configurations may be available depending on the particular device and manufacturer. A different configuration for chronic pacing was chosen for this patient (LV tip to can), which eliminated anodal capture.

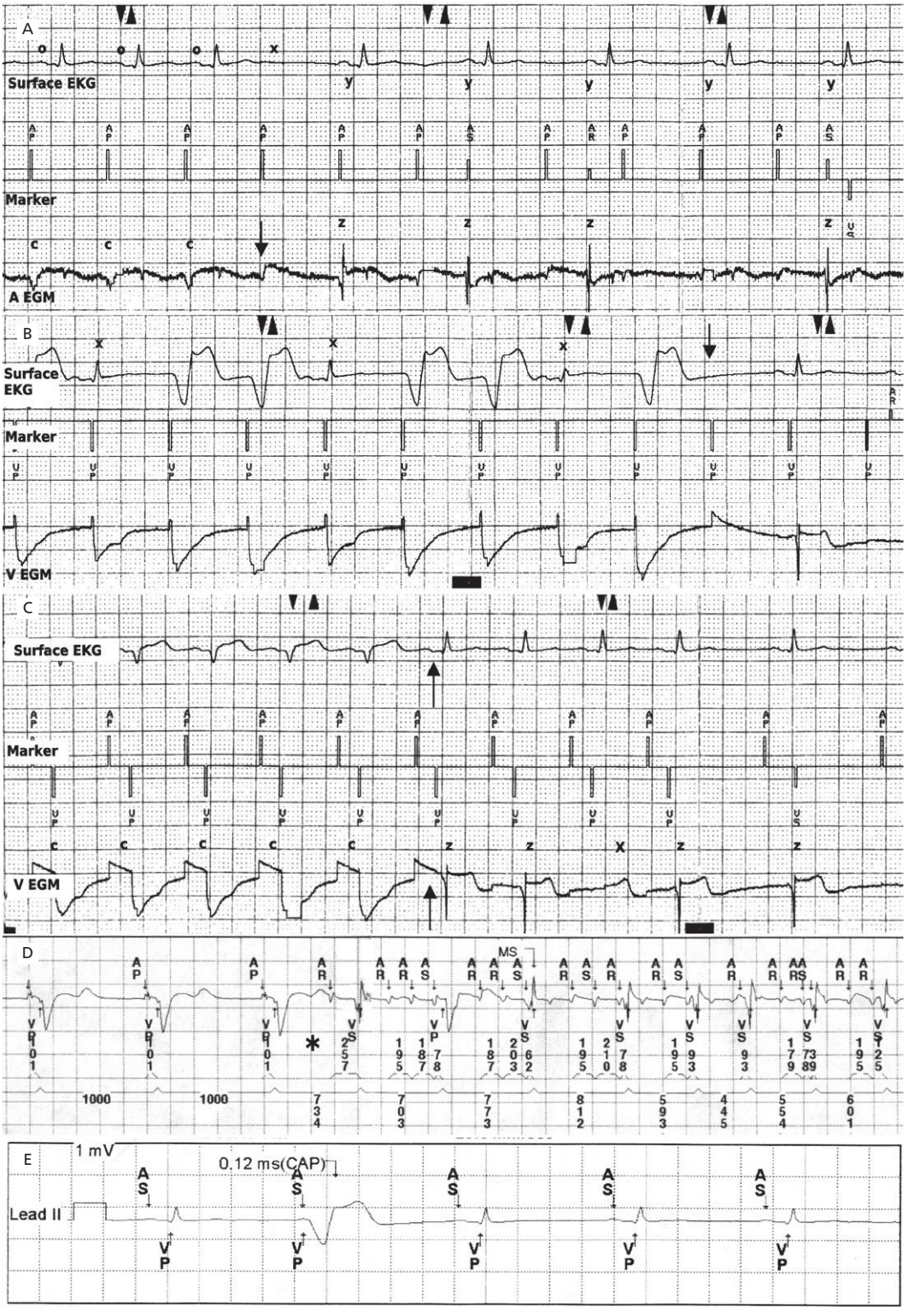

A
Surface EKG
Marker
A EGM
B
Surface EKG
Marker
V EGM
C
Surface EKG
Marker
V EGM
D
MS
1000
1000
E
1 mV
0.12 ms(CAP)
Lead II

Figure 7.18 Interpretation of intracardiac electrograms. (A) Real-time atrial electrogram (A EGM) in addition to marker channel and surface ECG during atrial threshold testing. Atrial output is automatically decremented by the pacemaker (double arrowheads). Initially, there is atrial capture based on the presence of a surface paced P wave (o) with each stimulus and consecutive activation of the ventricle. Capture is lost (arrow) with only minor change in the paced A EGM signal. There is no surface paced P wave present (x) as capture is lost and sinus P waves (y) and local atrial EGMs (z) are dissociated from the pacing stimulus. Note the subtle difference between the P wave morphology of the paced (o) and intrinsic P waves (y). (B) Ventricular threshold test in VVI mode in the same patient. As ventricular output is decremented (double arrowheads), there is variation in wide and narrow QRS complexes (x). This occurs because there is no ventriculoatrial (VA) conduction and every third beat is a capture beat from intrinsic sinus activation and not due to loss of capture. The clue is that on each occasion the narrow beat is simultaneous with the pacing spike. Once threshold is reached, true loss of capture is indicated (arrow) by the facts that no QRS complex follows the pacing spike and there is change in ventricular EGM (V EGM) morphology. If intrinsic beats confuse the situation, pacing rate may be increased or, as shown in (C), DDD mode may be used. Loss of capture is easily recognized with change in surface QRS morphology (arrow). The paced intracardiac EGM also changes—the deep negative component is absent (arrow) and subsequent conducted intrinsic activation appears (z). While there is no depolarization component present with beat x, there is a clear T wave indicating that local depolarization did occur (from intrinsic beat—this may be confirmed with surface ECG). (D) A stored EGM strip from a Medtronic pacemaker. Some devices are capable of storing only one EGM; thus, either the atrial or ventricular signal has to be chosen. The availability of a summed EGM, as shown here, may be helpful to differentiate between certain arrhythmias. The EGM is recorded between the atrial and ventricular lead and provides the composite of the atrial and ventricular activation. Sequential AV pacing takes place in the first part of the strip until atrial fibrillation develops (*) and mode switch (MS) takes place. Atrial depolarization is correctly marked as AS and AR; the larger ventricular signals are marked as VS. The strip confirms appropriate mode switch. (E) An example of automatic threshold testing in a Medtronic device. Note the markedly shortened PR interval with the beat during capture testing (CAP). As the device tests daily threshold (mainly at night), this finding during telemetry monitoring may cause some confusion regarding pacemaker function.

ventricular signals, their relationship has to be determined (i.e. presence of pacing and capture, driving chamber of an arrhythmia). The next step is to correlate the intracardiac EGMs to the marker channel signals. The marker channel reading is helpful because it signifies when the device senses events or paces, and correlating these to the intracardiac EGM components is key to evaluating proper function (Figure 7.18). Occasionally only a marker channel recording is available in stored event data, which is often helpful but in and of itself does not provide absolute diagnostic information as appropriate sensing or capture cannot be confirmed from the marker channel alone (Figure 7.19).

Problems with sensing

Undersensing; failure to sense

Pacing artifacts appearing at an unexpected interval often incite questions relating to sensing abnormalities. Sensing of intrinsic electrical activity is indeed of key importance as this is closely linked to pacemaker timing intervals. In most pacemakers there is a (programmable) fixed sensing level. If the amplitude of an intrinsic complex is less than the programmed sensitivity level, it will not be recognized by the device and the event will be disregarded in the timing cycle (Figure 7.15). There is occasionally confusion regarding the concept and relationship of sensitivity level to sensing. Only signals that measure above the programmed sensitivity are counted. Sensitivity is increased (i.e. smaller signals will be detected by the device) when the programmed sensitivity level is decreased (e.g. sensitivity level programmed from 2.5 mV to 0.6 mV) and *vice versa*.

Sensing algorithms that automatically re-adjust the sensing level have been increasingly introduced into newer generation devices.[14] In ICDs, fixed sensing in the ventricle cannot be used as it would risk undersensing of ventricular fibrillation (if the sensing level is set too high) or cause oversensing

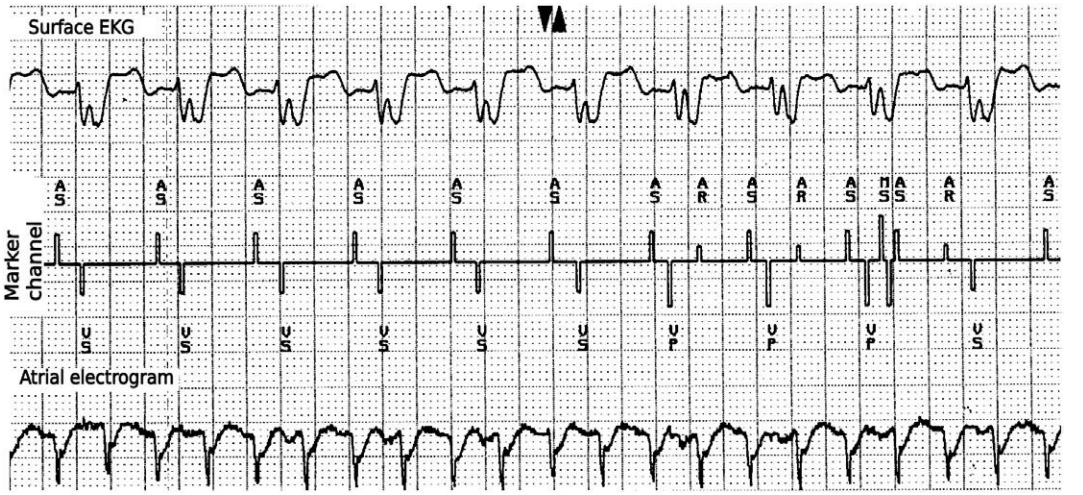


Figure 7.19 Tracing showing atrial undersensing during atrial flutter due to a long post-ventricular atrial blanking period (PVAB). Only every other atrial electrogram (EGM) is identified as an atrial-sensed (AS) event; the other atrial EGMs are blanked. The PVAB was changed from 200 ms to 140 ms (double arrowhead), which resulted in unblanking of the flutter EGMs (AR) and appropriate mode switching (MS). If only the marker channel on the left of the strip had been looked at without access to the atrial EGM, normal device function would have been indicated.

(if the sensing level is set too low). For this reason, variable sensitivity adjustment (or variable signal gain; Boston Scientific) is used in all defibrillators. In these algorithms, sensitivity is adjusted in a beat-to-beat fashion after each sensed or paced signal. Following a sensed event, sensitivity is set to a percentage of the signal and after a brief blanking period it gradually increases until maximum programmed sensitivity is reached or a new signal is sensed. In some ICDs, specific aspects of sensitivity adjustments are programmable, which is a very useful feature for the management of sensing problems, such as T wave oversensing. Variable sensitivity is increasingly being applied in the atrial channel. Atrial algorithms are specifically adjusted in order to minimize far-field R wave oversensing.

Pacemaker sensitivity level (especially in the ventricular channel) is generally programmed at 30–60% of the measured parameters. When choosing sensitivity settings for the ventricle, the polarity of the pacemaker system and clinical characteristics of the patient, such as pacemaker dependence and presence of variable amplitude signals [e.g. frequent premature ventricular complexes (PVCs)], have to be considered. Unipolar sensing (which is becoming increasingly less common) predisposes to oversensing of non-cardiac signals and in pacemaker-dependent patients especially, programming a less sensitive setting is advised (Figure 7.20). Attention should also be directed to rule out sensing abnormalities with PVCs, T waves, or myopotentials. Programming sensitivity in the atrial channel may be challenging. If there are intermittent atrial arrhythmias, measured EGM amplitude may change significantly between sinus rhythm and an atrial arrhythmia. If atrial arrhythmias are not sensed properly, intermittent palpitations may develop due to tracking and lack of mode switching (Figure 7.21). In contrast, if atrial sensitivity is too low, non-atrial signals may be oversensed (such as a far-field R wave) and result in inappropriate mode switching and loss of AV synchrony. In these cases, careful adjustment of atrial sensitivity and post-ventricular atrial blanking period (PVAB) is required (Figure 7.22). Optimization of PVAB and

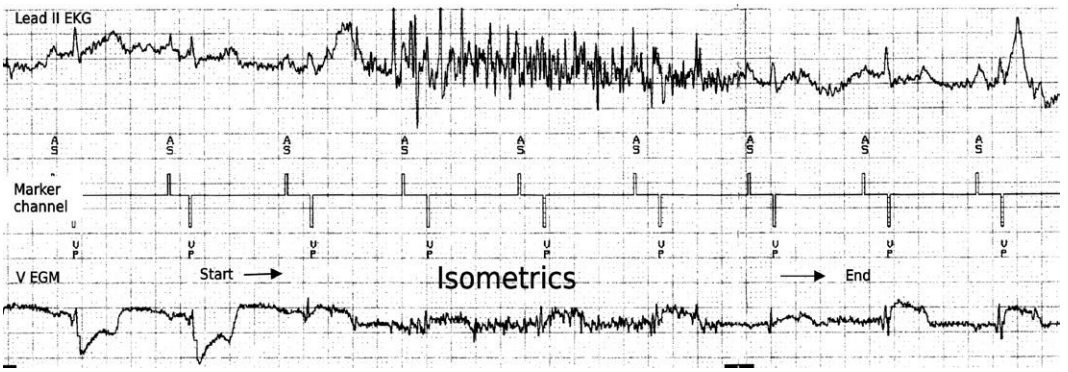


Figure 7.20 Noise on the right ventricular (RV) lead due to myopotential signals in a unipolar pacemaker. Following the initiation of isometric exercise, high-frequency noise is noted on the RV lead (isometrics). Sensitivity programming is adequate as there is no oversensing of the noise and atrial synchronous ventricular pacing takes place during the event.

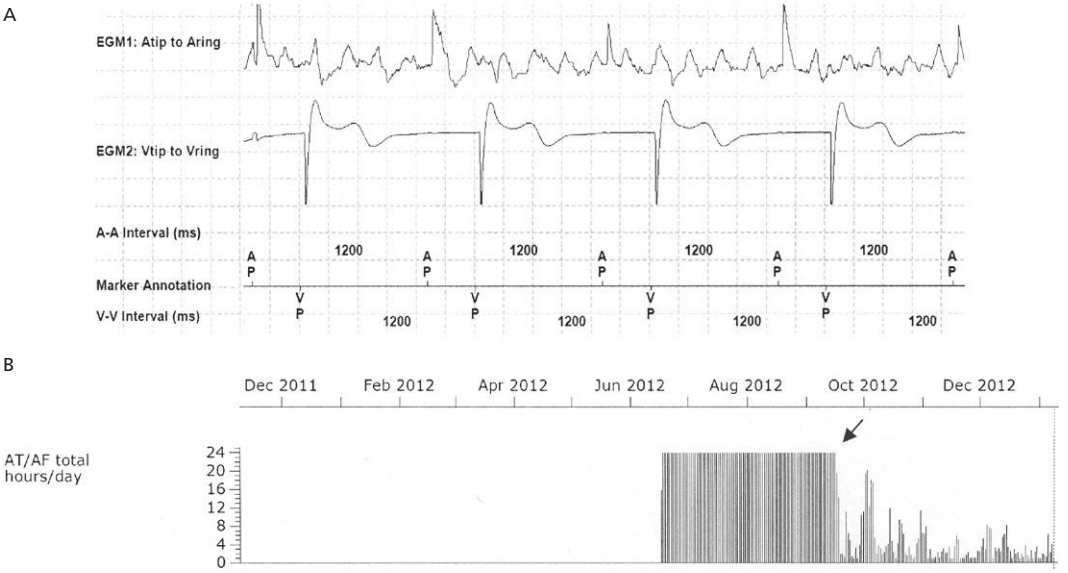


Figure 7.21 (A) An episode of atrial fibrillation (AF) with AV sequential pacing and undersensing of the atrial arrhythmia due to low amplitude signals. AF is present while sequential atrioventricular (AV) pacing takes place. (B) Summary of the daily AF episode burden. The patient developed persistent AF in June with appropriate detection of AF (AF present 24 h/day). Starting in September (arrow), the measured AF burden was reduced due to decreased P wave amplitude and undersensing.

atrial sensitivity setting allows adequate monitoring of atrial arrhythmias and appropriate mode switching in most clinical situations.[15]

In general, undersensing results in pacing at a higher than expected rate (the intrinsic signal does not inhibit pacing or modify pacing behavior due to the lack of sensing). Undersensing may be caused by inadequate programming of sensitivity settings or refractory periods, lead or device failure, lead micro- or macro-dislodgement, or a change in the signal amplitude due to change in tissue characteristics. If the lead is otherwise functional and

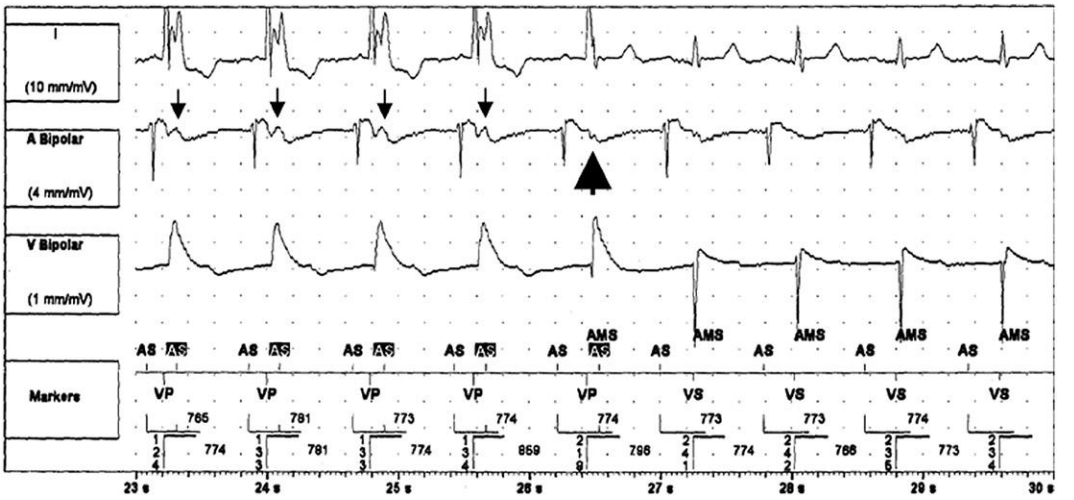


Figure 7.22 A method for testing far-field R wave oversensing in order to assist with programming of the post-ventricular atrial blanking period (PVAB). For the test purposes, atrial sensing is maximized (0.1 mV) and PVAB shortened to 60 ms. During ventricular pacing, far-field R wave signals (arrow) are oversensed. They fall in the PVARP and are marked as AS refractory (white AS in black box; small arrows). Events in the post-ventricular atrial refractory period (PVARP) count towards the mode switch counter and in this case inappropriate mode switch takes place (AMS; large arrow). Setting the PVAB 25–30 ms longer than the VP–AS refractory interval would prevent future far-field R wave oversensing. Alternatively, P wave sensitivity may be decreased. Note that far-field oversensing in this example is only present during ventricular pacing and not during ventricular sensing.

its position is stable, increasing the sensitivity is the first step. If programming options fail, lead repositioning may be required. Undersensing may occur even when sensitivity settings are programmed appropriately. Functional undersensing is an undersensing event that is due to an interaction between paced and sensed events and pacemaker refractory periods. As discussed in detail in Chapter 6, blanking and refractory periods are designed to minimize oversensing of undesirable cardiac signals and to eliminate interactions between atrial and ventricular pacing and tracking. A blanking period is initiated in all chambers after each pacing stimulus to minimize the chance of oversensing of a polarization artifact or a far-field chamber signal. If an intrinsic cardiac depolarization occurs during the blanking period (i.e. a PVC occurs at the time of atrial pacing), the signal may not be sensed (Figure 7.23). If a signal falls into the refractory period, it will be sensed and added to the counters, but in most cases it will not reset or affect the pacing timing cycle. Common clinical examples are those seen in the atrial channel during dual chamber pacing. The post-ventricular atrial refractory period (PVARP) is designed to eliminate tracking of a retrograde P wave in order to prevent pacemaker-mediated tachycardia. If the P wave falls in the PVARP, it causes functional undersensing. Clinical examples of this type of undersensing are seen following a PVC with retrograde conduction, upper rate behavior with pacemaker Wenckebach periodicity (during atrial tachycardia), or repetitive non–re-entrant ventriculoatrial synchrony (see "Pacemaker-mediated tachycardia and repetitive non–re-entrant ventriculoatrial synchrony"; Figure 7.24 and Figure 7.25). Another common example is when the PVAB covers every other flutter wave and results in undersensing of atrial flutter (Figure 7.23). Rapid pacing may also result in undersensing of ventricular tachycardia and delay or prohibit tachycardia therapy.[16] Functional undersensing is not a mechanical problem, but rather a programming problem, and invasive management is very rarely required. It is also important to recognize that under certain circumstances the pacemaker operates in asynchronous

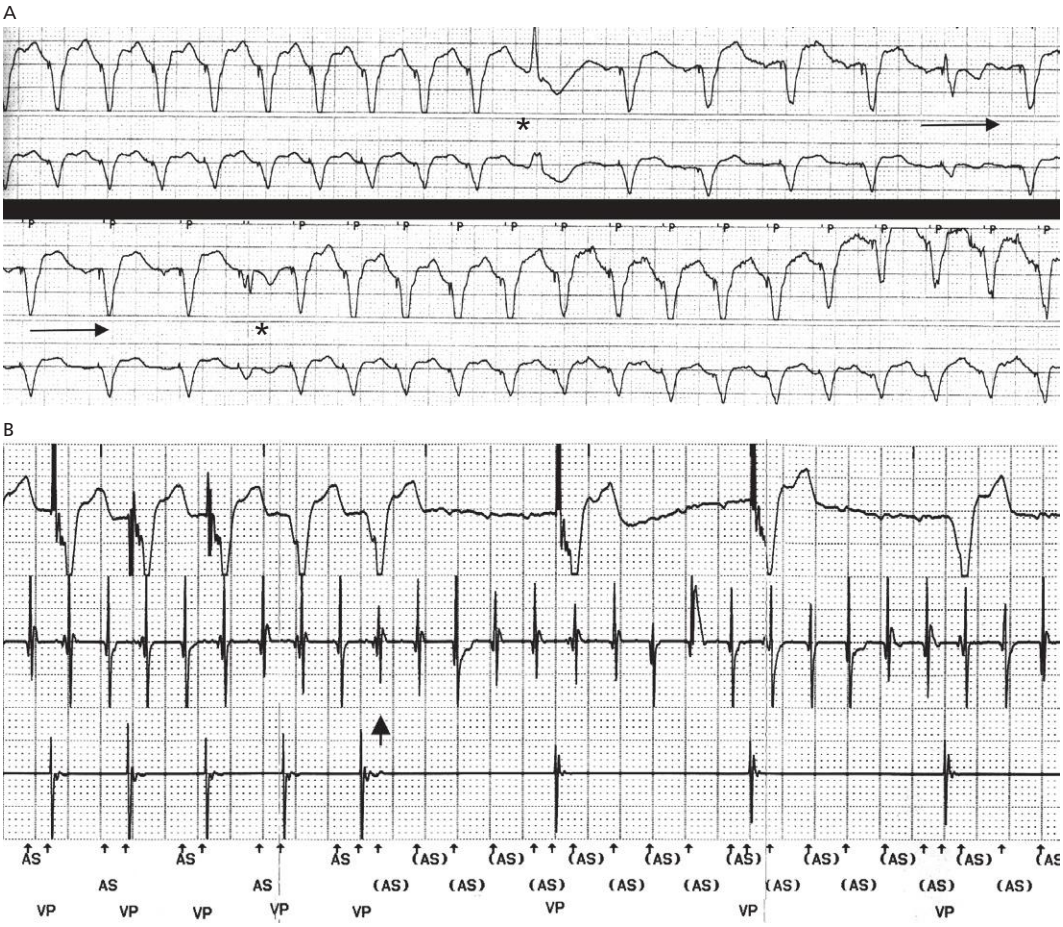


Figure 7.23 (A) An electrogram from a patient who complained of intermittent palpitations. The telemetry recording showed intermittent rapid ventricular pacing. The tachycardia is initiated and terminated with a premature ventricular contraction (PVC). The rhythm strip is a continuous recording. (B) In the same patient, pacemaker interrogation confirmed atrial flutter and intermittent 2:1 ventricular pacing. In the first part of the tracing, only every other atrial signal (AS) is sensed due to atrial blanking [every other atrial electrogram falls in the post-ventricular atrial blanking period –(PVAB)]. The atrial flutter response was turned "on," which allows uncovering of atrial activity by extending the post-ventricular atrial refractory period (PVARP). The first AS falls outside the PVAB, and the second AS is refractory and not tracked due to the extended PVARP. This allows appropriate mode switching. The first PVC in (A, *) changed the timing of the PVAB relative to the atrial depolarization and allowed uncovering of the flutter waves, whereas another PVC (*) had the opposite effect and 2:1 tracking recurred.

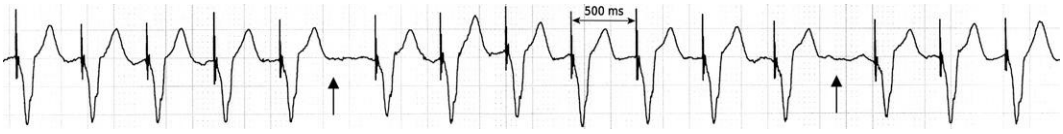


Figure 7.24 Rhythm strip from a patient with a dual chamber pacemaker who developed atrial tachycardia. The tachycardia was tracked with ventricular pacing (pacing stimulus precedes each QRS) until the upper tracking rate was reached at 120 bpm. Intermittent pauses are due to upper rate behavior as the P wave falls in the post-ventricular atrial refractory period (PVARP) and is not tracked.

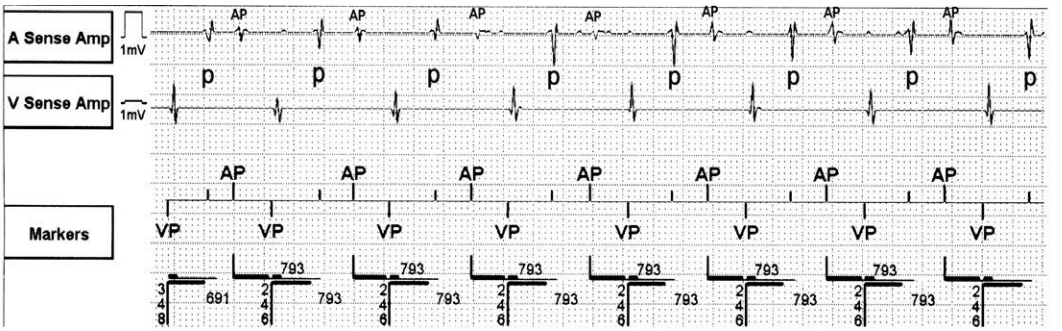


Figure 7.25 Repetitive non–re-entrant ventriculoatrial synchronous rhythm. The arrhythmia is perpetuated by ventricular pacing with retrograde atrial conduction. Atrial activation falls in the post-ventricular atrial refractory period (PVARP) and therefore is not tracked (p). If it had fallen outside the PVARP, the result would be pacemaker-mediated tachycardia. Close-coupled atrial pacing (AP) likely does not capture the atrium (functional loss of capture) and is followed by ventricular pacing (VP), which starts the cycle again.

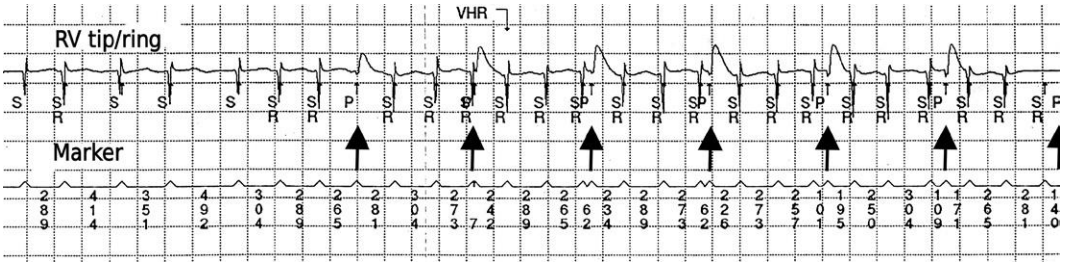


Figure 7.26 Ventricular high rate episode recorded in a single chamber Medtronic pacemaker. There is atrial fibrillation with a rapid, irregular ventricular response. Ventricular cycle length exceeds the ventricular refractory period (VRP; set at 320 ms) and sensed events are counted as sensed refractory (SR). These events are disregarded for pacing timing purposes and pacing is initiated at 857 ms/70 bpm after two consecutive R waves fall in the VRP (first arrow). Asynchronous pacing continues, as indicated by the subsequent arrows (marked as P on the marker channel) as long as the R waves fall in the VRP. VRP is reset after each refractory event. While SR events are not counted in pacemaker timing, they count towards the high rate V counter in addition to asynchronous pacing.

mode and intrinsic events are disregarded. A typical example of asynchronous pacing is seen when a magnet is placed over the device (magnet rate pacing) or when a device is programmed in asynchronous mode (e.g. during a procedure that may result in EMI or oversensing of non-cardiac signals). Pacemakers may temporarily switch to asynchronous mode automatically if noise is sensed. This safety feature is designed to minimize the risk of asystole due to oversensing of non-physiological signals. R waves during rapid ventricular rate may fall in the ventricular refractory period and cause asynchronous pacing (Figure 7.26).

Oversensing

Oversensing is an event when signals other than the local cardiac activation at the lead electrode site are counted as cardiac signal. These signals may include other signals from the heart (far-field signals from P and R waves or a near-field T wave), myopotentials (from the diaphragm or pectoral muscle), or electrical artifact (noise) related to structural abnormalities in the lead/pacemaker

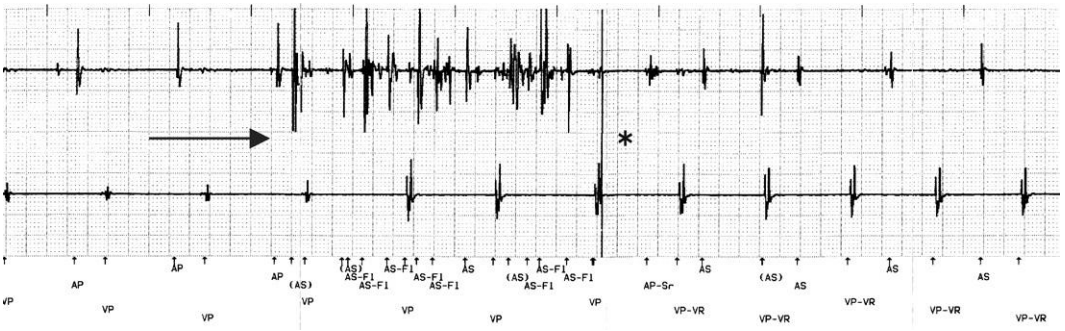


Figure 7.27 Atrioventricular (AV) sequential pacing with noise (arrow) due to lead integrity failure. Oversensing of electrical artifact results in tracking and subsequent mode switching to DDI mode (*). VP–VR, ventricular pacing with ventricular rate regularization.

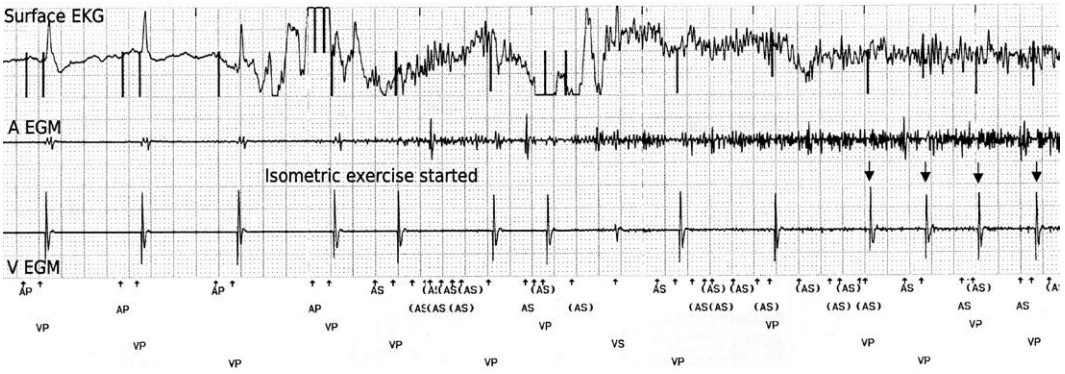


Figure 7.28 This patient with a dual chamber unipolar system presented at routine follow-up with palpitations and over 2000 episodes of mode switch. These episodes were due to pectoral muscle potential oversensing and were reproduced with isometric exercise. Oversensing resulted in loss of atrioventricular (AV) synchrony and occasional rapid ventricular tracking (arrows).

system (fracture, insulation defect, header connection problem) or environmental effects (EMI). In general, ventricular oversensing manifests as pacing below the programmed rate and atrial oversensing presents with tracking or mode switching to a non-tracking mode (if oversensing is recorded as atrial arrhythmia) or pacing below the programmed rate (in single chamber pacemakers). Thus, depending on the programmed pacing mode, oversensing in the atrial lead may cause intermittent high rate ventricular pacing due to tracking or cause spurious mode switching (Figure 7.27). It is important to categorize these episodes appropriately as they may be sources of symptoms or may be precursors of a more serious problem. Furthermore, oversensing episodes may be recorded in the device memory as tachyarrhythmias and failure to recognize the correct diagnosis may trigger recommendations for otherwise unnecessary or inappropriate therapies (Figure 7.28).

Specific types and characteristics of oversensing and management are discussed below. In general, especially when oversensing is suspected in an emergency situation, magnet application over a pacemaker will initiate asynchronous pacing and prevent asystole (as long as there is a working

pacemaker circuit and intact lead) until a programmer is available to reprogram the device. It is important to note that magnet application will not change the pacing mode in most ICDs, but it results in temporary suspension of ICD tachycardia therapy.

Cross-talk

An important and rare complication of dual chamber pacing is atrioventricular cross-talk. A particularly dangerous situation may occur during dual chamber pacing if, following atrial pacing, the electrical polarization from atrial pacing is sensed at the ventricular electrode and recorded as a sensed ventricular event. The result is inhibition of ventricular pacing (Figure 7.29) and possible asystole. The post-atrial ventricular blanking period (PAVB) is used in the ventricular-sensing algorithm to cover the immediate interval that follows an atrial pacing output signal in order to eliminate post-pacing signal oversensing. If the blanking period is not long enough, there is another programmable safety feature that may be used to minimize consequences of cross-talk, called safety pacing. This algorithm is designed to minimize the risk of asystole. There is a cross-talk window following the PAVB. If sensing occurs in this time interval, a ventricular pacing stimulus is initiated (at the programmed AV delay or shorter AV delay, depending on the specific device). This safety feature allows ventricular pacing even if there is oversensing in the cross-talk window (Figure 7.30). The best programming option to eliminate cross-talk is extension of the PAVB. Other options include changing to VVI/VDD mode or reducing the atrial pacing output and pulse width. Reducing the lower rate limit to allow intrinsic atrial activation may also help, but it is not a safe long-term solution as lack of atrial pacing in the future is not guaranteed. Due to the possible severe consequences of these events, in pacemaker-dependent patients it is prudent to check for cross-talk at the time of the original or new implant.

Oversensing cardiac signals

These events include double counting of T, R, or P waves (Figure 7.31). Prolonged bradycardia may result from oversensing of an intrinsic T wave (Figure 7.32). Electrolyte abnormalities, hyperkalemia, and severe hyperglycemia or severe ventricular hypertrophy have been associated with permanent or temporary T wave oversensing. T wave oversensing may be eliminated by extending the ventricular refractory period in pacemakers. T wave oversensing is a more common problem in ICDs because ventricular refractory periods are kept short to minimize the risk of undersensing ventricular fibrillation. In order to maximize sensing of small signals without double counting cardiac signals or oversensing non-cardiac signals, either signal gain is modified (automatic gain control) or various sensitivity adjustments are made with each sensed event (see Chapter 8). T wave oversensing may be eliminated in ICDs by decreasing sensitivity if R wave sensing is adequate. In some ICDs, post-sensing or post-pacing sensitivity settings are programmable and may be tailored to the specific clinical problem (adjustment of initial sensing level and decay delay timing in St. Jude Medical and Biotronik devices). In some ICDs (St. Jude Medical) there is also a programmable option for setting different sensitivities for pacing and tachycardia detection purposes.

Although less common with modern bipolar pacemaker leads with closely spaced electrodes, oversensing of the far-field R wave is still the most common cause of atrial oversensing. The best way to eliminate this problem is to pay meticulous attention to lead placement and assure a minimized far-field R wave recording during the implant procedure. Complete elimination during implant however may not be feasible or the problem may surface later with a change in P wave signal amplitude or in the relative position of the lead and development of a larger far-field signal. There are several programming options to eliminate far-field R wave oversensing, such as decreasing atrial sensitivity (programming a higher sensitivity cut-off if P wave sensing allows), increasing PVAB, or minimizing RV pacing (Figure 7.22). In some Medtronic ICDs, atrial blanking is minimized and instead an algorithm is used to differentiate between far-field signal oversensing and arrhythmias. As blanking is very short, atrial arrhythmia detection is markedly improved. If the far-field signal is intermittent or the algorithm fails, a traditional blanking period may also be programmed in the most current devices.

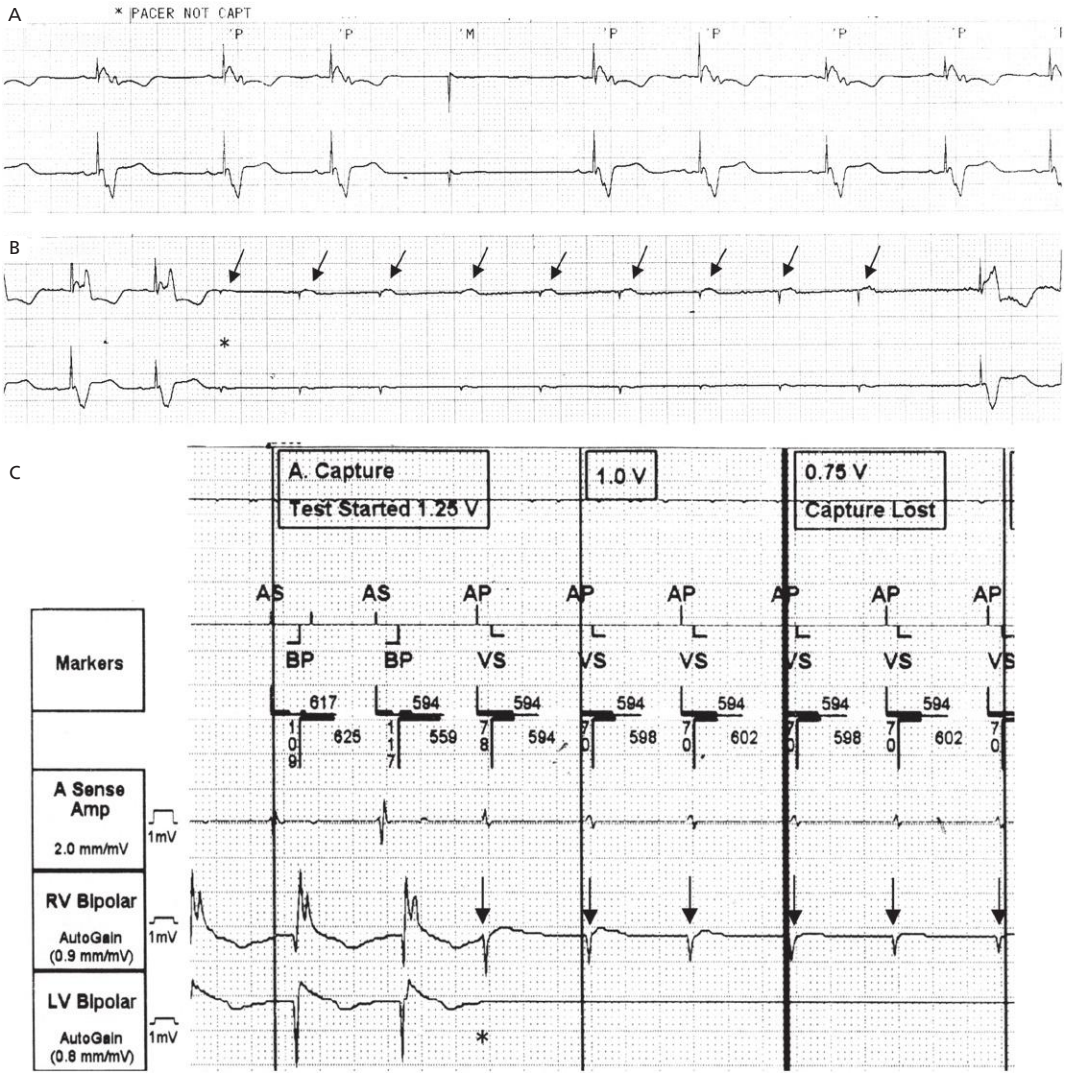


Figure 7.29 (A) Telemetry strip in a pacemaker-dependent patient following upgrade to a biventricular defibrillator. There is a pacing spike (M) followed by atrial capture, but no ventricular conduction or pacing. This finding raises the possibility of cross-talk. There is no loss of capture, contrary to the automatic alert at the top of the tracing. (B) Device interrogation reproduced asystole with atrial threshold testing in DDD mode (starting at the asterisk). Another possible explanation for the tracing would be temporary AAI pacing in a pacemaker-dependent patient. (C) Real-time electrogram during device interrogation confirmed cross-talk during atrial pacing. As the atrial threshold test started, a large signal became apparent on the right ventricular (RV) channel, corresponding to the atrial-paced event (arrows). This signal is sensed and the event is consistent with ventricular oversensing due to cross-talk (AP followed by VS). While there is no surface ECG, asystole is confirmed by the left ventricular (LV) lead electrogram (*). No safety pacing occurred in this case despite adequate programming.

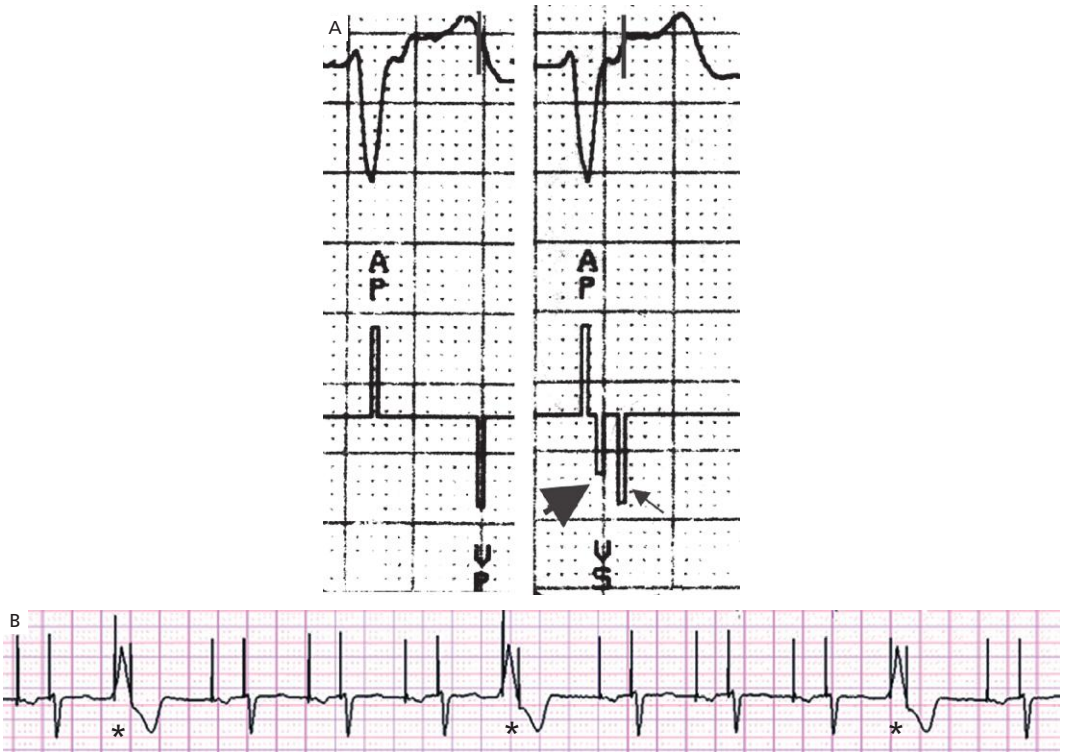


Figure 7.30 (A) Premature ventricular contraction (PVC) and simultaneous timing with atrial pacing. The first PVC falls in the post-atrial ventricular blanking period (PAVB) and is not sensed. Ventricular pacing occurs after atrioventricular (AV) delay times out, but is not captured as the ventricle is not fully repolarized. In the same patient, the second PVC occurs slightly later and it now falls in the cross-talk window (large arrow) and initiates safety pacing (small arrow). Note that atrioventricular (AV) delay is now shorter. (B) ECG strip showing AV sequential pacing and capture. There are three PVCs marked with asterisks. PVCs occur at the time of atrial pacing and during the AV interval. A PVC is sensed in the cross-talk window (interval following post-atrial ventricular blanking). As this event, from the device-sensing perspective, may represent cross-talk, a ventricular pacing stimulus is delivered at a shorter paced AV delay to minimize the risk of asystole. The shorter AV delay reduces the chance of pacing in the vulnerable area of the T wave if an intrinsic beat triggers safety pacing, as seen in this example. The beats marked with (*) are pseudo-pseudofusion beats (see text for details).

Oversensing non-cardiac signals

Other sources of oversensing are related to myopotential oversensing, EMI, or intermittent noise due to lead chatter and lead or connection integrity failure (Figure 7.33 and Figure 7.34). In many cases, the typical appearance of these artifacts establishes the diagnosis, but in atypical presentations, it may be more complex to make the diagnosis. It is very helpful to identify the circumstances of the event. Straining or coughing may point to diaphragmatic oversensing. Significant arm or upper body isometric exercise would be a typical trigger for pectoral muscle oversensing, especially in a unipolar system. Noise with structural abnormalities on the other hand has a probabilistic appearance, although certain events may trigger intermittent malfunction. For example, if noise is brought on by pocket manipulation, a faulty lead pin connection, or lead integrity failure has to be considered. A lead integrity abnormality usually results in changes in lead impedance, but changes may be subtle and intermittent, and stable

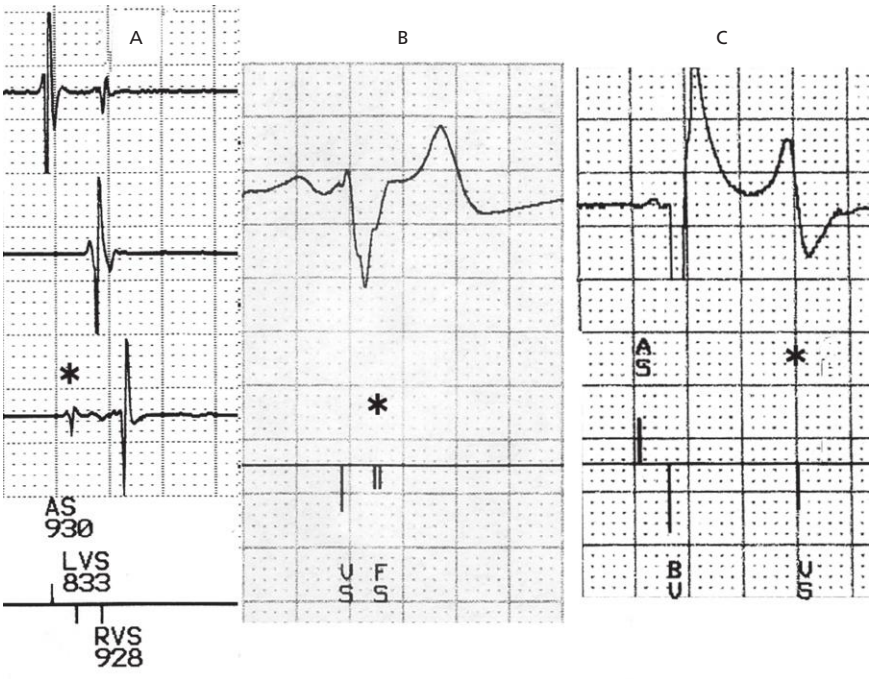


Figure 7.31 (A) Oversensing of a far-field P wave on the left ventricular (LV) lead (*, marked as LVS in the marker channel) in a biventricular device resulted in inhibition of pacing. Oversensing resolved after reprogramming the LV sensing configuration. (B) R wave double counting in an ICD. The late component of the R wave is counted as an FS event (VF sensed; marked with an asterisk) event, which follows the VS marker at a non-physiological interval (120 ms). Oversensing occurred only with a particular premature ventricular contraction (PVC) morphology. Decreasing right ventricular (RV) sensitivity eliminated the problem. (C) Example of T wave oversensing. The VS marker times out with the T wave on the electrogram (*). Adjustment of ventricular sensitivity mitigated the problem.

impedance does not completely rule out a structural abnormality. Other, non-structural causes of noise do not affect the lead impedance. As mentioned earlier, looking at the signal characteristics of noise is helpful. A myopotential oversensing signal is continuous and of sudden onset, high frequency, and relatively low amplitude. EMI is commonly sudden in onset, but the EGM appearance may be different depending on the specific source. It is generally a high frequency, continuous signal. Occasionally, a typical 60-Hz noise is seen. While the trigger for EMI commonly goes unrecognized unless there are symptoms, the time stamp from the event may help to correlate the activity or circumstances at the time of the event. Signal abnormalities related to structural hardware abnormalities usually cause make-or-break type EGM changes. Differentiation between conductor fracture and lead insulation failure is made primarily based on change in impedance (low with insulation failure, high with fracture). It is important to remember that impedance changes may vary and temporarily revert to normal. Insulation abnormality on the ring conductor cable may be suspected if pacing impedance during unipolar (tip to can) pacing is higher than during bipolar pacing. A chest X-ray has low yield in finding lead fracture, but it still should be obtained. Lead failure requires lead revision if clinically indicated. If lead integrity is intact, avoidance of the trigger or decreasing the sensitivity level is the next best step in management.

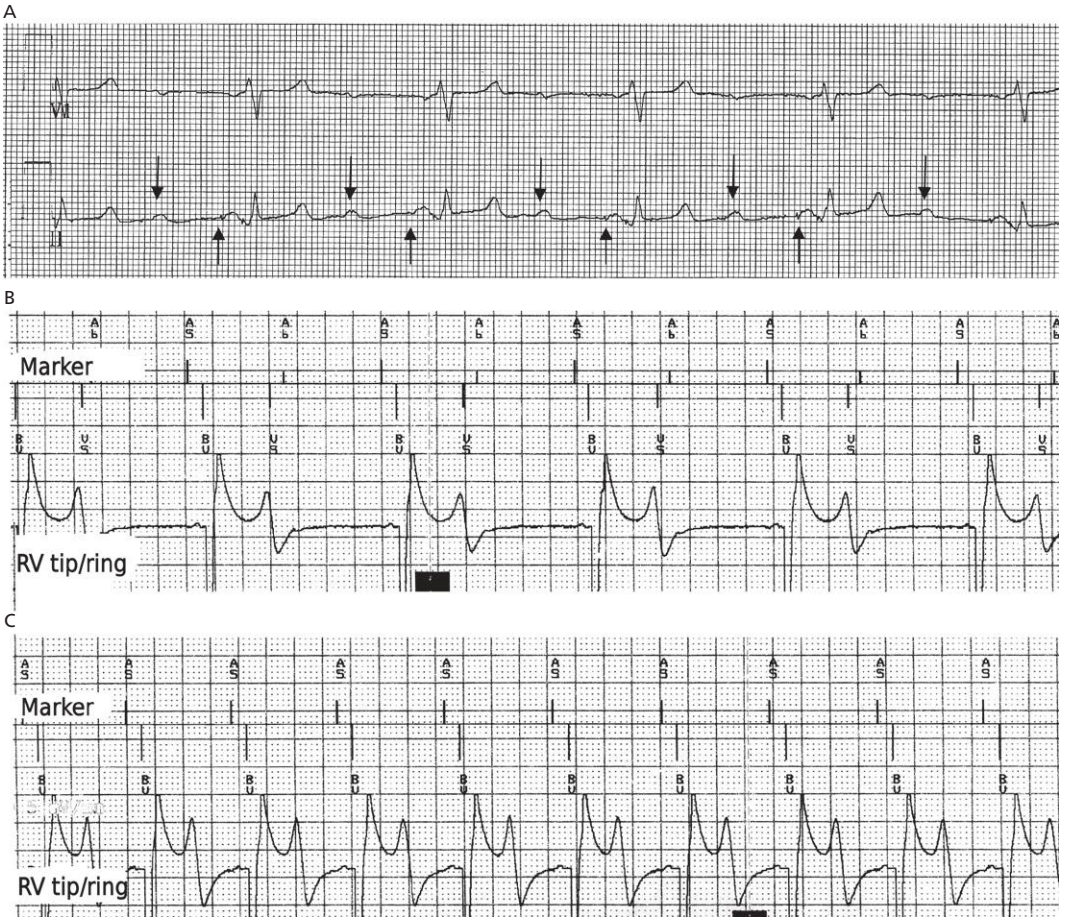


Figure 7.32 A pacemaker-dependent patient with biventricular pacing presented with new-onset heart failure symptoms. The pulse rate was in the 40s and (A) the ECG strip shows the presenting rhythm. There is alternating atrial pacing and sequential biventricular pacing (up arrows) and sinus without ventricular tracking (down arrows). (B) Device interrogation showed sinus rhythm with biventricular pacing (AS, BV). Every paced beat is followed by a VS marker which corresponds to the timing of the T wave. This represents T wave oversensing. Usually T wave oversensing results in a delay of the paced RR interval equal to the QT interval (350–500 ms). Here, as the T wave signal is oversensed as an R wave, a blanking period is initiated. The sinus beat falls in the blanking period and is not tracked. (C) Once ventricular sensitivity was decreased, appropriate tracking resumed. This patient had a biventricular ICD and therefore programming options were limited (see text for further discussion).

Figure 7.33 (A) Sinus rhythm at a rate close to the lower rate limit. Occasional atrial pacing occurs (*) and a pacing spike appears in the middle of the p wave. There is adequate sensing as the intrinsic P wave of $<$800 ms cycle length resets atrial pacing. Atrial capture is confirmed by a subtle degree of fusion in the intracardiac atrial EGM. (B) Example of atrioventricular (AV) sequential pacing. There is atrial capture (*) and conduction to the ventricle (arrows) with right bundle branch block (RBBB) in a 1:1 fashion. The ventricular pacing stimulus is delayed and appears late in the QRS. This phenomenon is more common in the setting of RBBB due to delayed activation at the site of the right ventricular (RV) lead. RV capture cannot be ascertained from this ECG alone as fusion is not proven. (C) AV sequential pacing and capture during the first three beats, which is followed by pacing artifacts without capture (the pacing spike is not followed by depolarization). The measured paced AV delay is 200 ms. The VA time and A–A time is indicated by the solid line and dashed line, respectively. The first non-captured beat (*) times out with the A–A interval after the last paced ventricular beat. This pacing spike is most likely of ventricular origin. An atrial spike would time out with a shorter VA interval. Further investigations revealed

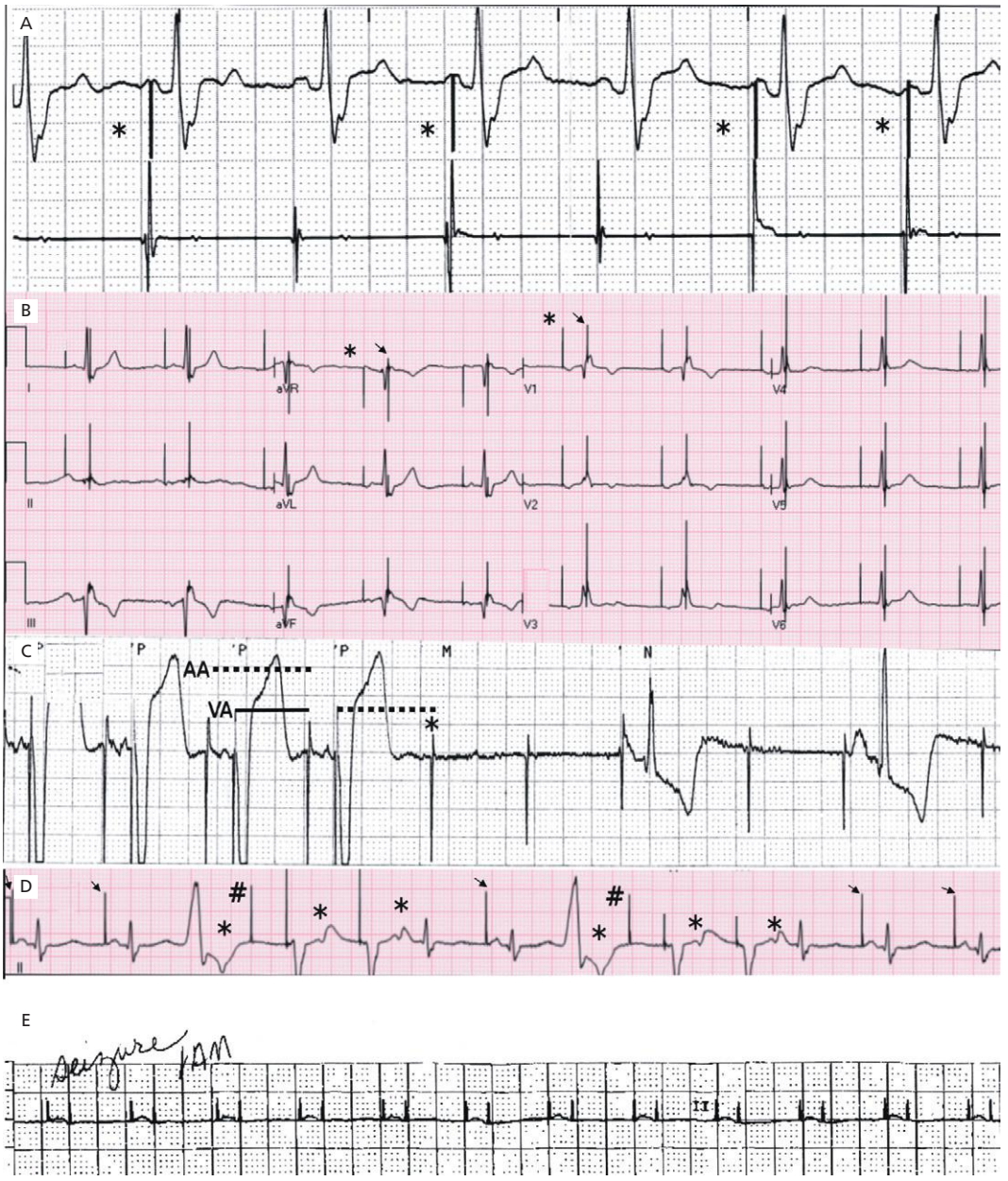


Figure 7.33 (*Continued*) evidence of lead fracture. (D) An example ECG of dual chamber pacing and premature ventricular contractions (PVCs). Atrial pacing is followed by atrial capture and normal intrinsic conduction (arrows). PVC causes retrograde P wave activation (first *). The retrograde P wave falls in the post-ventricular atrial refractory period (PVARP), and atrial pacing follows at a time when the atrium is still refractory (#) and causes (functional) loss of atrial capture (atrial pacing without capture). The next two P waves (*) are retrograde and are the result of ventricular pacing. The sequence is terminated with an echo beat (third and sixth *). The same sequence is repeated with the subsequent PVC. (E) A rhythm strip from a pacemaker-dependent patient who developed seizure-like activity and syncope while in hospital. His pacemaker was upgraded to an ICD 8 months before the admission. He suffered a myocardial infarction and was diagnosed with intermittent loss of ventricular capture due to exit block. The telemetry strip shows an episode of dual chamber pacing with prolonged loss of ventricular capture. Exit block was likely due to the recent myocardial infarction. Cross-talk is ruled out by the presence of ventricular pacing. He remained stable after RV pacing output was increased. This unusual event would have been prevented if the autocapture feature had been available in the device.

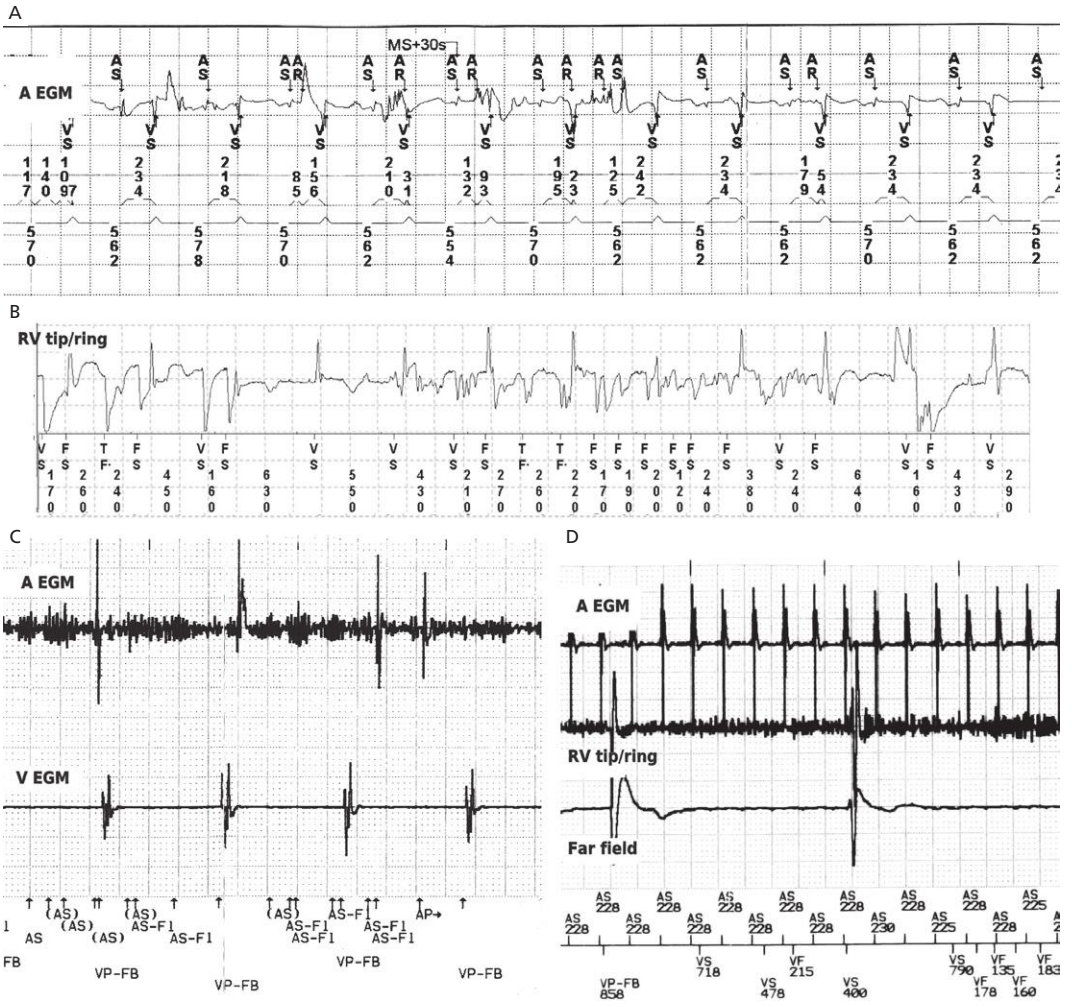


Figure 7.34 (A) Noise, recorded as a mode switch episode, appearing in the right atrial (RA) lead electrogram following a pacemaker generator change. There was fluctuation in lead impedance and the patient complained of pectoral muscle stimulation during atrial pacing. Pectoral stimulation was worse with bipolar pacing and improved with unipolar pacing. The patient was referred for lead replacement due to suspected fracture. Fluoroscopy showed inappropriate lead pin position and the diagnosis of a loose set-screw was made during intraoperative testing (see corresponding Figure 7.13A). The lead was functioning normally. (B) Fracture of the pace/sense portion of a Sprint Fidelis lead (Medtronic). There is evidence of make-or-break signals, occasional saturation of the amplifier, and non-physiological RR intervals. (C) Electromagnetic interference and noise on the atrial lead recorded as a mode switch episode. The origin of this noise could not be determined. (D) Diaphragmatic muscle potential oversensing in an ICD lead during straining. There is bradycardia due to inhibition of pacing and tachycardia detection is initiated. Oversensing resolved once ventricular sensitivity was decreased.

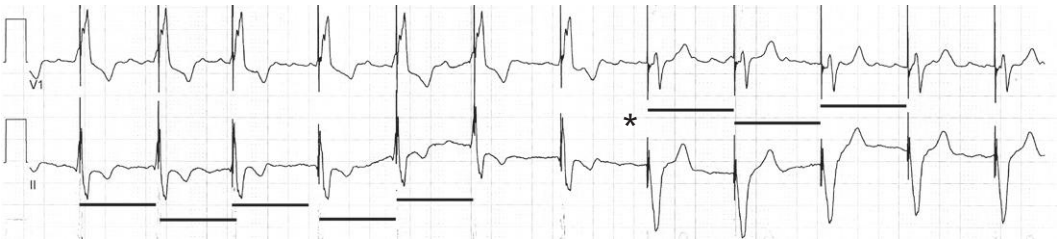


Figure 7.35 Example of atrial fibrillation in a patient with a pacemaker. The first part of the tracing shows atrial fibrillation and a right bundle branch QRS morphology. Pacing artifacts are apparent with each QRS complex, but pacing spikes are timed *after* the initiation of the QRS. The RR intervals are irregular (marked with solid lines, which are of equal length), but the R wave always precedes the pacing spike. This is consistent with triggered pacing. Triggered pacing (or ventricular sensed event) algorithms are commonly used in biventricular devices to maximize biventricular pacing during rapid atrial arrhythmias or premature ventricular contractions (PVCs). The upper rate of triggering is programmable and is usually set well above the base rate (see text for further details). Once the ventricular response slows (*), biventricular pacing ensues. Note that pacing rate has slowed and is regular. There is a change in QRS morphology and pacing spikes now precede each QRS. This is normal behavior. If rate control and/or rhythm control fails, atrioventricular (AV) node ablation may be considered in some patients.

Problems with capture

Pacing capture is confirmed by documenting a stable relationship between the pacing stimulus and depolarization of the cardiac chamber (Figure 7.15). If lack of capture is suspected (pacing artifact present without a corresponding cardiac depolarization), change in capture threshold, pacing during the cardiac refractory period, lead dislodgement, lead fracture, pacemaker generator failure, or metabolic factors have to be considered (Figure 7.30 and Figure 7.33). Pacing artifact may appear within a P wave or QRS complex and is occasionally considered to be a device malfunction. It is important to understand that a bipolar pacing electrode records summed electrical activity from a relatively small cardiac area and the local activation in this area may be delayed compared to the earliest electrical activity in the corresponding chamber. In these situations a pacing artifact may be delayed and appear following the onset of a P wave or QRS complex, and result in fusion or pseudofusion. Fusion means that the surface EGM has a morphology "in-between" that of the intrinsic and purely paced complex, and evidence of fusion confirms capture from the pacing site. Pseudofusion occurs when the pacing artifact appears after the initiation of the P wave or QRS complex, but the morphology is identical to the intrinsic complex. In this case, capture cannot be assessed. An example of ventricular pseudofusion is illustrated in Figure 7.33. In biventricular devices, the goal is to provide maximum percentage ventricular pacing. All major manufacturers offer some sort of algorithm that allows triggered pacing in the LV and/or RV if a ventricular signal is sensed. The trigger for pacing is a sensed signal either in the RV or LV chamber (such as a PVC or conducted atrial arrhythmia). Consequently, the resultant triggered pacing will occur at the time of earliest intracardiac sensing, which is commonly timed after the initial part of the QRS complex. Characteristically, a pacing spike is seen after the initiation of an R wave, mimicking loss of sensing or capture (Figure 7.35). The rationale for these algorithms is to provide at least some ventricular resynchronization to conducted complexes (or PVCs) when the ventricular response exceeds the programmed lower pacing rate. The effectiveness of these algorithms in changing clinical response to biventricular pacing is moderate at best.[17]

Pseudo-pseudofusion occurs when timing of an atrial pacing spike co-incides with the early part of the QRS complex, commonly with a PVC. Due to summation of the atrial and ventricular EGMs on the ECG, these spikes appear to

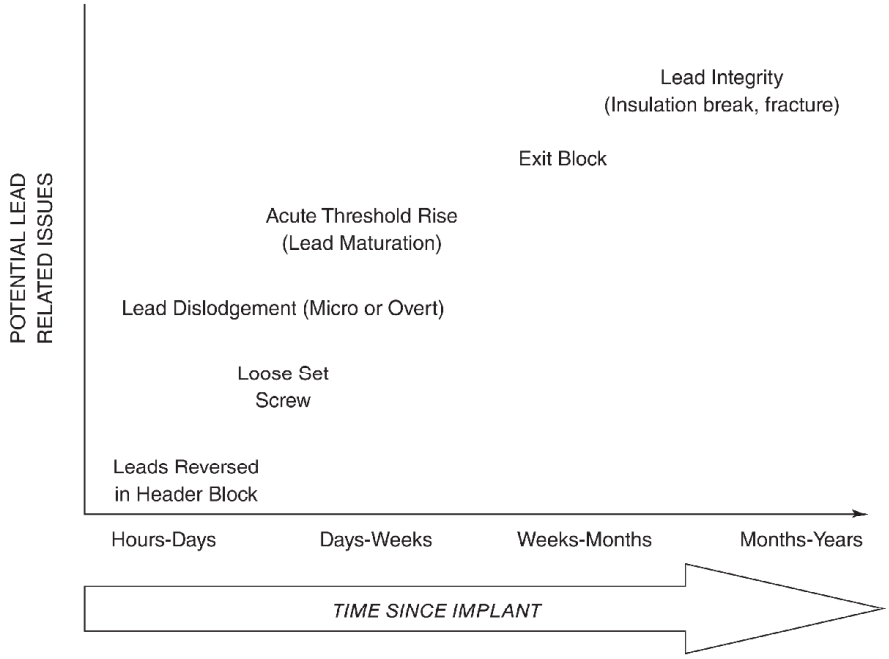


Figure 7.36 Relationship between time since device implantation and commonly observed lead-related complications.

cause the QRS complex but in fact they are independent.

When there is loss of capture at a time when the myocardium is expected to be excitable, a broad differential diagnosis has to be considered. If loss of capture occurs within a few weeks of a new implant, once appropriate programming of output is confirmed, the search should start for lead dislodgement, lead perforation, loose set-screw, air bubble in the header, or exit block at the lead tip due to maturation (Figure 7.36). Air in the pacer pocket in a unipolar pacing system may also result in change in pacing threshold. Under more chronic circumstances, every component of the pacing system has to be scrutinized (Table 7.3 and Figure 7.37). It is important to be methodical and systematic, starting with the generator (is the battery status OK?, was pacing output programmed appropriately?, is there a change in threshold?) and the lead (is there a change or fluctuation in lead impedance?, has there been a gradual or sudden change?). If the basic system parameters are stable, provocative arm exercise or pocket manipulation may result in noise and suggest lead integrity failure or myopotential oversensing. A chest X-ray helps to distinguish lead dislodgement and may identify lead fracture. Clinical history may reveal initiation of new medication (most typically, Vaughan–Williams class I antiarrhythmic agents) or presence of renal failure. Abnormalities in serum electrolytes, such as acidosis or hyperkalemia, should always be considered (Figure 7.38). A history of recent procedures such as surgery, radiofrequency ablation, cardioversion, MRI scan, or radiation therapy may point towards secondary lead or device abnormality. Immediate management should include increasing pacing output and treating the underlying cause(s) if possible. If an appropriate safety margin cannot be programmed, placement of a temporary pacemaker may be considered for select patients until resolution of the problem.

Programming adequate pacing output is an important part of safe pacing therapy. Temporarily, an increased pacing output is required following a new lead implant to cover occasional threshold changes in the first weeks to months of the lead maturation period. Chronic output parameters are usually programmed 8–12 weeks after implant. Expert opinion may differ on programming

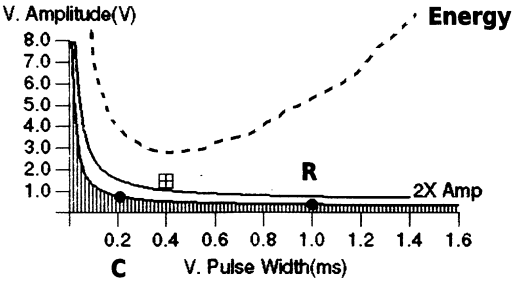


Figure 7.39 Print-out of calculated strength–duration curve in a Medtronic pacemaker. The device measures voltage threshold at 1 ms (R; rheobase) followed by pulse width threshold at twice the rheobase voltage (C, chronaxie). The safety margin setting for 2× amplitude is indicated. For illustration purposes, a dotted line of relative energy expenditure per pacing stimulus has been manually added. Increasing the voltage at the extreme left part of the strength–duration curve or multiplying the pulse width above 0.4 ms would result in a rapid increment in energy without providing an appropriate safety margin in capture. In this example, a 2× amplitude safety margin at pulse width 0.1 ms would require about a 4-V amplitude output and result in similar safety as programming 2 V at 0.2-ms pulse width. Similarly, increasing the pulse width above 0.6 ms (without changing the amplitude) would not meaningfully improve the safety margin but would increase energy expenditure significantly.

special algorithm (Table 7.4), sensor-based pacing, runaway pacemaker, and antitachycardia pacing. These specific causes will be discussed below.

Special algorithms

Questions may occasionally arise when an ECG in a pacemaker patient shows no pacing artifacts or the rate of pacing appears to be slower or faster than expected. The programmed base rate and sensor rate are the main determinants of minimum pacing rate in a single chamber device. Exceptions to this rule may be seen when special algorithms are operational that are designed to minimize pacing near the intrinsic heart rate (e.g. rate hysteresis or sleep mode). These algorithms allow the heart rate to decrease below the base rate, and pacing will only ensue again at the base rate if the intrinsic heart rate reaches the lower hysteresis rate.

Most manufacturers provide algorithms to promote overdrive pacing over the intrinsic sinus rate in an attempt to regularize the rate, minimize short–long cycles, and reduce the occurrence of atrial arrhythmias. These algorithms manifest as accelerated atrial pacing rate (i.e. post mode switch response, atrial preference pacing, post mode switch overdrive pacing). Some of these algorithms are now less commonly used as their overall clinical benefit has been shown to be minimal. Rate regularization, especially during atrial fibrillation (AF), may help with rate control or reduce symptoms related to irregular ventricular rate. Accelerated pacing rate may be seen when these algorithms are operational (e.g. ventricular rate regularization, conducted AF response). More recent data point to possible adverse effects from unnecessary pacing, especially in the RV. Increased RV pacing has been shown to promote systolic dysfunction and AF.[18,19] Algorithms are now increasingly used to allow intrinsic ventricular activation, either by using AV search hysteresis or special, hybrid pacing modes. These hybrid pacing modes (RythmIQ™, Boston Scientific; Managed ventricular pacing™, Medtronic; SafeR™, Sorin) may cause unusual ECG presentations, such as a very prolonged PR interval, occasional AV block, and sudden changes in AV timing (Figure 7.40). Temporary changes in AV timing may also be seen during automatic threshold testing. If capture is determined by measuring the evoked response, fusion has to be minimized. Some algorithms achieve this by temporary shortening of the AV interval for the duration of the threshold test (Figure 7.18E).

Sudden accelerated pacing may be seen when pacing treatment is programmed "on" for management of cardioinhibitory autonomic syndromes. Algorithms initiate an accelerated pacing rate for 1–2 min (or longer if desired) if the intrinsic rate suddenly decreases significantly (e.g. rate drop response, sudden brady response; Figure 7.41).

In certain advanced pacemakers, programmable antitachycardia pacing (ATP) therapy is available for the treatment of atrial arrhythmias. After the tachycardia is detected, bursts of rapid overdrive pacing are initiated in an attempt to terminate the arrhythmia. Multiple rounds of pacing may be programmed for these episodes and present as cycles of rapid atrial pacing. Ventricular ATPs are

Table 7.4 Pacemaker functions associated with pseudo-malfunctions

	Diagnostic clue
Pacing when not expected	
Rate smoothing	Graded rate slowing toward lower rate limit
Rate drop response	Abrupt pacing 90–110 bpm after sudden slowing
Dynamic atrial overdrive	Atrial pacing after atrial ectopy
Ventricular rate regularization	Pacing after shorter VV intervals in atrial fibrillation
Ventricular-based timing	Faster ventricular rate during A_PV_S–A_PV_P cycle
Safety pacing	Ventricular pacing with shortened AV delay
Separate mode switch rate or post-mode switch overdrive rate	Pacing during or after atrial tachyarrhythmia or oversensing
Atrial pace for AV resynchronization	Pacing simultaneous with PVC or delayed after atrial ectopy
Atrial pacing preference	Atrial pacing after atrial-sensed events
Automated capture determinations	Closely coupled stimuli for P wave or QRS, sudden increase in paced rates
No pacing when expected	
Hysteresis	Pause after sensed events
Rate smoothing	Graded rate acceleration toward upper rate limit
PMT intervention	Ventricular output absent after A_SV_P near upper rate limit
Mode switching	Failure to track atrial activity
Separate mode switch rate	Lower pacing rate during mode switch
Intrinsic AV conduction search	Periodic extension of AV delay
Non-competitive atrial pacing	Delay in atrial output following atrial sense in PVARP
Separate sleep rate	Reduced lower rate limit at rest
Atrial-based timing	Prolongation of V–V interval during A_PV_S–A_PV_P cycle
Automatic sensing check	Periodic delay in pacing after prolonged pacing
MVP/RythmIQ/SafeR algorithms	AAI or VVI pacing behavior and allowed AV block (with pause) before switching to DDD mode
Apparent undersensing	
Mode switching	Failure to track atrial activity
PMT intervention	Failure to track single P wave during prolonged A_SV_P at upper rate limit
Rate-adaptive AV delay	Evidence of shorter AV delays at faster rates
Non-tracking modes (DDI, DVI, etc.)	Typical non-tracking behavior
Blanked flutter search	Failure to track P wave when atrial tracking at rate $<$2 times TARP
Noise mode	Evidence of EMI
PVARP extension post-PVC	Failure to sense P wave after PVC

AV, atrioventricular; EMI, electromagnetic interference; MVP, Managed ventricular pacing, Medtronic; PMT, pacemaker-mediated tachycardia; PVARP, post-ventricular atrial refractory period; PVC, premature ventricular contraction; RythmIQ, AAI(R) with VVI back-up, Boston Scientific; SafeR, AAI/DDD mode pacing, Sorin Group; TARP, total atrial refractory period.

frequently used in ICDs for treatment of ventricular tachycardia.

Triggered pacing

In dual chamber devices, complex interactions between atrial- and ventricular-sensed events and pacing may be encountered, depending on the programmed pacing mode (see Chapter 6). In the commonly used DDD mode, lower rate pacing is determined by the base rate, whereas a faster rate may be due to atrial tracking or sensor-based pacing rate (Figure 7.23). On the other hand, if the

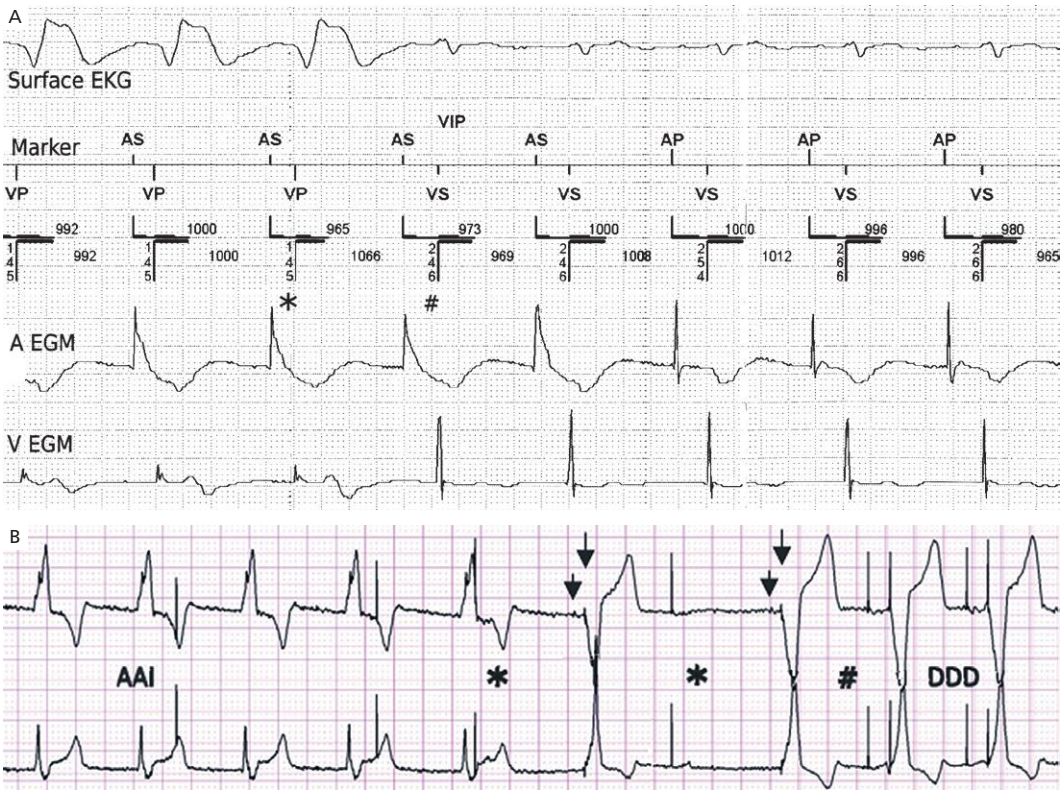


Figure 7.40 (A) Operation of an algorithm to allow intrinsic activation and minimization of ventricular pacing. The ventricular intrinsic preference (VIP™) algorithm extends the atrioventricular (AV) delay (in this example from 145 ms to 245 ms, marked by * and #, respectively) and allows the intrinsic ventricular activation to take place. Note the change from VP to VS on the marker channel and from wide to narrow QRS on the surface ECG as the AV delay is extended and intrinsic conduction returns. (B) ECG showing managed ventricular pacing (MVP™) mode behavior. AAI pacing takes place at the beginning of the tracing with a very long AV interval. When AV block develops (first *), AV pacing takes place with a short (80 ms) AV interval (first double arrow). If AV block occurs in two of four beats (second *), the device switches to DDD mode (#). The second AV block event (second *) is also followed by AV pacing with a short AV delay. This is a typical response and represents normal pacemaker behavior.

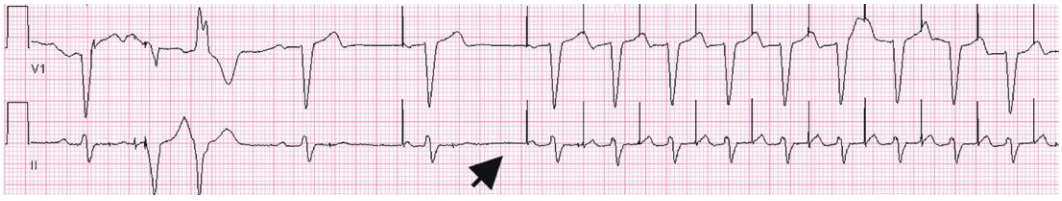


Figure 7.41 Rate drop response in a patient with carotid sinus hypersensitivity. There is a sudden drop of heart rate (following tracked premature atrial and ventricular contraction) to 50 bpm for two beats, which initiates dual chamber pacing at 115 bpm for 2 min (arrow).

intrinsic rate exceeds the base rate and sensor-modulated rate, pacing will be inhibited; this is normal pacemaker behavior. Depending on the clinical circumstances, these episodes may be asymptomatic, or may be associated with palpitations or, rarely, with more severe hemodynamic compromise.

In DDD mode, at the initiation of an atrial tachycardia or AF, tracking will take place if mode switch is not programmed "on" or until the algorithm is initiated (Figure 7.42). If noise occurs in the atrial channel and tracking is programmed "on," pacemaker behavior is often similar to what is seen during an atrial arrhythmia, such as tracking or mode switching. Maximum ventricular tracking or sensor rate will determine the peak paced heart rate. Intermittent palpitations and rate changes may also develop if there is periodic

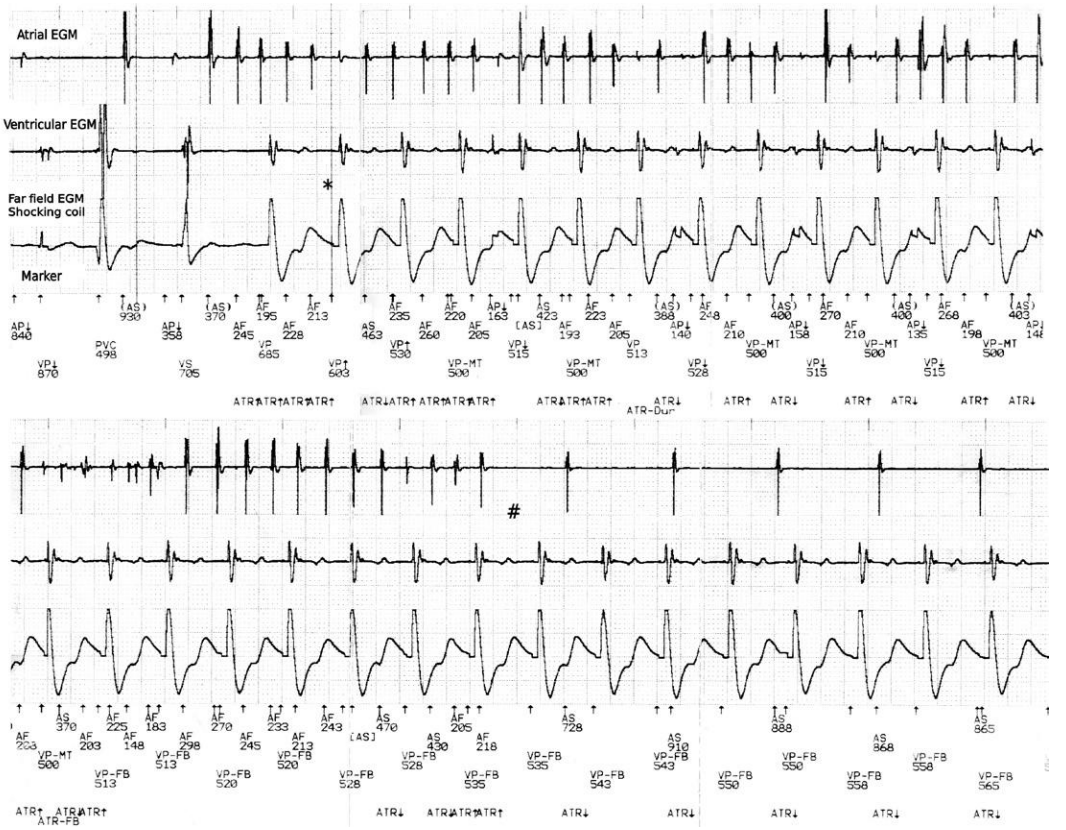


Figure 7.42 Continuous tracing retrieved from a dual chamber ICD memory. Atrial fibrillation starts following a premature ventricular contraction (PVC) and retrograde conducted P wave. Atrial depolarization falls in the post-ventricular atrial refractory period (PVARP) and subsequent atrial pacing results in initiation of the arrhythmia. There is an immediate change in pacing rate due to tracking. Subsequent pacing occurs at a slower rate due to rate smoothing down (*; VP↓). There are also examples in the tracing where rate smoothing causes accelerated pacing (VP↑) in order to reduce irregularity in the ventricular rate. Once appropriate mode switching occurs, ventricular-based timing slowly decreases the pacing rate (fallback rate, marked as VP–FB) until the programmed mode switch lower rate is reached (note the slowing of pacing rate in the bottom tracing). At the termination of the arrhythmia (#), VVI pacing continues with ventriculoatrial (VA) dissociation until the mode switch episode terminates (not shown on the tracing). Symptoms in this patient may occur due to rapid pacing or loss of AV synchrony.

undersensing during an atrial arrhythmia. A common problem is seen with atrial flutter when tracking occurs at a 2:1 rate. In these cases, every other atrial activation falls in the PVAB, while the other events are sensed and tracked up to the maximum tracking rate. Algorithms have been designed and used by all manufacturers to temporarily extend the PVARP, which allows functionally undersensed atrial events to be uncovered and promotes proper mode switching (Figure 7.23). At the termination of an arrhythmia, reversal of these rate changes may be seen, going from tachycardia to sudden bradycardia. Different algorithms have been designed to minimize symptoms due to irregular ventricular rate by reducing sudden heart rate changes (rate smoothing up and down; ventricular rate regularization, Boston Scientific; conducted AF response, Medtronic). These algorithms may be operational during an irregular rhythm and cause pacing at an unexpected rate. An example of these algorithms is illustrated in Figure 7.42.

Pacemaker-mediated tachycardia and repetitive non–re-entrant ventriculoatrial synchrony

PMT remains a relatively common problem, although sustained episodes are less common with the advent of contemporary algorithms that are designed to prevent or identify and terminate them. The basic mechanism of the arrhythmia is persistent retrograde atrial conduction following ventricular pacing while the retrograde, non-refractory atrial signal is continuously tracked with ventricular pacing. Therefore, beat-to-beat ventricular pacing and atrial sensing is necessary to maintain the circuit. Pacing mode has to be dual chamber with tracking (PMT cannot be present with AAI, DDI, or VVI pacing, or ventricular sensing). The most common initiating trigger is a PVC with retrograde atrial conduction that falls outside of the atrial refractory period. Other common situations include loss of atrial sensing and failed capture of the subsequent atrial paced beat due to tissue refractoriness. Subsequent ventricular pacing would cause retrograde atrial activation and initiate PMT. Other possibilities are programmed long AV delays with ventricular pacing, loss of atrial capture (spontaneously or during atrial threshold test), or termination of VVI pacing to DDD mode (i.e. ventricular threshold test in VVI mode or end of mode switching). Symptoms may be absent or include palpitations or pacemaker syndrome. The tachycardia rate is variable, depending on the VA conduction time and programmed AV delay, but typically the heart rate is close to the upper tracking rate. PMT may be terminated by applying a magnet over the device. This will initiate a temporary asynchronous, non-tracking pacing mode. Alternatively, non-tracking pacing modes may be programmed "on" with a programmer. For long-term management, reversible causes need to be treated first, such as adjusting sensing or pacing output. The next step is to test for retrograde conduction and measure retrograde VA conduction time. Based on this information, PVARP has to be extended beyond the timing of the retrograde atrial signal. If indicated, special PMT prevention algorithms may be used, such as atrial pacing on PVC or PVARP extension on PVC. If PMT is detected and a PMT termination algorithm is programmed "on," most commonly the PVARP is extended for one beat and this usually breaks the tachycardia (Figure 7.43). Occasionally, upper rate behavior is misclassified by the device as PMT. In this case, there will be no change in tachycardia rate when extended PVARP is applied, but one beat that falls in the PVARP will not be tracked.

Occasionally, elimination of PMT results in the appearance of another, relatively common arrhythmia, called repetitive non–re-entrant ventriculoatrial synchrony. The initiating triggers are the same as for PMT. In this case, the retrograde P wave falls in the atrial refractory period (PVARP) and therefore is not tracked. As the event is recorded in PVARP, it is not counted for timing purposes. Thus, if the next V–AP interval is short enough to find the atrium unexcitable, there will be functional loss of capture. Atrial pacing will be followed by ventricular pacing, which causes retrograde atrial conduction and the rhythm perpetuates. Algorithms are available to limit this problem. For example, the non-competitive atrial pacing algorithm (in Medtronic devices) takes into consideration the atrial event in PVARP (normally

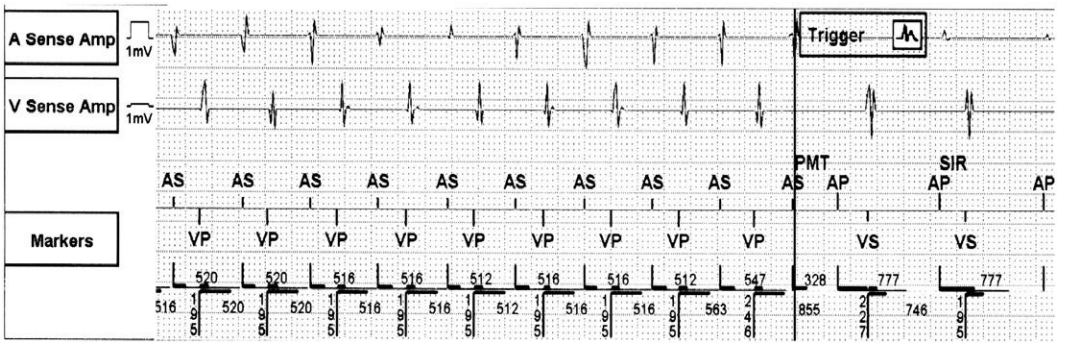


Figure 7.43 Treatment of pacemaker-mediated tachycardia in a St. Jude Medical device. Once the pacemaker-mediated tachycardia (PMT) algorithm is satisfied, sensed atrial signal (AS) is not tracked but is followed by atrial pacing. This breaks the tachycardia and atrial pacing at the sensor-indicated rate (SIR) resumes.



Figure 7.44 This tracing is an example of proarrhythmia due to repetitive non-re-entrant ventriculoatrial synchronous rhythm. A retrograde P wave (AS) following ventricular pacing (VP) falls in the PVARP and is not counted for timing purposes. Subsequent closely coupled atrial pacing results in induction of atrial fibrillation (arrow).

disregarded for timing purposes) and delays the next atrial pacing event beyond the refractory period of the atrium (nominally 300 ms). Programming features that decrease the atrial escape interval (long AV delay, high atrial pacing rate) promote the development of this rhythm and *vice versa*. Symptoms are usually consistent with pacemaker syndrome and a high level of suspicion is required to make the diagnosis. In certain devices the event may trigger mode switching or cause arrhythmia, and these episodes may be recorded in the device memory (Figure 7.44).

Sensor-driven pacing

Rate-modulated pacing is an important programming feature for patients with chronotropic incompetence. Sensors are used to obtain simulated information regarding activity level in order to mimic a physiological heart rate response that is

appropriate for that level of activity. While there have been significant efforts to develop pacemaker algorithms for automatic adjustments in sensor-driven pacing rate, programming and fine tuning rate-modulating sensors, especially in an active and young person, may be challenging. Depending on the specific sensor or combination of sensors, there may be many instances in which inappropriate rate acceleration occurs. Some examples of this are detailed in this section. Activity sensors, such as accelerometers, monitor the movement and vibrations of the body. These sensors may activate during a bumpy automobile, airplane, or helicopter ride, or in the hospital environment when moving the patient or tapping on the patient's chest. Other types of activities, such as bicycling or swimming, may be undersensed. Minute-ventilation sensors estimate exertion by measuring transthoracic impedance changes related to ventilation. Interference may occur in the hospital environment due to erroneous signals related to monitoring equipment, or during mechanical ventilation or an echocardiography examination. Hyperventilation or excessive arm movement may also promote sensor-driven pacing with minute-ventilation sensors. QT sensor-based pacemakers modify heart rate based on catecholamine-induced changes in the QT interval and are prone to false activation due to medication or ischemia-induced QT changes.

Runaway pacemaker

Runaway pacing, an uncontrolled rapid pacing above the programmed upper rate, is a serious medical emergency. Pacing rates from 150 to 1000 bpm have been reported, but most cases were described decades ago. The number of these rare abnormalities has dramatically declined with hermetic sealing of the devices, improvements in battery technology, and development of central processing unit (CPU)-controlled circuitry. A runaway pacemaker, in contrast to a PMT, is not affected by magnet application, and the pacing rate with PMT will not exceed the programmed upper pacing or tracking rate. If emergency VVI pacing through the programmer fails to override the tachycardia, emergency device replacement is required.

Analysis of stored device data

Storage and diagnostic capabilities in modern pacemakers and ICDs continue to improve. Automatic sensing and pacing capabilities, auto-adjustment, and increasing compatibility with telephone or internet-based remote monitoring have revolutionized the follow-up of device patients. Summaries of basic device information, in addition to lead trends, extensive counter information, and stored EGMs, allow the providers to obtain a more complete picture of the clinical events and device information.

Basic device data

The basic device data provide the backbone information regarding the device function. This includes information about battery status, which may be expressed as measured battery voltage, battery impedance, or graphical expression as "gas-gauge." In most contemporary devices there is also a reference to predicted battery longevity. Lead parameters include the measured impedance, polarity, and previous threshold measurements. Longitudinal recordings of lead impedance and threshold information are invaluable during long-term follow-up and serve as a reference to identify lead abnormalities. Programming parameters summarize the pacing mode and basic intervals (Figure 7.45).

Event counters and histograms

There are different counters and statistical data that provide a rough overview of pacing and rhythm characteristics. These measured parameters include percentage of pacing and sensing in each chamber, and frequently subgroups are also identified, such as the relationship of sensing and pacing between the chambers. Counters often show the number of premature atrial contractions or PVCs and percentage of atrial arrhythmias or mode switches. The validity of the data summary depends on the characteristics of the patient and also the sensing accuracy of the pacemaker (Figure 7.21). For example, a high ventricular pacing percentage may be present by the device counter, yet this finding in the presence of pseudofusion may not indicate a true clinical ventricular pacing percentage. Critical review of the histograms

(graphical or numerical) is helpful to screen for chronotropic incompetence or to identify possible clusters of tachyarrhythmias based on the bimodal distribution of the heart rate. This information may be useful in patients who have unexplained palpitations and helps to direct further investigations (Figure 7.46).

Arrhythmia logbook and stored electrograms

EGM recording capability is a very important component of the diagnostic armamentarium in pacemakers and ICDs. In most pacemakers, a memory segment is reserved for storing EGMs. Based on the clinical circumstances and the type of problem investigated, or perhaps for general screening purposes, programming may be adjusted to focus EGM recording on certain types of arrhythmias or abnormalities, such as atrial or ventricular tachyarrhythmias, PMT episodes, mode switches, or noise reversion recording (may be helpful when there are questions about environmental effects or a subclinical lead integrity problem). While these logbooks and EGMs are very helpful to clarify symptoms or identify arrhythmias, the EGMs have to be carefully reviewed and adjudicated as misclassification may frequently occur (Figure 7.8, Figure 7.18D, Figure 7.34, Figure 7.46, and Figure 7.47).

Summary

Long-term management and follow-up is markedly enhanced in current pacemaker systems by their increased automatization and extensive diagnostic capabilities. A wealth of information is stored in modern pacemakers: lead and battery data, and capture and sensing characteristics with automatic sensing and pacing adjustments. These systems work very well the majority of the time and allow quick and efficient patient follow-up. When faced with a problem, troubleshooting is markedly eased if adequate records are available. These records should include data on the implanted

A

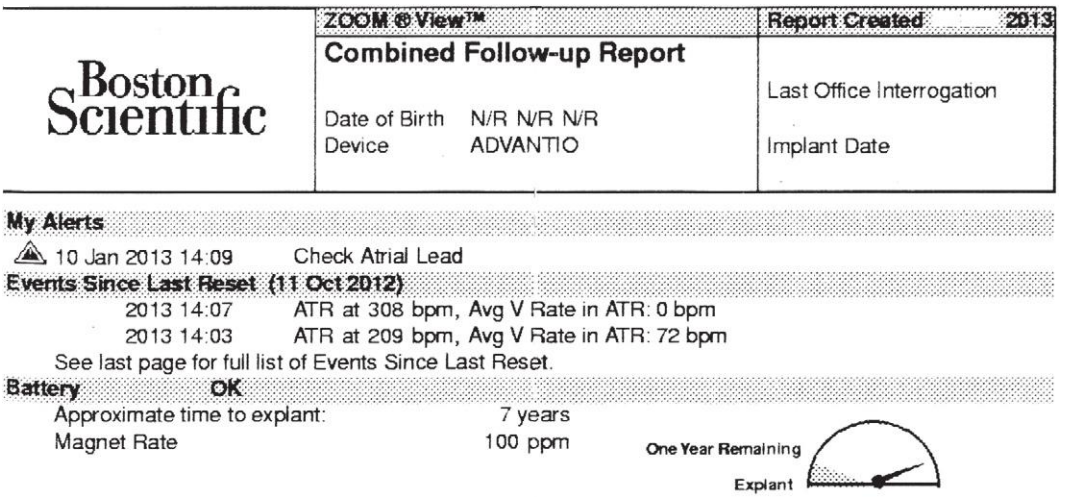


Figure 7.45 (A,B) Basic device data and programming parameters from a print-out of a Boston Scientific pacemaker. Battery and lead status, lead parameters, and atrial arrhythmia burden are illustrated in a graphical fashion (B). These graphs suggest that there are episodes of atrial arrhythmias and also variable p wave amplitude. Decreased p wave amplitude is seen during atrial arrhythmias. Appropriate diagnosis cannot be made based on these data unless intracardiac tracings are available to confirm these findings. The discontinuities in the right ventricle (RV) amplitude recordings are the result of frequent RV pacing and periodic inability to measure R wave amplitude. There is some variation in lead impedance in this patient without any lead abnormality.

B

Settings

Ventricular Tachy Settings
- Ventricular Tachy EGM Storage: On
- Detection Rate: 160 bpm

Atrial Tachy Settings
- ATR Mode Switch: 170 bpm DDIR

Brady Settings

Mode	DDDR
Lower Rate Limit	60 ppm
Maximum Tracking Rate	120 ppm
Maximum Sensor Rate	130 ppm
Paced AV Delay	130 - 180 ms
Sensed AV Delay	110 - 150 ms
A-Refractory (PVARP)	370 ms
V-Refractory (VRP)	230 - 250 ms

Pacing Output	
Atrial	3.5 V @ 0.5 ms
Ventricular	Auto 1.6 V @ 0.4 ms
Sensitivity	
Atrial	Fixed 0.25 mV
Ventricular	Fixed 2.5 mV
Leads Configuration (Pace/Sense)	
Atrial	Bipolar
Ventricular	Bipolar
Rate Adaptive Pacing	
Minute Ventilation	On
Accelerometer	Passive

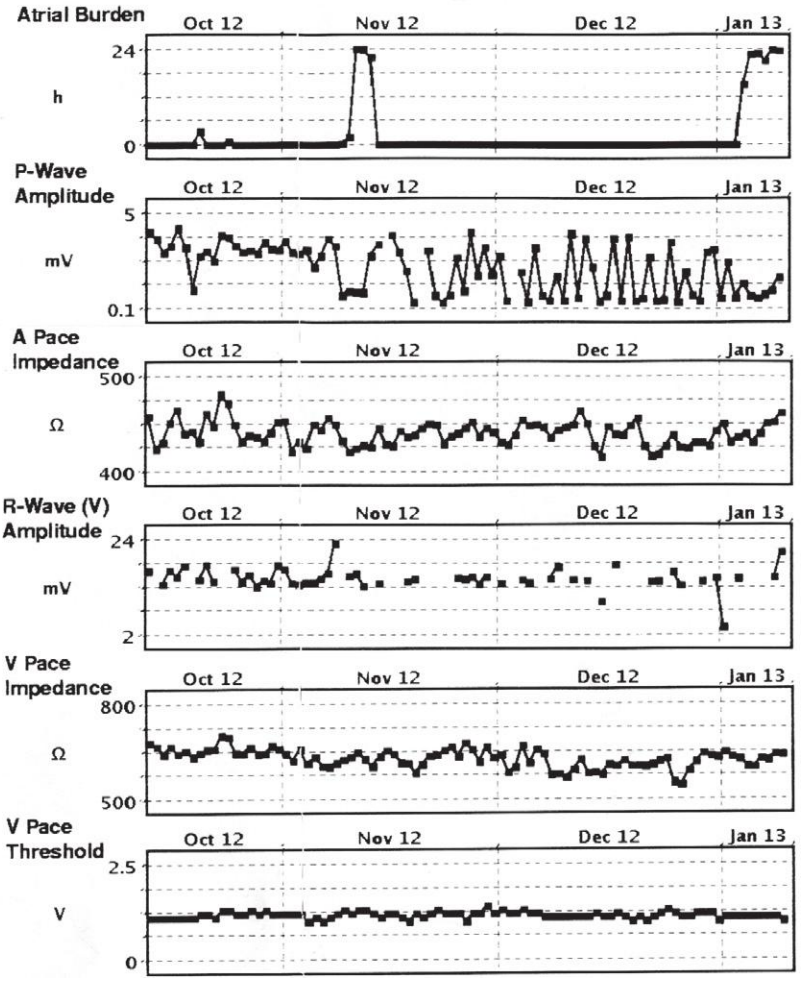
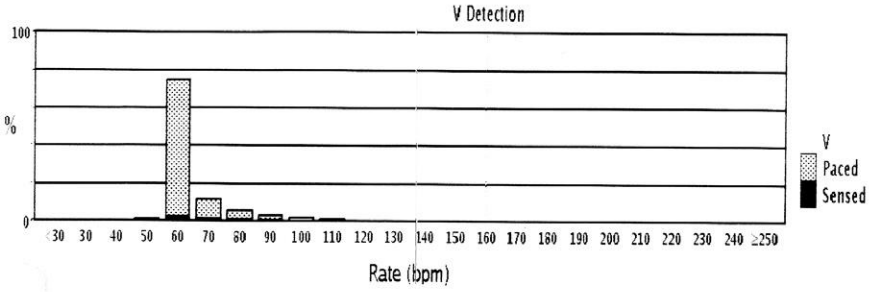


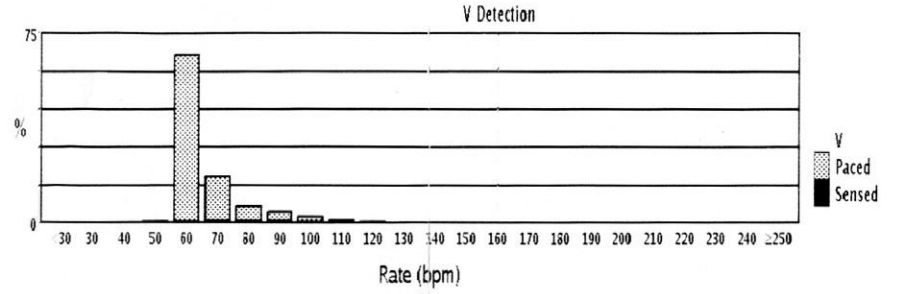
Figure 7.45 (*Continued*)

Brady Counters	Reset Before Last 2012	Since Last Reset 2012
Counters		
% A Paced	77	58
% V Paced	95	96
Intrinsic Promotion		
AV Search +		
% Successful	0	0
Rate Hysteresis		
% Successful	0	0
Atrial Burden		
Episodes by Duration		
< 1 minute	0	175
1 min - < 1 hr	0	236*
1 hr - < 24 hr	0	51
24 hr - < 48 hr	0	0
> 48 hr	0	0
Total PACs	39.7K	126.8K*
Ventricular Counters		
Total PVCs	3.4K	21.5K
Three or More PVCs	7	3

Histograms Reset Before Last (2012) (Continued)



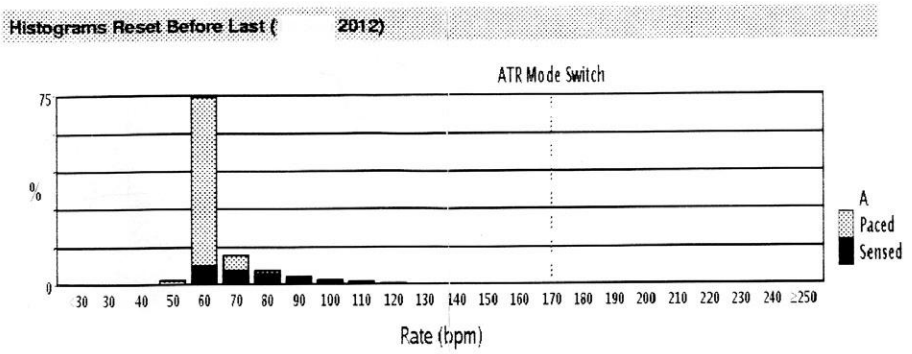
Histograms Since Last Reset (2012) (Continued)

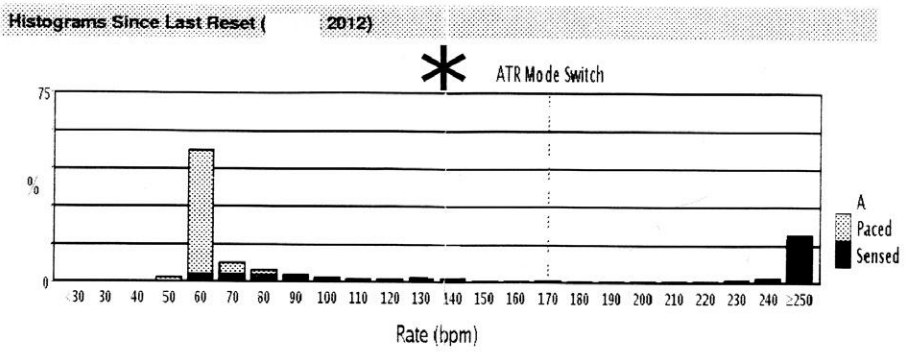


All Events Since Last Reset (11 Oct 2012)

2013 14:07	ATR at 308 bpm, Avg V Rate in ATR: 0 bpm
2013 14:03	ATR at 209 bpm, Avg V Rate in ATR: 72 bpm
2013 14:02	ATR at 182 bpm, Avg V Rate in ATR: 74 bpm
2013 14:00	ATR at 181 bpm, Avg V Rate in ATR: 75 bpm

Figure 7.46 Summary page of counters and histogram information from a Boston Scientific pacemaker. A significantly increased number of premature atrial contractions and high rate atrial events are seen compared to the previous device check (*).





All Events Since Last Reset (Continued) (2012)

2013 13:56	ATR at 185 bpm, Avg V Rate in ATR: 72 bpm
2013 13:46	ATR at 279 bpm, Avg V Rate in ATR: 90 bpm
2013 13:43	ATR at 220 bpm, Avg V Rate in ATR: 105 bpm
2013 13:31	RV Auto
2013 11:52	ATR at 216 bpm, Avg V Rate in ATR: 71 bpm
2013 11:47	ATR at 225 bpm, Avg V Rate in ATR: 104 bpm
2013 11:32	ATR at 217 bpm, Avg V Rate in ATR: 78 bpm
2013 11:30	ATR at 181 bpm, Avg V Rate in ATR: 81 bpm
2013 11:17	ATR at 198 bpm, Avg V Rate in ATR: 77 bpm
2013 09:58	ATR at 296 bpm, Avg V Rate in ATR: 75 bpm
2013 09:47	ATR at 168 bpm, Avg V Rate in ATR: 81 bpm
2013 09:44	ATR at 194 bpm, Avg V Rate in ATR: 85 bpm
2013 15:32	NonSustV at 163 bpm
2012 17:40	NonSustV at 153 bpm
2012 13:29	NonSustV at 144 bpm
2012 20:14	NonSustV at 174 bpm
2012 17:21	NonSustV at 163 bpm
2012 19:58	PMT at 120 bpm
2012 16:30	NonSustV at 168 bpm
2012 14:26	NonSustV at 163 bpm
2012 23:25	NonSustV at 163 bpm
2012 23:25	NonSustV at 162 bpm

Figure 7.46 (*Continued*)

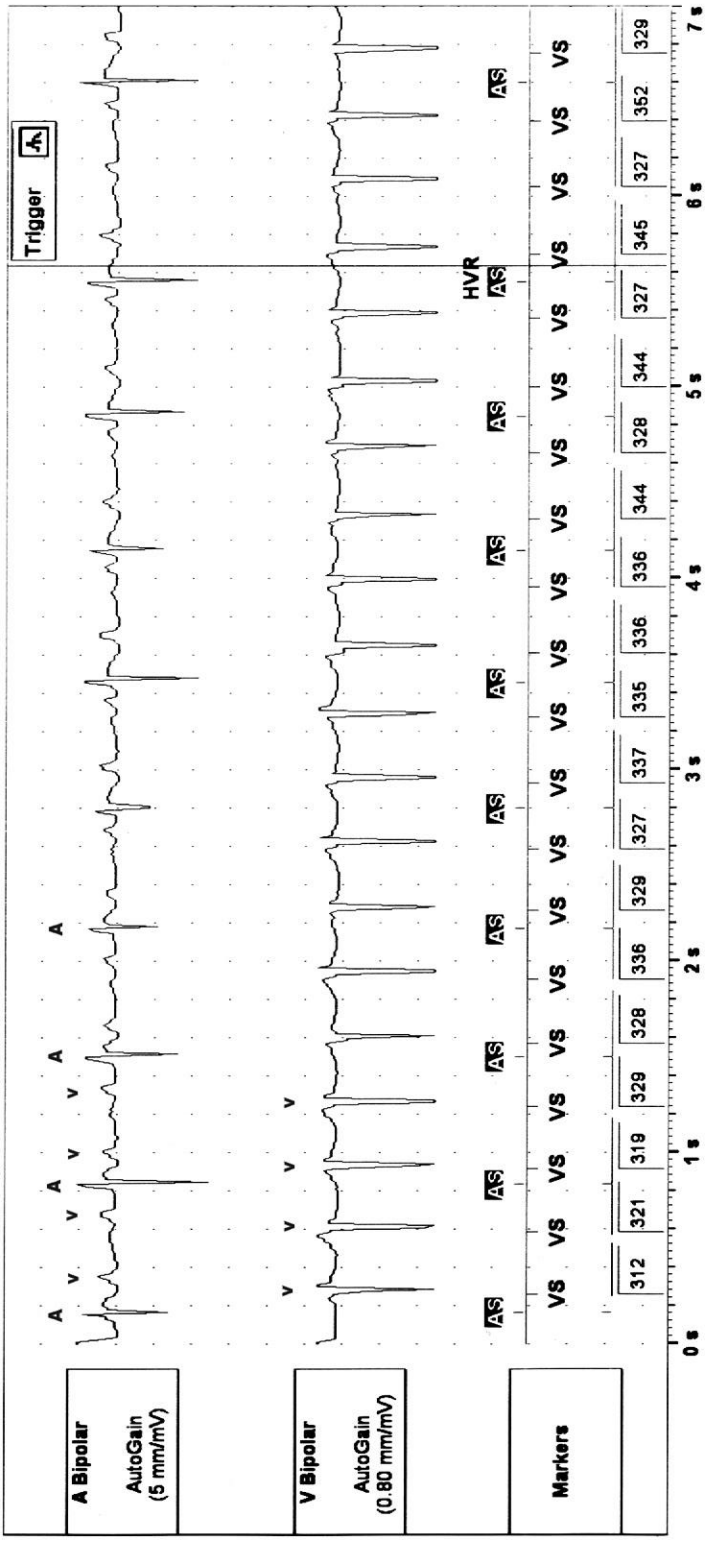


Figure 7.47 High ventricular rate recorded in a pacemaker memory. The ventricular channel (V Bipolar) records a tachycardia (VS, ventricular sensed) with dissociation from the atrial signals (A Bipolar; AS, atrial sensed). The first four ventricular events are marked with (v). The corresponding (v) signals on the atrial channel represent far-field R wave signals. Large electrograms (A) are dissociated atrial signals. The presence of VA/AV dissociation indicates that the episode is ventricular tachycardia.

device, indication of device therapy, chest X-ray, ECG; prior device data on battery status, lead integrity, capture threshold; and stored device data and EGMs. Review of symptoms, co-morbidities, clinical history, and results of focused physical examination provides important information for directing further management decisions. If an abnormality is identified, a very thorough step-by-step evaluation is required, while keeping a wide differential diagnosis in mind until the particular problem is clarified. It is important to retrieve and review any earlier information that may be available in a remote site if time and the nature of the problem allow. If needed, supplementary information from ancillary tests (ECG, chest X-ray, echocardiogram, event monitor, Holter monitor) may be obtained to evaluate a specific question. As unusual device behavior may mimic system abnormalities, when unsure it may be helpful to seek assistance from the device company's technical service representative.

Despite these advances, current pacing systems are far from perfect due to many confounding factors. The basic principles of pacing have remained unchanged and detailed understanding of the pacing system, patient characteristics, and device algorithms is imperative for appropriate troubleshooting. Without this detailed understanding, problems may be overlooked and the device patient harmed as a result.

References

1 Jacob S, Shahzad MA, Maheshwari R, Panaich SS, Aravindhakshan R. Cardiac rhythm device identification algorithm using X-Rays: CaRDIA-X. *Heart Rhythm* 2011; 8(6): 915–922.

2 Hauser RG, Hayes DL, Kallinen LM, *et al.* Clinical experience with pacemaker pulse generators and transvenous leads: an 8-year prospective multicenter study. *Heart Rhythm* 2007; 4(2): 154–160.

3 Burri H, Senouf D. Remote monitoring and follow-up of pacemakers and implantable cardioverter defibrillators. *Europace* 2009; 11(6): 701–709.

4 Maisel WH, Moynahan M, Zuckerman BD, *et al.* Pacemaker and ICD generator malfunctions: analysis of Food and Drug Administration annual reports. *JAMA* 2006; 295(16): 1901–1906.

5 Manegold JC, Israel CW, Ehrlich JR, *et al.* External cardioversion of atrial fibrillation in patients with implanted pacemaker or cardioverter-defibrillator systems: a randomized comparison of monophasic and biphasic shock energy application. *Eur Heart J* 2007; 28(14): 1731–1738.

6 Last A. Radiotherapy in patients with cardiac pacemakers. *Br J Radiol* 1998; 71(841): 4–10.

7 Swerdlow CD, Gunderson BD, Ousdigian KT, Abeyratne A, Sachanandani H, Ellenbogen KA. Downloadable software algorithm reduces inappropriate shocks caused by implantable cardioverter-defibrillator lead fractures: a prospective study. *Circulation* 2010; 122(15): 1449–1455.

8 Liu J, Brumberg G, Rattan R, Jain S, Saba S. Class I recall of defibrillator leads: a comparison of the Sprint Fidelis and Riata families. *Heart Rhythm* 2012; 9(8): 1251–1255.

9 Sharif MN, Wyse DG, Rothschild JM, Gillis AM. Changes in pacing lead impedance over time predict lead failure. *Am J Cardiol* 1998; 82(5): 600–603.

10 Hirschl DA, Jain VR, Spindola-Franco H, Gross JN, Haramati LB. Prevalence and characterization of asymptomatic pacemaker and ICD lead perforation on CT. *Pacing Clin Electrophysiol* 2007; 30(1): 28–32.

11 Essebag V, Champagne J, Birnie DH, *et al.* Nonphysiologic noise early after defibrillator implantation in Canada: incidence and implications: a report from the Canadian Heart Rhythm Society Device Committee. *Heart Rhythm* 2012; 9(3): 378–382.

12 Ammann P, Sticherling C, Kalusche D, *et al.* An electrocardiogram-based algorithm to detect loss of left ventricular capture during cardiac resynchronization therapy. *Ann Intern Med* 2005; 142(12 Pt 1): 968–973.

13 Coman JA, Trohman RG. Incidence and electrocardiographic localization of safe right bundle branch block configurations during permanent ventricular pacing. *Am J Cardiol* 1995; 76(11): 781–784.

14 Alings M, Vireca E, Bastian D, *et al.* Clinical use of automatic pacemaker algorithms: results of the AUTOMATICITY registry. *Europace* 2011; 13(7): 976–983.

15 Kolb C, Wille B, Maurer D, *et al.* Management of far-field R wave sensing for the avoidance of inappropriate mode switch in dual chamber pacemakers: results of the FFS-test study. *J Cardiovasc Electrophysiol* 2006; 17(9): 992–997.

16 Wood MA, Ellenbogen KA, Shepard RK, Clemo HS. Atrioventricular sequential pacing by an implantable cardioverter defibrillator during sustained ventricular tachycardia: what is the mechanism? *J Cardiovasc Electrophysiol* 2002; 13(12): 1309–1310.

17 Kamath GS, Cotiga D, Koneru JN, *et al.* The utility of 12-lead Holter monitoring in patients with permanent

atrial fibrillation for the identification of nonresponders after cardiac resynchronization therapy. *J Am Coll Cardiol* 2009; 53(12): 1050–1055.

18 Tse HF, Lau CP. Long-term effect of right ventricular pacing on myocardial perfusion and function. *J Am Coll Cardiol* 1997; 29(4): 744–749.

19 Sweeney MO, Hellkamp AS, Ellenbogen KA, *et al*. Adverse effect of ventricular pacing on heart failure and atrial fibrillation among patients with normal baseline QRS duration in a clinical trial of pacemaker therapy for sinus node dysfunction. *Circulation* 2003; 107(23): 2932–2937.

8

CHAPTER 8

The implantable cardioverter–defibrillator

Michael R. Gold[1] *and Charles Swerdlow*[2]

[1] Medical University of South Carolina, Charleston, SC, USA
[2] Cedars Sinai Medical Center, David Geffen School of Medicine at UCLA, Los Angeles, CA, USA

The implantable cardioverter–defibrillator (ICD) has undergone a remarkable transformation since it was first developed by Mirowski and colleagues[1] and FDA approved for use in 1985. The early pulse generators were large, requiring thoracotomy for epicardial patch placement, and were implanted in the abdomen. This complex surgery resulted in postoperative hospitalization averaging approximately 1 week. The pulse generators had a longevity of less than 2 years and almost no diagnostic or pacing capabilities. Modern devices provide detailed information on the morphology and rates of arrhythmias, with stored electrograms (EGMs) available before, during, and after therapy. A variety of physiological parameters, including heart rate variability, activity level, transthoracic impedance, and atrial and ventricular rates, are catalogued independent of arrhythmias, and lead impedances and sensed EGM amplitudes (i.e. R waves and P waves) are measured automatically and stored in the memory. All of these data can be accessed remotely, allowing for early detection and analysis of problems with less frequent in-office interrogations needed. The downsizing of pulse generators, in combination with improvements of lead design and shock waveforms, allows the simplicity of defibrillator implantation to approach that of pacemakers, with outpatient placement now routine. Despite the marked reduction in size and increase in diagnostic capabilities, device longevity is now greater than 8 years. ICDs have the capabilities to treat multiple problems, not only life-threatening ventricular arrhythmias but also bradyarrhythmias, atrial arrhythmias with dual chamber devices, and congestive heart failure (CHF) with biventricular pacing. Most recently, subcutaneous lead systems were developed for ICDs without any transvenous components. In this chapter, the indications for use, mechanisms underlying defibrillation, design of ICD systems, as well as the practical applications of this therapy will be reviewed.

Indications and supporting evidence

ICD implantation was initially used for patients who had already experienced a life-threatening ventricular arrhythmia (i.e. secondary prevention). It was only later that these devices were validated for primary prevention among patients with no known history of sustained ventricular arrhythmia to prevent sudden cardiac death (SCD). A summary of the current indications for ICD therapy is given in Table 8.1.[2,3]

Cardiac Pacing and ICDs, Sixth Edition. Edited by Kenneth A. Ellenbogen and Karoly Kaszala.
© 2014 John Wiley & Sons, Ltd. Published 2014 by John Wiley & Sons, Ltd.

Table 8.1 Summary of indications for ICD therapy

Secondary prevention	
Class I	Patients with a history of sudden cardiac arrest (SCA), VF, hemodynamically unstable VT, or unexplained syncope with LV dysfunction and inducible VT
Primary prevention	
Class I	Patients with ischemic cardiomyopathy who are at least 40 days post-MI with an LVEF of ≤30–40%, NYHA functional class II or III, receiving optimal medical therapy, and have reasonable expectation of survival with a good functional status at >1 year Patients with non-ischemic cardiomyopathy, NYHA class II–III, LVEF ≤30–35%, receiving optimal medical therapy, and have reasonable expectation of survival with a good functional status at >1 year
Class IIa	Ischemic cardiomyopathy patients with NYHA functional class I, LVEF ≤30–35%, receiving optimal medical therapy, and have reasonable expectation of survival with a good functional status at >1 year ICD in combination with biventricular pacing in patients with NYHA functional class III or IV, receiving optimal medical therapy, in sinus rhythm with a QRS of >120 ms, and a reasonable survival expectation of >1 year Patients who are at high risk of SCA due to genetic disorders, such as long QT syndrome, Brugada syndrome, hypertrophic cardiomyopathy, and arrhythmogenic right ventricular cardiomyopathy (ARVC), and have reasonable expectation of survival with a good functional status at >1 year
Class IIb	Non-ischemic cardiomyopathy patients with NYHA functional class I, LVEF ≤30–35%, receiving optimal medical therapy, and have a reasonable expectation of survival with a good functional status at >1 year

LV, left ventricular; LVEF, left ventricular ejection fraction; MI, myocardial infarction; NYHA, New York Heart Association; VF, ventricular fibrillation; VT, ventricular tachycardia.

Secondary prevention

The use of ICDs in patients who had survived an aborted cardiac arrest or an episode of sustained ventricular tachycardia (VT) that was refractory to antiarrhythmic drug therapy was the standard for more than a decade. The Antiarrhythmic Versus Implantable Defibrillator (AVID) study compared ICD implantation with antiarrhythmic drug use (primarily amiodarone) among patients with aborted cardiac arrest or poorly tolerated VT.[4] Patients were randomized to initial therapy with an ICD or to a class III antiarrhythmic drugs. There was a significant reduction in mortality in the group randomized to ICD implantation. The benefit of the ICD was most marked among patients with a reduced left ventricular ejection fraction (LVEF) (<35%). In the Canadian Implantable Defibrillator Study (CIDS), 659 patients with VT, ventricular fibrillation (VF), or syncope were randomized to antiarrhythmic therapy with amiodarone or ICD implantation. A 20% reduction in mortality was observed in the ICD group, although this did not reach statistical significance. However, subsequent analyses have shown that an LVEF of less than 35%, age more than 70 years, and advanced CHF were characteristics of the patients who were most likely to benefit from ICD implantation.[5] In the Cardiac Arrest Study Hamburg (CASH) study, 288 patients with a history of cardiac arrest were randomized to receive metoprolol, amiodarone, or propafenone, or to undergo ICD implantation. There was increased mortality in the group treated with propafenone, and a 28% decreased mortality among the patients who received ICDs.[6] These studies established the benefit of ICD therapy as first-line treatment among patients with a history of life-threatening arrhythmias, particularly those with left ventricular dysfunction; thus, antiarrhythmic drugs have been relegated to adjunctive therapy to reduce arrhythmia recurrence rates.

Primary prevention

The Multicenter Automatic Defibrillator Implantation Trial (MADIT) and Multicenter Unsustained Tachycardia Trial (MUSTT) were the first large studies of ICD use in primary prevention of SCD. These trials evaluated patients with coronary

artery disease, left ventricular systolic dysfunction, non-sustained VT, and inducible sustained monomorphic VT. In the MADIT study, patients were randomized to receive either an ICD or "conventional" medical therapy, which was most commonly amiodarone.[7] In the MUSTT study, patients were randomized to either no antiarrhythmic therapy or drug therapy guided by electrophysiology study. In 46% of the latter group, ICD implantation was performed because of the failure of antiarrhythmic drugs to suppress inducible arrhythmias.[8] Despite these differences in study design, the results of the two trials were remarkably similar; ICD use decreased mortality by greater than 50% in these cohorts with ischemic cardiomyopathy.[9]

A further analysis of MUSTT indicated limited prognostic value of the electrophysiology study for risk stratification.[10] Moreover, subsequent primary prevention studies simplified the identification of patients who will benefit from ICD placement, eliminating the need for electrophysiology testing. The MADIT II study was a prospective randomized trial of 1232 subjects with previous myocardial infarction (MI) and ejection fraction of 30% or less.[11] Spontaneous non-sustained VT or electrophysiology testing were not required for enrollment in this trial. The ICD and control groups had similar clinical characteristics with a mean age of approximately 65 years, 67% with CHF [New York Heart Association (NYHA) class II–IV] and mean LVEF of 23%. During a mean follow-up of 20 months, the mortality rates were 14.2% in the ICD group and 19.8% in the control group.

The Sudden Cardiac Death in Heart Failure Trial (SCD HeFT) was the first large multicenter primary prevention study to eliminate the inclusion criteria of coronary artery disease. In this trial, 2521 subjects with CHF (NYHA class II and III) and left ventricular systolic dysfunction (ejection fraction $\leq$35%) were randomized, irrespective of etiology (i.e. ischemic or non-ischemic cardiomyopathies).[12] ICD implantation, but not amiodarone, was shown to reduce all-cause mortality. Similar mortality reductions were observed among the subgroups with ischemic and non-ischemic cardiomyopathies. The Defibrillators in Non-Ischemic Cardiomyopathy Treatment Evaluation (DEFINITE) study randomized 458 subjects with dilated, non-ischemic cardiomyopathy and frequent ventricular ectopy to receive an ICD or optimal medical therapy. There was a strong trend toward a mortality reduction in the ICD cohort, and a significant reduction in the incidence of SCD.[13]

Other indications

One cohort that is particularly difficult to manage is those patients with structural heart disease and a history of syncope. These patients have been excluded from most prospective, randomized studies because, on the one hand, they do not have documented arrhythmias to be included in secondary prevention studies, and, on the other hand, they cannot be classified as asymptomatic for inclusion in primary prevention trials. Present guidelines recommend ICD implantation in patients with dilated cardiomyopathy or structural heart disease and syncope of undefined cause.[2,3] Another group of patients in whom ICD implantation may be indicated are those with hypertrophic cardiomyopathy who have at least one major risk factors for SCD.[14] These risk factors include a history of VT (sustained or non-sustained detected by Holter monitor), recurrent syncope, a family history of sudden death, exercise-induced hypotension, and marked septal thickness ($>$30 mm). ICD use is also becoming more common among patients with primary electrical disease, such as the Brugada syndrome,[15] arrhythmogenic right ventricular (RV) cardiomyopathy, and long QT syndrome, particularly among patients with a history of marked QT prolongation and cardiac arrest or syncope.[16] There are several other systemic conditions, such as sarcoidosis and myotonic dystrophy, that are associated with increased incidence of sudden death. The use of ICDs in these populations is evolving as there is a paucity of controlled studies to guide clinical practice. Current indications of an ICD implantation are illustrated in a simplified flowchart in Figure 8.1.

High-risk patients who do not benefit from ICDs

Not all high-risk groups benefit from ICD implantation, as shown by the Coronary Artery Bypass Graft (CABG) Patch, Defibrillator in Acute Myocardial Infarction Trial (DINAMIT), and Immediate Risk Stratification Improves Survival (IRIS) trials. In the CABG Patch trial, patients

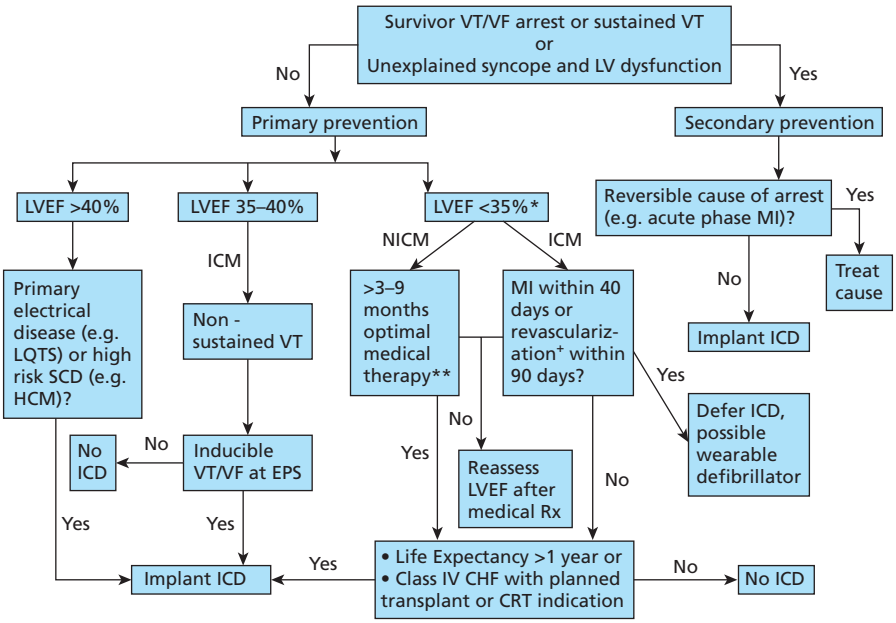


Figure 8.1 Flow chart summarizing indications for ICD implant. CHF, congestive heart failure; CRT, cardiac resynchronization therapy; EPS, electrophysiological study; HCM, hypertrophic cardiomyopathy; ICM, ischemic cardiomyopathy; LQTS, long QT syndrome; LVEF, left ventricular ejection fraction; MI, myocardial infarction; NICM, non-ischemic cardiomyopathy; Rx, therapy; VF, ventricular fibrillation; VT, ventricular tachycardia; *LVEF <35% with class II or III heart failure or <30% with class I heart failure; **period of 3–9 months on medical therapy after new diagnosis of NICM not part of scientific guidelines but required for reimbursement in the US; +, surgical or percutaneous procedures.

with ischemic cardiomyopathy and an abnormal signal-averaged electrocardiogram (SAECG) were randomized to receive an ICD or no antiarrhythmic treatment at the time of CABG surgery. No effect on mortality was observed with ICD use in this cohort.[17] The DINAMIT study evaluated patients with acute MI, left ventricular systolic dysfunction, and reduced heart rate variability (HRV). No mortality benefit was observed with ICD implantation.[18] The IRIS trial had a very similar design with similar outcomes.[19] The reasons for the failure of these studies to show a benefit of ICD therapy are unclear. The use of non-invasive risk stratifiers, such as signal-averaged ECG or heart rate variability, may be insufficient to identify a high-risk cohort. Also, the competing mortality risks early post-MI may offset any benefit of ICD therapy. This was suggested by a subsequent analysis of DINAMIT showing that increased non-arrhythmic death offset the benefit of a reduction of arrhythmic death in the ICD arm.[20] However, these studies have clearly demonstrated that clinical trials and not "common sense" need to guide the decision to implant devices. Table 8.2 summarizes the major ICD trials for primary prevention of SCD.

One major challenge today is to develop better methods to risk stratify patients for SCD, allowing clinicians to implant devices only in those patients who will be likely to use them appropriately. The major trials for primary prevention mentioned above have shown that only approximately one-third of patients who receive ICDs for primary prevention will receive an appropriate shock for a ventricular tachyarrhythmia over 4–5 years. The results of retrospective analyses of clinical predictors of ICD shocks or mortality generally show that the incidence of shocks or mortality increases with the severity of heart failure, the lower the ejection fraction, QRS prolongation, atrial fibrillation, renal failure, and age. Clinical scores were developed to

Table 8.2 Selected ICD trials for primary prevention of sudden cardiac death (SCD)[5–11]

Trial	*No. of patients*	*Etiology*	*Major inclusion criteria*	*Hazard ratio for overall mortality (ICD)*	*P value*
MADIT	196	ICM	EF ≤35%, NSVT, inducible VT	0.46	0.009
MUSTT*	704	ICM	EF ≤40%, NSVT, inducible VT	0.45*	<0.001
MADIT II	1232	ICM	EF ≤30%, prior MI	0.69	0.016
SCD-HeFT	2521	ICM and NICM	EF ≤35%, CHF NYHA class II or III	0.77	0.007
DEFINITE	458	NICM	EF ≤35%, PVCs or NSVT	0.65	0.08
COMPANION†	1520	ICM and NICM	EF ≤35%, CHF NYHA class II or III, QRS >120	0.64†	0.003
DINAMIT	676	ICM	EF ≤35%, HRV, recent MI (<40 days)	1.08	0.66
CABG Patch	900	ICM	EF ≤35%, CABG, abnormal SAECG	1.07	0.64

*The MUSTT results listed are the adjusted relative risk for overall mortality for patients receiving electrophysiologically-guided therapy with an ICD compared with no antiarrhythmic therapy.

†The COMPANION results listed are for CRT + ICD versus medical therapy alone. The hazard ratio for overall mortality for CRT alone versus medical therapy was 0.76 ($P = 0.059$).

CABG Patch, Coronary Artery Bypass Graft Patch; CHF, congestive heart failure; COMPANION, Comparison of Medical Therapy, Pacing, and Defibrillation in Heart Failure Trial; DEFINITE, Defibrillators in Non-Ischemic Cardiomyopathy Treatment Evaluation; DINAMIT, Defibrillator in Acute Myocardial Infarction Trial; EF, ejection fraction; HRV, heart rate variability; ICM, ischemic cardiomyopathy; MADIT, Multicenter Automatic Defibrillator Implantation Trial; MI, myocardial infarction; NICM, non-ischemic cardiomyopathy; MUSTT, Multicenter Unsustained Tachycardia Trial; NSVT, non-sustained VT; NYHA, New York Heart Association; PVC, premature ventricular contraction; SAECG, signal-averaged ECG; SCD-HeFT, Sudden Cardiac Death in Heart Failure Trial; VT, ventricular tachycardia.

help identify subgroups of patients most likely and least likely to benefit from ICDs for primary prevention of SCD.[21] In contrast to clinical factors, markers of arrhythmia vulnerability such as T wave alternans have been less useful for risk stratification of subjects in randomized trials.[22]

Finally, perhaps the most important dilemma with regard to prevention of SCD and prophylactic use of ICDs is the fact that most of the SCD victims do not meet current indications for ICD implantation. Population-based studies from both Maastricht, the Netherlands, and Oregon have shown that about one-half of SCD victims had an LVEF of greater than 50% prior to their event, and only 20–30% of these patients had severe left ventricular dysfunction that warranted ICD implantation according to current guidelines.[23,24] In order to make an impact on the absolute number of sudden deaths per year, further studies are needed to identify those patients who are at high risk for SCD, but do not have advanced structural heart disease.

Fibrillation and defibrillation

Effect of shocks

An electrical stimulus interacts with cardiac cells via its resultant electrical field, which is proportional to the local rate of change of the applied voltage with respect to distance (spatial derivative). The cardiac response to the shock is determined by the passive and active (ion channel) properties of cell membranes, properties of electrical connections between cells, and possibly by direct effects on intracellular events such as calcium release.

The electrophysiological requirement for defibrillation may be contrasted with the requirement for pacing. Pacemakers deliver a stimulus through closely-spaced electrodes sufficient to depolarize local myocardium during diastole (phase 4 of the action potential) and initiate self-propagating depolarization. In contrast, initiation and termination of VF by shocks requires an electrophysiological effect throughout both ventricles during the plateau or repolarization phases of the action potential

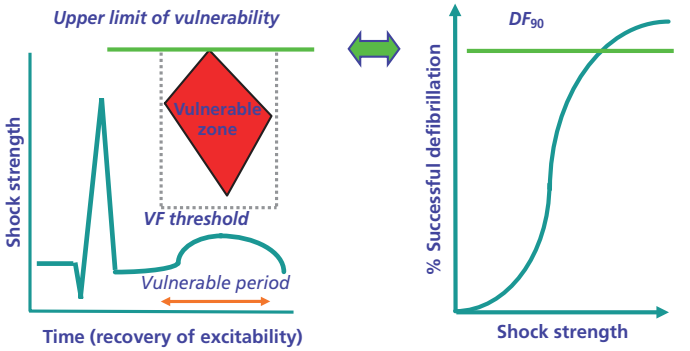


Figure 8.2 The cardiac vulnerable zone is the range of shock strengths and coupling intervals after the R wave or pacing pulse that induces VF. Left: The vulnerable zone is shown as a rhomboid-shaped region in a two-dimensional space defined by time (coupling interval) on the abscissa and shock strength on the ordinate. The upper border (upper limit of vulnerability, ULV; green solid line) and the lower borders [ventricular fibrillation (VF) threshold; dotted horizontal line] are defined by shock strength. Note that the ULV will be identified accurately only if a shock times at the most vulnerable interval corresponding to the peak of the vulnerable zone. Because this interval cannot be determined from first principles, clinical vulnerability testing requires a scan of several shocks timed at intervals close to the peak of the T wave. The inner (left) and outer (right) borders, denoted by dotted vertical lines, are defined by time (coupling interval). The interval during which shocks induce VF is the vulnerable period. Right: An idealized defibrillation probability-of-success curve. The ULV closely approximates the shock strength that defibrillates with a probability of 90% (DF_{90}).

(phases 2 and 3, respectively). Shocks may have both direct effects related to the strength of the local electrical field and indirect effects related to the creation of *virtual electrodes*, secondary sources of electrical potential in tissue sites remote from the stimulating electrodes.[25]

Vulnerable zone for shock-induced ventricular fibrillation and the upper limit of vulnerability

In organized rhythm, the *vulnerable period* is that portion of the relative refractory period of the cardiac cycle during which shocks induce ventricular fibrillation (VF). Shocks in the vulnerable period induce VF only if their strength is in an intermediate range, at or above the VF threshold and less than a limiting shock strength referred to as the *upper limit of vulnerability* (ULV). Clinically, the ULV is the weakest shock strength at or above which VF is not induced when the shock is delivered in the most vulnerable interval. The combination of shock coupling intervals (relative to the R wave or pacing stimulus) and shock strengths that induce VF in a regular rhythm define the *vulnerable zone*. It is displayed as a bounded, homogeneous, spatiotemporal region in a two-dimensional display defined by time (coupling interval) on the abscissa and shock strength on the ordinate (Figure 8.2, left panel).[26–29]

The leading hypothesis for the mechanism by which shocks induce VF is shock-induced formation of a "critical point' around which re-entry occurs. Two types of critical points have been described. Winfree used topological principles to predict that shocks initiate VF through the spatiotemporal co-incidence of critical values of local electrical field strength and refractoriness forming a "critical point" around which unidirectional block and re-entry occur.[27] Subsequently, Efimov *et al.* used optical mapping to identify "phase singularities" caused by shock-induced virtual electrodes that result in adjacent regions of depolarization and hyperpolarization, around which re-entry occurs.[25] An alternative hypothesis postulates that shocks trigger VF by initiating delayed afterdepolarizations (DADs).[30]

Fibrillation

The dominant mechanism of VF is re-entry. The traditional theory of re-entry is based on slow conduction in relatively refractory myocardium and conduction block. It conceptualized VF as

meandering wavefronts of activation following varying paths determined by changing locations of refractoriness and conduction block. Newer studies emphasize the importance of wavefront splitting ("wave break") caused by dynamic properties of conduction and restitution, and generation of new wavefronts when the leading edge of one wavefront interacts with the trailing edge of another.[31] Some studies have identified approximately repeatable activation fronts over a short period of time, which could be explained by either anchoring of a meandering wavefront or a stable "mother rotor" splitting into multiple daughter wavefronts.[32] The distinction is potentially important, since the "mother rotor" hypothesis implies that successful electrical therapy need only terminate this source rotor. However, present evidence favors a model of VF involving independent wavefronts rather than a mother rotor, and defibrillation therapy focuses on this model.

ICD pulse generators

ICD pulse generators (Figure 8.3) include a clear plastic header, to which the leads are attached, and a titanium casing or "can" that houses the electronic components. These include the battery; "hybrid" circuit board; telemetry communication coil; and high-voltage components, including the transformer, capacitor, and output circuitry.

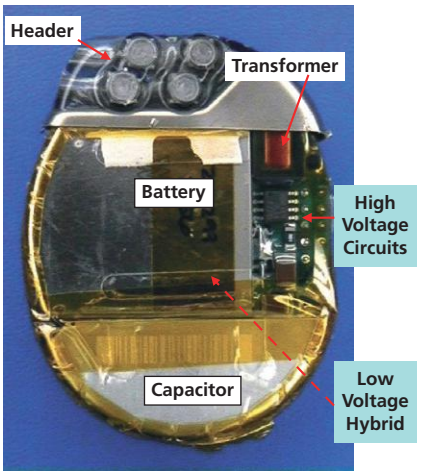


Figure 8.3 ICD generator with housing removed. See text for details.

Present transvenous ICDs package these components into a can with a volume in the range of 30–35 cm^3.[33]

The hybrid board consists of electronic circuits and components embedded in a silicon wafer, including the microprocessor ("mini-computer"), which has two main functions: (1) it processes incoming electrical signals, either transmitted commands sent from the programmer and received by the telemetry circuitry or cardiac signals transmitted via the leads, after these signals are filtered and amplified; and (2) it stores device diagnostics and EGMs, which can be downloaded to the programmer or remote-monitoring base station.

We provide brief discussions of batteries, high-voltage capacitors, high-voltage circuitry, and defibrillation waveforms.

Batteries

At implant, the battery's electrochemical potential represents the total energy available to the ICD over its service life for all monitoring, processing, and therapeutic functions. Unlike pacemaker batteries, ICD batteries must be able to deliver high current (up to 3 A) and high power (up to 10 W) for several seconds to charge the high-voltage capacitors; in addition, they must be able to deliver high current consistently over the battery's service life. Like pacemaker batteries, performance over time must be predictable to provide an elective replacement indicator.

Most ICD batteries consist of lithium anodes and silver–vanadium oxide ($Ag_2V_4O_{11}$) cathodes, often abbreviated as Li–SVO. This chemistry can deliver high current and has the advantages of using measured voltage as an indicator of battery status. Unlike the iodide cathode in lithium iodide batteries used in pacemakers, the SVO cathode is reduced in multiple steps (Figure 8.4). The first corresponds to the reduction reactions $V^{+5} + e^- \rightarrow V^{+4}$ and $Ag^{+1} + e^- \rightarrow Ag^{+0}$. It results in a progressive decrease in cell open-circuit voltage from the initial value of about 3.2 V to about 2.6–2.7 V. Providing there is enough lithium anode, a second reduction of SVO occurs corresponding to the reaction $V^{+4} + e^- \rightarrow V^{+3}$. This results in a long voltage plateau between 2.6–2.7 V and about 2.4 V, referred to as "middle of life" (MOL). Note that the cell voltage during charging

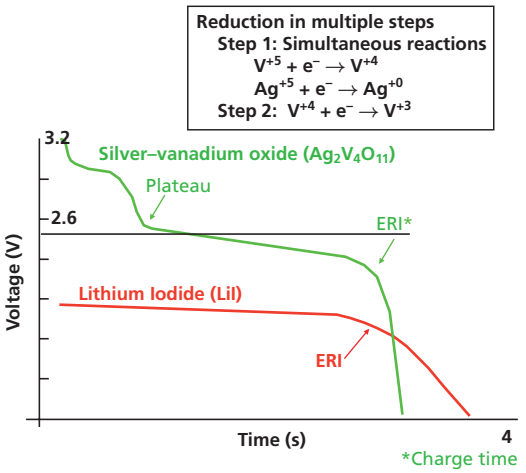


Figure 8.4 Idealized battery discharge curve of lithium–silver vanadium oxide (Li–SVO) cells used in early ICDs and, for comparison, lithium iodide cells used in pacemakers. The SVO cell has a voltage plateau at 2.6–2.7 V, corresponding to multiple reduction steps at the SVO cathode. The elective replacement indicator (ERI) voltage occurs at the end of the plateau. In comparison, the iodide pacemaker battery has a more constant voltage, corresponding to a single reduction step at the cathode.

(loaded voltage) is significantly less than the open circuit voltage.[34]

The first Li–SVO batteries had excess lithium in comparison with SVO. Most of these cathode-limited batteries were subject to build up of a high-resistance film coating on the lithium anode. The large internal voltage drop across this film increases the battery's internal resistance and transiently reduces its output (loaded) voltage (Figure 8.5). This problem is worst around the MOL plateau if the battery has not been pulsed recently by charging the high-voltage capacitor. High current pulses remove lithium from the film and make it thinner. All cathode-limited SVO cells exhibit substantial prolongation of charge time toward their elective replacement time.

Anode-limited Li–SVO batteries have less lithium and more SVO. There is only sufficient lithium to reduce SVO once. There batteries reach elective replacement time before MOL voltage delay occurs so that charge times remain short throughout their service life, without the need for frequent pulsing of the battery. The trade-off is that these "charge–time optimized" batteries have slightly lower energy density than cathode-limited batteries. Another solution to the problem of voltage delay is to use a secondary battery to maintain the voltage on a cathode-limited Li–SVO battery when necessary. The secondary battery uses a lithium anode with a carbon monofluoride (CFx) cathode.

An alternative battery design uses a lithium anode with a manganese dioxide cathode ($LiMnO_2$). This design is not subject to voltage delay and thus provides stable charge times up to elective replacement time without battery pulsing. Because the open cell voltage remains nearly constant until elective replacement time, it cannot be used to monitor battery status (Figure 8.6). Instead, elective replacement time is based on a measure of total charge delivered over the service life.

The high-voltage capacitor

A capacitor consists of two conductors, separated by an insulator (dielectric; Figure 8.7). Capacitors serve three functions: (1) store electrical charge on the surface of the conductors; (2) determine the duration required to deliver the defibrillation shock waveform; and (3) store electrical energy in the field between the two conductors.

When a parallel plate capacitor (Figure 8.7) is charged, the conductor at higher potential receives a charge Q, and the conductor at lower potential receives an equal and opposite charge so the net charge on the capacitor is zero. Capacitance (C) is the capability to store charge as a function of voltage. It is defined as the ratio of the charge on either conductor to the potential difference (V) between them:

$$C = \frac{Q}{V} = \frac{k\varepsilon_0 A}{d}$$

The right side of the equation indicates that capacitance is directly proportional to the surface area of each conductor (A) and inversely proportional to the distance (d) separating them. It is also directly proportional to the effectiveness of the dielectric in the space separating them, as measured by the dielectric constant (k). The final term in the equation (ε_0) is a fundamental physical constant that defines the ability of a vacuum to store

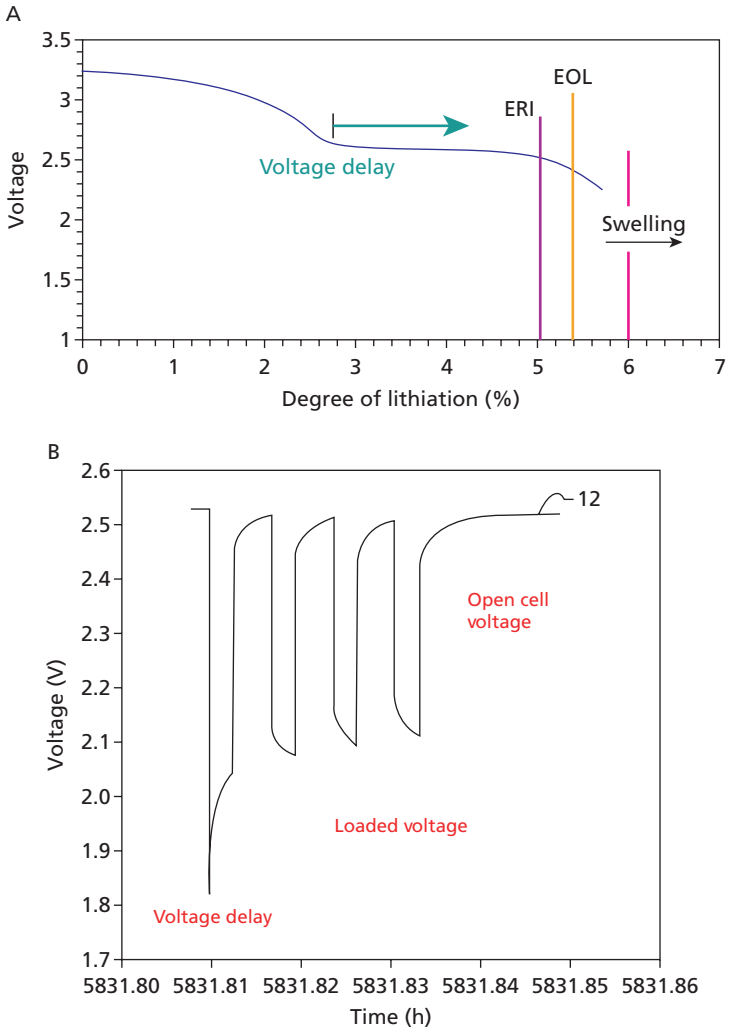


Figure 8.5 (A) Voltage delay in a lithium–silver vanadium oxide (Li–SVO) cell in the middle of its life. EOL, end of life; ERI, elective replacement indicator. (B) If the cell has not been recently discharged, loaded voltage can fall to values close to the approximately 1.5 V necessary to operate ICD circuitry reliably. Repeated discharge results in less drop from open to loaded cell voltages.

energy in an electric field, known as the electrical permittivity of free space. Thus, capacitance is maximized by a design in which conductors with large surface area are separated by thin but highly effective dielectric insulators.

The rate at which the capacitor is discharged determines the duration of the defibrillation waveform. When a capacitor charged to a voltage V is discharged, the voltage decays exponentially as a function of time:

$$V(t) = e^{-t/\tau s}$$

where t is the time since the start of the discharge and τ_s is the shock system time constant, the time for voltage to decrease to $1 - e^{-1}$ (about 37% of the initial value). Since $\tau_s = RC$ (where R is the pathway resistance), voltage as a function of time is given by:

$$V(t) = e^{-t/RC}$$

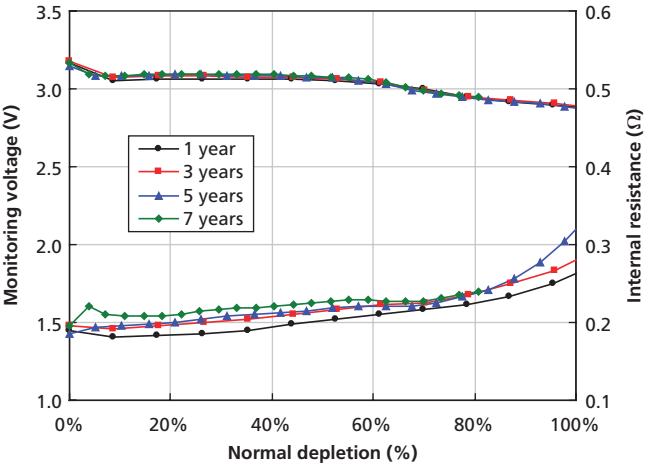


Figure 8.6 Discharge curve of a lithium–manganese dioxide battery. The battery voltage is nearly constant during discharge, independent of the time period over which the discharge occurs. Internal resistance remains low until the battery is 80% discharged, resulting in nearly constant charge times. A "charge meter" is used to determine the elective replacement indicator because voltage does not decrease significantly. This chemistry is not subject to the voltage delay that occurs with silver vanadium oxide cells. (Source: Boston Scientific Corporation. Reproduced with permission of Boston Scientific.)

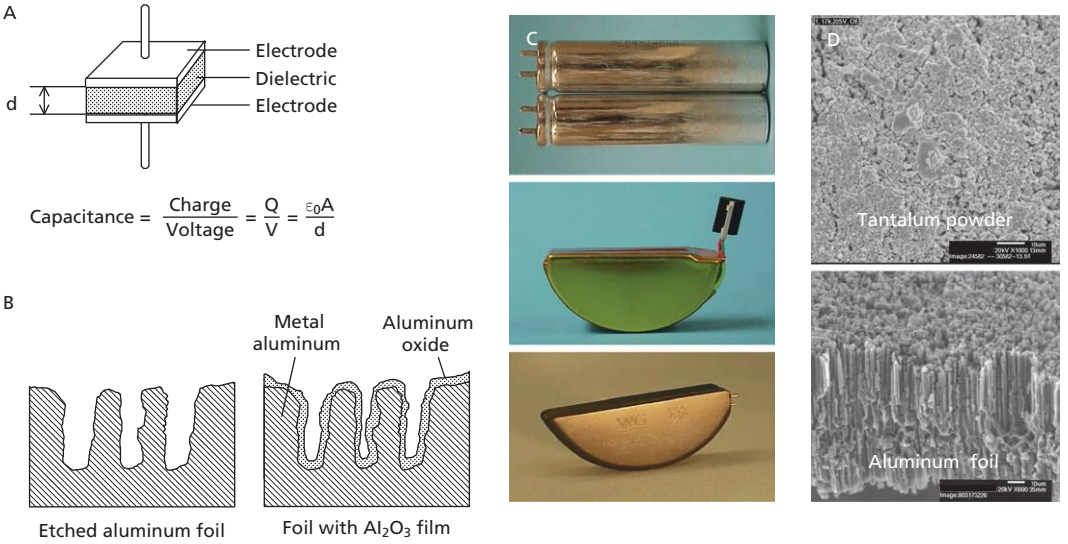


Figure 8.7 (A) A flat plate capacitor. The formula for capacitance indicates that stored charge is proportional to electrode area. (B) An aluminum foil electrolytic capacitor. (C) Evolution of capacitor technology. From top to bottom: photoflash aluminum foil electrolytic capacitors used in early ICDs, flat aluminum foil electrolytic capacitors developed for smaller size and contoured shape, and wet-tantalum electrolytic capacitor with higher energy density. (D) Scanning electron micrographs of tantalum powder and etched aluminum foil showing large surface area for storing charge.

Voltage approaches zero asymptotically, slower for a large capacitance and high-resistance defibrillation pathway and faster for a small capacitance and low-resistance pathway.

The energy stored in a capacitor (E_{std}) is given by:

$$E_{std} = \frac{1}{2}CV^2$$

This equation links stored energy—the key determinant of ICD size—to the voltage stored on the capacitor, which—except for minor voltage loss in the output circuit—is equal to the initial shock waveform voltage (V_i). "Delivered energy (E_{del})," has no direct influence on either defibrillation or ICD design. It is calculated most simply by subtracting the final (residual) energy stored in the capacitor at the end of the waveform from the initial stored energy:

$$E_{del} = \frac{1}{2}CV_i^2 - \frac{1}{2}CV_f^2$$

where V_f is the "final" or trailing edge voltage (Figure 8.8).

ICD capacitors have an energy density that ranges from 3 J/cm^3 for aluminum capacitors to 5 J/cm^3 for tantalum capacitors. Higher energy density reduces pulse generator size. For example, to store 40 J of energy requires minimum component volumes (without housing) of about 13 cm^3 for aluminum capacitors and 8 cm^3 for tantalum capacitors. In comparison, batteries have an energy density of over 3000 J/cm^3, hundreds of times greater. However, capacitors need only to store energy for one shock, while batteries must store all the energy used by all ICD functions over their service life.

ICD high-voltage capacitors are electrolytic capacitors, most often using aluminum or tantalum anodes (positive electrodes) and electrolyte solutions for the cathode. The anodes are processed to achieve a large surface area, increasing capacitance. For aluminum capacitors, the anode starts as a thin foil that has been etched to create a large number of tunnels (Figure 8.7). Tantalum capacitors use an anode made from tantalum metal powder pressed into a porous pellet and heated until the metal particles bond to each other (sintered), but still remain porous. For either material, a dielectric oxide film is grown (formed) electrochemically on the surface of the anode. Although tantalum capacitors have higher energy density than aluminum capacitors, they are also denser and cannot be charged to as high a voltage. ICDs use

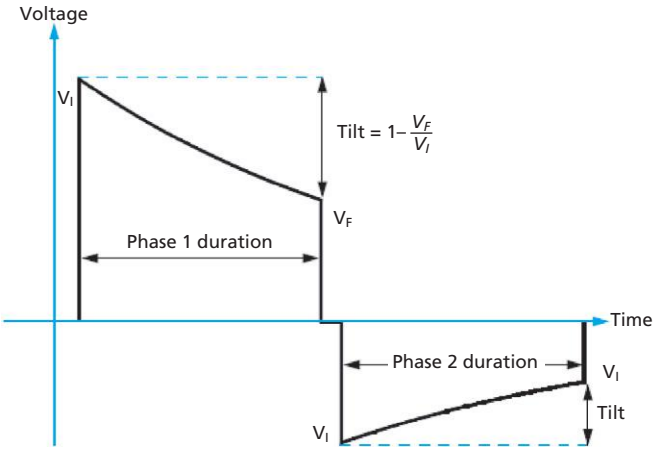


Figure 8.8 Biphasic defibrillation waveform plot of voltage as a function of time. A monophasic waveform is equivalent to phase 1 of the biphasic waveform. This waveform has phases of equal duration, each with a 50% tilt. In general, the duration of phase 2 should be equal to or less than the duration of phase 1 for the range of capacitances used in ICD generators and the range of resistances encountered in defibrillation pathways. See text for details.

either two aluminum or three to four tantalum capacitors in series to achieve leading edge shock voltages of 750–900 V.

If aluminum capacitors are not charged periodically, microscopic imperfections develop in the dielectric oxide film, and the dielectric begins to "leak," permitting current to flow through these imperfections during capacitor charging. As a result, charging is less efficient and the charge time increases 20–50%. Note that mid-life voltage delay in Li–SVO batteries also results in increased charge times, and delays in excess of 50% usually are due to battery voltage delay. Deformation is less of an issue for tantalum capacitors than aluminum ones.[35]

When the capacitor is charged after prolonged disuse, the strong electrical field created by charging regrows the dielectric layer, sealing the leaks and restoring charge time. Regrowth is fastest where the dielectric is thinnest (at the leaks). The process by which charging the deformed capacitor to high voltage regrows the oxide dielectric layer is known as capacitor reformation. The rate at which the oxide layer regrows is proportional to field strength and duration,[35] with a time constant measured in minutes. For efficient reformation, the capacitor is discharged through a high resistance to maintain its charge for several minutes. Thus, therapeutic or aborted shocks do not efficiently reform capacitors because they charge the capacitor for only a few seconds.

Each capacitor reformation consumes 0.5–1% of battery life, so capacitors should not be reformed more frequently than required. Typically, capacitors need reforming at about 6-month intervals. To maintain short charge times, ICDs automatically reform the capacitor, typically at programmable intervals. Unlike battery voltage delay, the rate of capacitor deformation is independent of the age of the ICD, and thus capacitors do not need to be reformed more frequently as the ICD ages. However, the same charging process may be used to reform capacitors and reverse battery voltage delay.

ICD circuitry

The high-voltage charging circuit (Figure 8.9) converts the low-voltage output of the battery to the high-voltage output that charges the output capacitor for delivery of the shock. This circuit operates under daunting constraints: First, both the battery and shock are direct current (DC) elements, but the physics of transformers requires alternating current (AC), because only a changing electric field stores energy in the transformer's magnetic field. Second, the voltage step-up is huge, over two orders

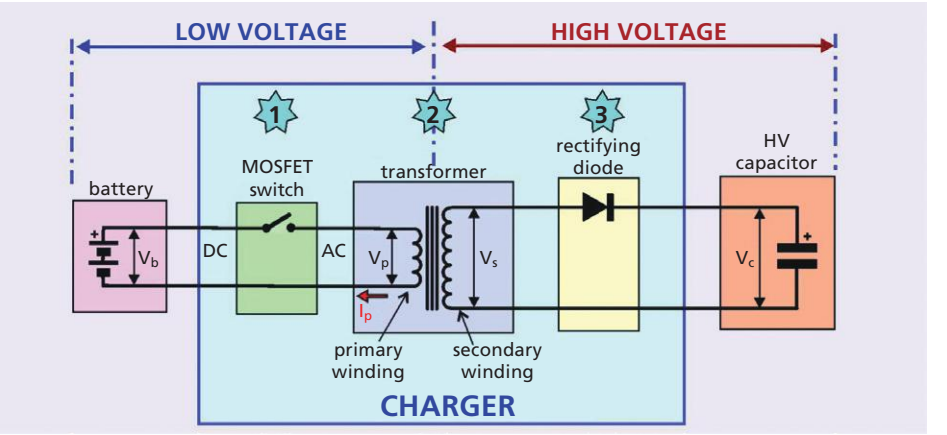


Figure 8.9 High-voltage (HV) charging circuit. See text for details. V_b, V_p, V_s, and V_c represent voltages across the battery, primary winding of the transformer, secondary winding of the transformer, and the capacitor. I_p denotes current in primary circuit. DC/AC, direct/alternating current. (Source: Stroobandt, Barold, Sinnaeve. *Implantable Cardioverter-Defibrillators Step by Step*, Oxford: Wiley-Blackwell, 2011. Reproduced with permission.)

of magnitude (from about 2 V in the loaded battery to over 800 V in the charged capacitor). Third, the circuit must be small, lightweight, and efficient. Fourth, it must not generate cross-talk in the ICD's highly-sensitive sensing circuitry.[5] The circuit should charge the capacitor as fast as possible so that a shock is not delayed after VF is detected. However, charging the high-voltage circuit places great current drain on the battery, which reduces the loaded battery voltage; voltages below about 1.5 V may result in failure of the ICD's control circuitry and inability to deliver a shock. The last problem is addressed by a compromise that reduces current drain and increases charge time to maintain a minimum voltage for other ICD circuits.

The ICD's "DC-to-DC" or "fly back" transformer generates AC by rapidly opening and closing a switch (typically with a frequency 30–100 kHz) in the circuit between the battery and the transformer. This is referred to as "chopping" the battery's output. The switch is kept open for about 10 μs, allowing charge to flow onto the primary winding and storing energy in the magnetic field of the transformer's ferromagnetic core. The speed of switching is dictated by the maximum magnetic field strength of the transformer coil, composed of a high-frequency magnetic iron ceramic that saturates at about 0.3 T.

The efficiency of charging circuits is in the range of 50%, so that storing 40 J of energy on the capacitor drains the battery of 80 J. Consider the required current and power: a typical battery consists of two cells in parallel, each with an open cell voltage of about 3 V and loaded cell voltage of about 2 V, so the terminal voltage during charging is about 4 V. If current flows from the battery at an average of 2 A, the power output is $2\,A \times 4\,V = 8\,W$ in the primary circuit. In 10 s, this permits 80 J to flow into the transformer's primary winding and 40 J to flow from the secondary winding into the capacitor.

The circuit through which the capacitor discharges the shock must tolerate both high voltages and high currents. For example, if an 800-V shock is delivered into a 40-Ω defibrillation pathway, the peak current is 20 A, in a range that trips household circuit breakers. Current flow in these circuits is regulated by switches that are both robust and respond rapidly during the shock. They are referred to as insulated gate bipolar transistors (IGBTs). These switches both reverse polarity after phase 1 of the biphasic waveform and truncate the waveform based on tilt or duration.

Because the risk of arcing or shorting increases non-linearly with voltage, high-voltage components in the can and header must be properly spaced and insulated from low-voltage components to prevent catastrophic electrical overstress failure due to high current flow in low resistance pathways. Some ICDs have operated these circuits near their tolerance level, and various forms of arcing from high-voltage circuits have been responsible for both isolated and systematic ICD failures.[36]

Lead abrasions in the pocket resulting in insulation defects between the active can electrode and high-voltage conductor of opposite polarity (to the right ventricular defibrillation coil) provide a particularly challenging problem. Consider an 800-V shock delivered into an insulation defect with an 8-Ω resistance. The resulting peak current is 100 A, more than enough to trip any household circuit breaker and cause catastrophic damage to the output circuit. To prevent such destructive peak currents, modern ICDs have a shorted high-output protection feature that aborts the shock if the peak current exceeds the performance rating of the output circuit. This prevents the shock from being delivered, but the assumption is that the shock would not reach the patient if the pathway resistance is too low.

ICD leads

Transvenous leads are the "weak link" in the ICD system. They are the most common component to fail and have been the subject of much controversy over the past decade.[37,38] Early ICD leads implanted before the mid 1990s had a co-axial design, similar to pacing leads. Typically, the tip conductor would be central with the ring conductor and then the defibrillation conductor more peripheral. Few remain in service. Modern ICD leads are multilumen, with conductors running in parallel through a single, flexible insulating lead body consisting of silicone, polyurethane, or fluoropolymers. The advantages of this design include greater space efficiency resulting in smaller leads, and greater

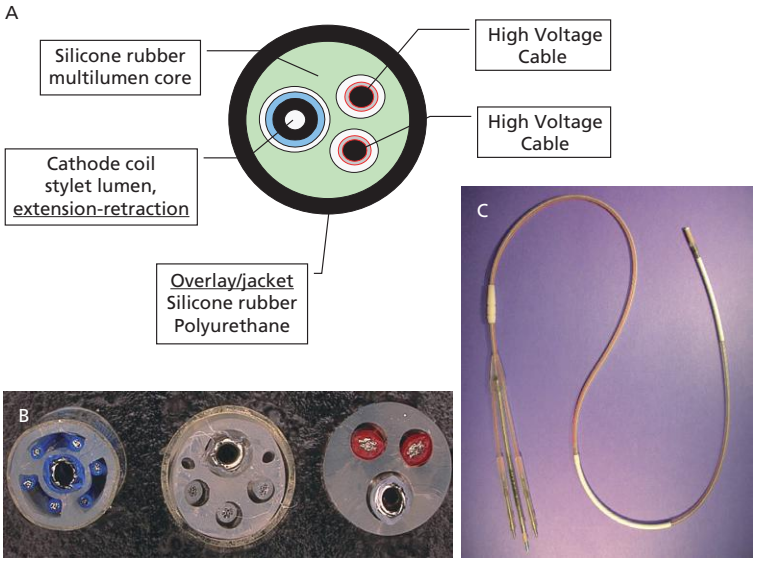


Figure 8.10 (A) Schematic cross-section of a modern dual-coil, integrated-bipolar ICD lead. (B) Cross-sections of (left to right) a dual-coil true bipolar lead with redundant cables (St. Jude Medical Durata™), a dual-coil true bipolar lead with single cables and strain relief lumens (Medtronic Quattro™), and a dual-coil, integrated bipolar lead (Boston Scientific Reliance G™). (C) Dual-coil, true bipolar ICD lead with older IS-1 style individual connectors for pace/sense bipole and each high-voltage electrode. (Source: Medtronic, Inc. Reproduced with permission of Medtronic, Inc.)

resistance to compressive forces by including extra lumens within the lead body. Figure 8.10 illustrates a schematic and diagram of a modern ICD lead design. A radiograph of a single-lead system, including a dual-coil integrated defibrillation lead and an active left pectoral pulse generator, is shown in Figure 8.11. The sensing electrodes of defibrillation leads can either be "true bipolar" or integrated bipolar (Figure 8.10). For true bipolar sensing, dedicated small surface area electrodes are used as the cathode or anode, similar to a pacing lead. For integrated or extended bipolar sensing, the distal RV defibrillation coil serves as the anode for sensing. This allows the lead design to have one less electrode, but it may be prone to oversensing of remote signals such as diaphragmatic myopotentials, particularly in older generation systems.

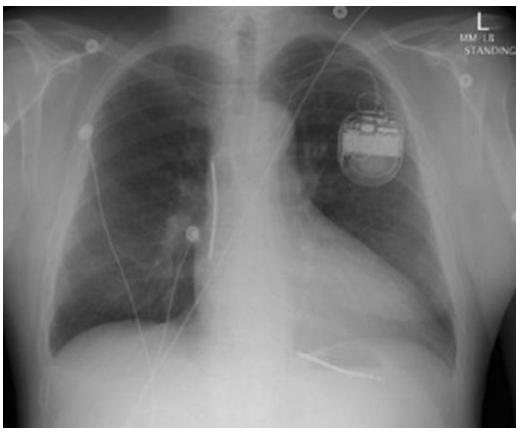


Figure 8.11 Radiograph of a single chamber ICD system. Note the left pectoral pulse generator and the integrated, dual-coil lead with the tip in the right ventricular apex.

Lead insulation can have an important impact on long-term stability and function. Silicone is inert, biostable, and biocompatible, but has a high co-efficient of friction. It is soft, making it prone to damage during implantation, and can swell over time. Polyurethane is biocompatible, and has a high tensile strength, making small lead diameters possible, and a low co-efficient of friction, but is prone to environmental stress cracking and metal ion oxidation, which cause insulation breaches and lead failure. Previous reports highlighted the high failure rate of polyurethane leads,[39]

particularly those with a co-axial design, so they are avoided given the superiority of alternative insulators. Fluoropolymers [e.g. polytetrafluoroethylene (PTFE) and ethylene-tetrafluoroethylene] are the most biocompatible materials and have high tensile strength, allowing small lead size, but are stiff and susceptible to damage from traction when the lead migrates; they are prone to insulation micro-defects, and have a difficult manufacturing process. Contemporary lead systems have an insulating body made of silicone, in some instances supplemented by an outside polyurethane layer to reduce friction, abrasion, and scar formation (and not for insulation). Metal ion oxidation is avoided as polyurethane is not in direct contact with the conductors. The conductors are often insulated with an extra thin layer of fluoropolymer. Coating of leads with expanded PTFE or backfilling shocking coils with medical adhesive has been shown to reduce tissue ingrowth into the lead coils and thereby make future extraction easier, if necessary.[40]

Defibrillation waveforms

The waveform of an electrical pulse is the temporal pattern of its amplitude, measured by voltage (or current). An ICD's shock waveform interacts with cardiac electrical activity via its electric field, which is the instantaneous spatial derivative of shock voltage. The response of the heart to the shock field is mediated by the passive and active (ionic channel) properties of cell membranes, properties of electrical connections between cardiac cells, and possibly the direct intracellular electrical effect.

The waveform parameters that most directly influence defibrillation are voltage and duration. Voltage is a critical parameter because its spatial derivative defines the electrical field that interacts with the heart. Similarly, waveform duration is critical because the shock interacts with the heart for the duration of the waveform. Further, the heart's response to a defibrillation shock occurs over a period that depends on time-dependent passive and active ion-channel processes of cardiac cell membranes, as well as time-dependent intracellular and tissue properties, collectively referred to as the time constant of cardiac tissue (τ_m, pronounced "tau" with the subscript "m" for cell membrane).[41–44] Thus, the electrical measure of defibrillation that is most relevant physiologically is voltage (or voltage gradient) as a function of time.

Shock energy is the most often cited metric of shock strength and an ICD's capacity to defibrillate, but it is not a direct measure of shock effectiveness. However, the maximum energy stored in an ICD's output capacitor is a major determinant of the size of the battery and capacitor, and thus the overall size of the pulse generator. Since minimizing pulse generator size is an important clinical goal, designing ICDs that defibrillate with minimum stored energy is an important engineering goal.

Schuder & Stoeckle first reported that transthoracic defibrillation was more effective when the waveform discharge was stopped (truncated) rather than being allowed to decay indefinitely (untruncated),[45] and most, but not all, studies of ICD waveforms support the benefit of truncation. A single capacitor can produce a biphasic waveform if the polarity of the output circuit is reversed after truncation, and this is the mechanism by which ICDs generate biphasic waveforms (Figure 8.8).

Truncation may be defined either by waveform duration or "tilt." Tilt is defined by the expression:

$$Tilt = 1 - \frac{V_F}{V_i}$$

where V_F is the final ("trailing edge") voltage and V_i is the initial ("leading edge") voltage (Figure 8.8). Consider a capacitive discharge waveform that is truncated after one time constant (τ_s) so that the final voltage is 37% of the leading edge voltage. This corresponds to a tilt of 63%. Historically, waveform truncation was first performed by tilt for engineering reasons. Commercial ICDs use either tilt or duration for truncation, depending on the manufacturer. Empirically, both approaches can produce efficient waveforms using the capacitors in current biphasic waveform ICDs with standard transvenous leads.[46]

Currently, no comprehensive theory permits design of ICD waveforms from first principles. However, a passive resistor–capacitor (RC) network model,[47] first developed in the 1930s and

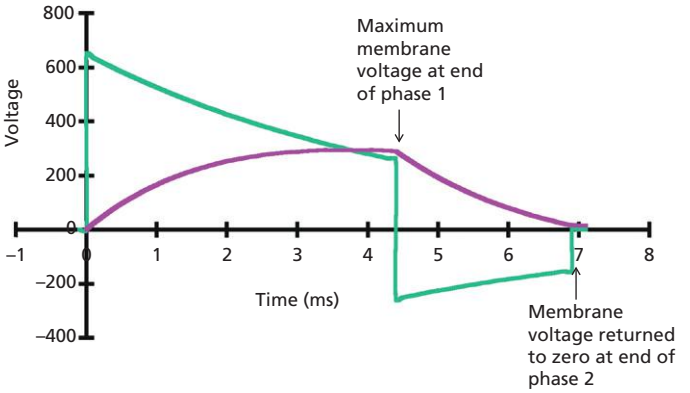


Figure 8.12 Biphasic waveform and predicted cell membrane responses. According to the membrane response model, the efficient biphasic waveform is truncated when the membrane voltage change that occurred during phase 1 has been reversed. (Source: Adapted from Kroll MW 1994.[42] Reproduced with permission of John Wiley & Sons Ltd.)

subsequently applied to modeling defibrillation waveforms, provides rough estimates that have been used clinically.[48] The model has two principal assumptions: (1) the goal of a monophasic shock and the first phase of a biphasic shock is to maximize the voltage change in the cardiac cell membrane at the end of the shock for a given stored energy—thus, its optimal duration relates to the membrane's time constant τ_m, and (2) the goal of the second phase is to discharge the membrane potential back to the zero potential, removing the charge deposited by the first phase,[6] sometimes referred to as "charge balancing" or "charge burping"[44,49] (Figure 8.12). It is remarkable that a model based on such a simplistic approximation can provide clinically useful guidance for optimizing defibrillation waveforms. One of its most important predictions relates to the strength–duration relationship for defibrillation.

The plot of defibrillation threshold (DFT; usually leading-edge voltage) as a function of waveform duration is known as the defibrillation strength–duration curve, analogous to the strength–duration curve for pacing. Since there is no true DFT, the plotted value may be considered as the shock strength required to achieve a given probability of defibrillation, such as 90%; but for simplicity we refer to it as the DFT. As shown in Figure 8.13, the effect on DFT of equivalent change in duration is much greater at short durations than long durations. The long-duration asymptote for DFT (the lowest value for an infinite pulse width) is referred to as the *rheobase*. The *chronaxie* is defined as the duration of a waveform that has a DFT of twice the rheobase amplitude. The chronaxie is close to the membrane time constant (τ_m).

For square waves, the RC model predicts that the waveform duration that minimizes stored energy has a duration equal to the chronaxie. For capacitive-discharge defibrillation waveforms, the pulse duration for minimum energy is a "compromise" between the optimal duration for response of the cell membrane (chronaxie or τ_m) and the optimal duration for the capacitor to deliver its charge (system time constant, $\tau_s = RC$), shorter for small capacitors and low-resistance pathways and higher for large capacitors and high-resistance pathways.[35]

The physics of capacitive-discharge waveforms links the energy stored in the ICD's capacitor to the voltage and duration of the delivered defibrillation waveform. Stored energy is proportional to capacitance and the square of voltage. Further, the time dependence of a capacitive-discharge exponential waveform is given by the system time constant τ_s, (which is the product of capacitance and pathway resistance). Thus, the shock output capacitance is a critical intermediary in establishing the relationship between stored energy—the key determinant of ICD size—and waveform voltage as a function of time, the key determinant of defibrillation efficacy.

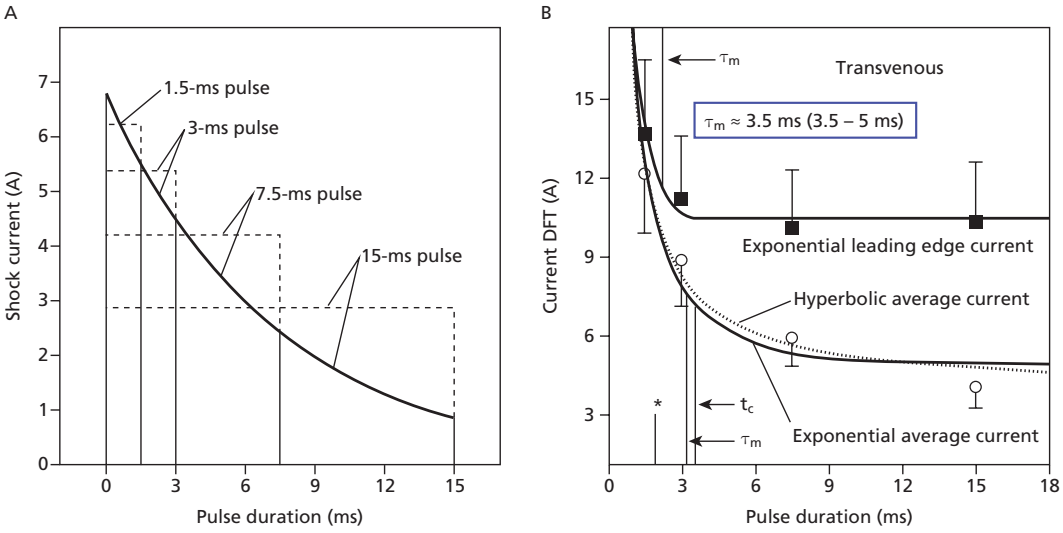


Figure 8.13 Strength–duration curve and estimation of cell membrane time constants for defibrillation. (A) Defibrillation thresholds (DFTs) were determined for monophasic waveforms truncated at four different durations: 1.5 ms, 3.0 ms, 7.5 ms, and 15 ms. The average current for each pulse is shown by the dotted lines. (B) Strength–duration curves. The mean $DF_{50} \pm SD$ is shown for average current (open circles) and leading-edge current (closed squares). The average current data are similar for both the hyperbolic and exponential curves. They diverge at very long and very short pulse durations beyond the range of this graph. The vertical lines denote model time constants: chronaxie (t_c) for the hyperbolic model, membrane time constants (τ_m) for the two exponential models, and exponential chronaxie (*). (Source: Swerdlow *et al*. 1997.[50] Reproduced with permission of Wolters Kluwer Health.)

The RC model also predicts that, for any given τ_m and pathway resistance, there is optimal capacitance that permits defibrillation with the lowest possible stored energy, provided duration is optimized for that capacitance. The predicted optimal duration for an optimal capacitance is equal to τ_m.[44,50] However, larger capacitors provide a greater safety margin for a fixed leading-edge voltage, and the stored-energy DFT penalty for greater than optimal capacitance is small for values less than about 150% of the predicted optimal value. Most ICD capacitors are in the range of 120–150% of predicted optimum, although a few have higher values.

Most estimates of defibrillation τ_m are in the range of 2.5–5 ms, an order of magnitude greater than the chronaxie for pacing. For $\tau_m = 3.5$ ms, predicted optimal capacitance is 87.5 μF. Commercial ICDs use output capacitors in the range of 105–150 μF, permitting efficient defibrillation with pulse durations of 3.5–6 ms for the first phase of biphasic waveforms. The DFT for biphasic waveforms is less sensitive to the duration of phase 2 than that of phase 1. For capacitance values in commercial ICDs, the duration of phase 2 should be at least 3 ms.

The virtual electrode hypothesis of defibrillation[51] predicts that post-shock virtual electrodes launch new wavefronts toward the anode. Thus, a cathodal shock produces "expanding" pro-arrhythmic wavefronts that propagate away from a physical RV cathode, but an anodal shock produces "collapsing," self-extinguishing wavefronts that propagate toward a physical RV anode.[52] Thus, a RV cathode produces expanding, pro-arrhythmic wavefronts, whereas a RV anode produces collapsing, self-extinguishing wavefronts. In experimental studies, the beneficial effects of anodal shocks are significant for monophasic waveforms and inefficient biphasic waveforms, but insignificant for the efficient biphasic waveforms used in commercial ICDs. A possible explanation for this difference is

that phase 2 of efficient biphasic waveforms results in "charge balancing" that discharges the virtual electrodes.

Sensing, detection, and arrhythmia discrimination

Rate sensing

Sensing of ventricular tachyarrhythmias is a critically important function of an ICD system. The ability to sense small-amplitude signals rapidly during VF, while not oversensing T waves or noise in the absence of tachyarrhythmias, is mandatory for proper ICD function. This goal was difficult to achieve with fixed gain sensing, as is used in pacemaker systems. All ICD pulse generators use automatic adjustment of sensing threshold to ensure appropriate detection of ventricular arrhythmias. Unlike pacemakers, ICDs increase the amplifier sensitivity over time between sensed or paced ventricular events to search for low-amplitude fibrillatory EGMs that may be missed at lower sensitivities, while retaining relatively insensitive settings shortly after the sensed ventricular EGM to prevent T wave oversensing (Figure 8.14).

Undersensing of VF was rarely noted with early epicardial or bipolar transvenous leads after automatic gain or sensitivity was employed. Data from large clinical trials of integrated transvenous leads have demonstrated excellent detection of VT and VF, indicating that clinically important undersensing is very rare.[53] As noted previously, both true bipolar sensing, with a dedicated tip and ring, and integrated sensing, where the distal coil is used for both sensing and shocks, are available in commercial devices. Typically, sensed R wave amplitude of greater than 5 mV in the baseline rhythm (i.e. sinus or atrial fibrillation) is sufficient to insure adequate sensing of VF. Uniformly excellent sensing of VF was recently shown in a comparative study of multiple transvenous and subcutaneous ICD pulse generators, using both dedicated bipolar and integrated leads.[54]

Although undersensing of ventricular tachyarrhythmias is very unusual with modern lead systems and pulse generators, oversensing of other biological signals is now more common. The maximum sensitivity of transvenous pulse generators is increased (up to 0.15 mV) with contemporary low-noise amplifiers and even lower for subcutaneous devices. At maximal sensitivity, myopotentials arising from the diaphragm or pectoral muscles can cause inappropriate ICD discharges. This problem is more likely to occur during periods of ventricular pacing, when the amplifier sensitivity is maximized, and with integrated bipolar ICD leads. Often, a history of coughing or straining preceding ICD discharges can be elicited from the patient, suggesting that myopotential oversensing is present. Such oversensing can be confirmed by monitoring ventricular EGMs during provocative maneuvers such as handgrip, Valsalva, or deep inspiration. Several strategies have been used to prevent further ICD oversensing, including decreasing the maximum sensitivity of the pulse generator, decreasing the bradycardia pacing rate, or increasing the atrioventricular (AV) delay to minimize ventricular pacing, prolonging the detection intervals to prevent shocks from transient oversensing, and implanting a separate rate-sensing lead in the RV outflow tract more distant from the

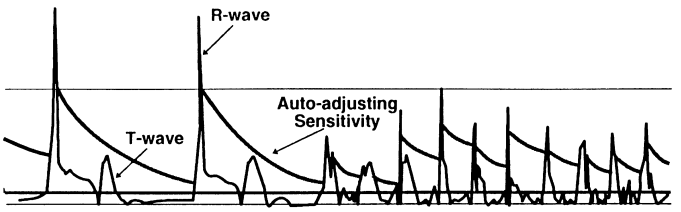


Figure 8.14 Schematic of automatic adjustment of sensitivity during sinus rhythm and ventricular fibrillation. In sinus rhythm, sensitivity increases slowly to avoid oversensing T waves. However, with the onset of ventricular fibrillation, high sensitivity is maintained to minimize undersensing. (Source: Medtronic, Inc. Reproduced with permission of Medtronic, Inc.)

diaphragmatic surface. Oversensing of T waves with double-counting is another problem observed more frequently with modern pulse generators because of increased maximum sensitivity and aggressive sensing algorithms. Again, this can often be avoided with device reprogramming, including reducing the maximum sensitivity, prolonging the refractory period, or reducing the aggressiveness of the autosensitivity algorithm.

Extensive data logging capabilities are present in pulse generators. All systems provide beat-to-beat interval data for detected tachyarrhythmias. This is helpful for identifying the arrhythmias associated with shocks. For example, very irregular intervals are suggestive of atrial fibrillation (AF), whereas the sudden onset of a regular tachycardia is indicative of either monomorphic VT or paroxysmal supraventricular tachycardia (SVT). A very rapid rhythm with non-physiological intervals (<130 ms) is indicative of a sensing malfunction, typically due to either a lead defect or a loose set-screw in the pulse generator header.

Stored EGMs can be used as a further diagnostic tool (Figure 8.15). This significantly improves the ability to interpret the appropriateness of defibrillation shocks.[55] The electrodes used to record the EGM may or may not be the same electrodes used for the detection of arrhythmias. "Near-field" EGMs are recordings of the local bipolar ventricular EGM, which is also used for arrhythmia detection. This can either be true bipolar sensing, with recording from the electrode tip to a more proximal ring, or extended bipolar sensing from the tip to a RV shocking coil. For "far-field" EGMs, recordings are made between shocking electrodes, which for a typical transvenous lead system includes a RV coil, a left pectoral active pulse generator, and often a more proximal coil in the right atrium or superior vena cava. Far-field recordings potentially allow for the identification of atrial activity to aid in arrhythmia classification. In addition, the change in morphology of ventricular arrhythmias is often more obvious in the far-field EGMs. The source of stored EGMs is important for interpreting arrhythmia episodes, particularly inappropriate therapy. For example, if the far-field EGM recorded from the shocking electrodes is being monitored, then this is not the same signal that is being sensed by the amplifier for the determination of tachyarrhythmias. Thus, if no tachycardia is noted at the time of therapy for a rapid rate, then oversensing of the rate-sensing lead

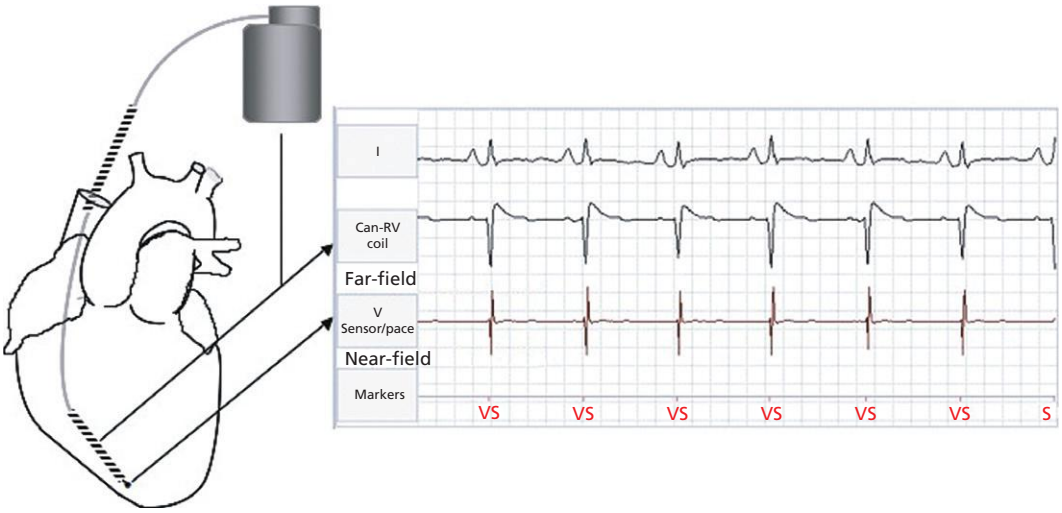


Figure 8.15 ICD electrograms. Near-field electrograms are true bipolar recordings between the tip and ring electrodes of the right ventricular (RV) lead. Far-field electrograms are recorded between the RV coil and the ICD can, which gives a more global representation of ventricular activity, not dissimilar from a precordial ECG lead. A surface ECG lead (top tracing) and a marker channel are also printed on this output, illustrating how the ICD interprets these signals. VS indicates sensed ventricular activity.

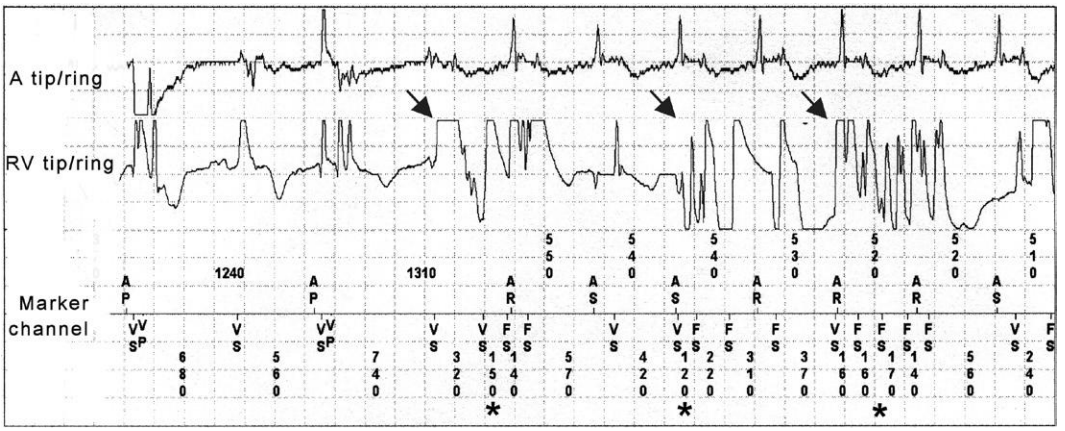


Figure 8.16 Stored electrograms from a dual chamber ICD with a fracture of the pace/sense component of the right ventricular ICD lead. Note the oversensing of non-physiological electrical activity on the near-field (RV tip-to-ring) electrogram (*). This was interpreted by the device as ventricular fibrillation, as highlighted on the marker channel, and a shock was delivered (not shown). Also note the make-or-break type pattern of the noise with intermittent saturation of the amplifier (arrows). The patient received multiple inappropriate shocks for this noise, necessitating a lead revision procedure. A tip–ring: near-field atrial channel; AP, atrial-paced event; AS, atrial-sensed event; FS, ventricular-sensed event in VF rate zone; RV tip–ring: near-field RV bipolar signal; VP: ventricular-paced event; VS, ventricular-sensed event.

can be deduced, but extraneous "noise" may not be demonstrated. Examples of stored EGMs with a lead malfunction are shown in Figure 8.16. With dual chamber ICDs, direct atrial recordings further simplify the interpretation of arrhythmias (Figure 8.17).

Arrhythmia detection

Arrhythmia detection requires effective sensing of the intrinsic cardiac activity and the fulfillment of the programmed detection algorithm. For VT, most ICDs require that a certain number of consecutive RR intervals be shorter than the tachycardia detection interval for the VT zone (Figure 8.18). Because the VF EGMs may transiently be very low in amplitude and undersensed, the VF detection algorithms require that a certain percentage (typically 75%) of RR intervals in a rolling window of cardiac cycles be shorter than the VF detection interval (see Figure 8.18). If the rate and duration criteria for detection of VF are met and shock therapy is programmed, the ICD charges the high-voltage capacitor, a process that typically takes 5–12 s. Before delivering the shock, the ICD confirms (re-confirms) that a tachyarrhythmia is still present by checking a few intervals after the charging has completed. If VT or VF is no longer present, the shock is aborted (Figure 8.19). After each delivered therapy, the ICD must determine whether the tachycardia was terminated. The re-detection criteria after therapies are usually somewhat less demanding than the initial detection criteria for each zone. The detection criteria in the VT zone may be modified by algorithms to prevent inappropriate therapy for SVTs. In fact, recent studies have shown that marked prolongation of detection times and rate cut-offs are associated with better outcomes with ICD systems and fewer delivered shocks.

SVT–VT discrimination

The SVT–VT discrimination algorithm is a programmable sub-algorithm of the detection process for VT/VF. It withholds therapy if SVT is diagnosed. This sub-algorithm is applied after a sequence of sensed events meets the rate and duration criteria for VT or VF, and—in some ICDs—after these sensed events are validated as representing true ventricular activations (versus



Figure 8.17 Dual chamber electrograms from a cardiac resynchronization ICD show polymorphic ventricular tachycardia (VT) with atrioventricular (AV) dissociation treated with shock. Atrial and high-voltage ("Shock") electrograms and the dual chamber marker channel are shown. The arrowhead denotes shock, designated by CD (charge delivered) on the marker channel. After the shock, the atrial rhythm is sinus with premature atrial contractions; the ventricular rhythm is biventricular paced (BV) with premature ventricular contractions (PVCs) in the sinus rate zone (VS). The second BV beat (BV/VS) has a slightly shorter paced AV delay (110 vs. 130 ms) than the first BV beat because a PVC occurs during the AV delay, triggering "safety pacing," a feature that reduces cross-talk inhibition. (Source: Swerdlow CD, Hayes DL, Zipes DP. Cardiac pacemakers and cardioverter-defibrillators. In *Braunwald's Heart Disease: A Textbook of Cardiovascular Medicine*, 9th Edition, Bonow RO, Libby P, Mann DL, Zipes DP and Braunwald E, eds. Philadelphia: Elsevier Saunders, 2013. Reproduced with permission of Elsevier.)

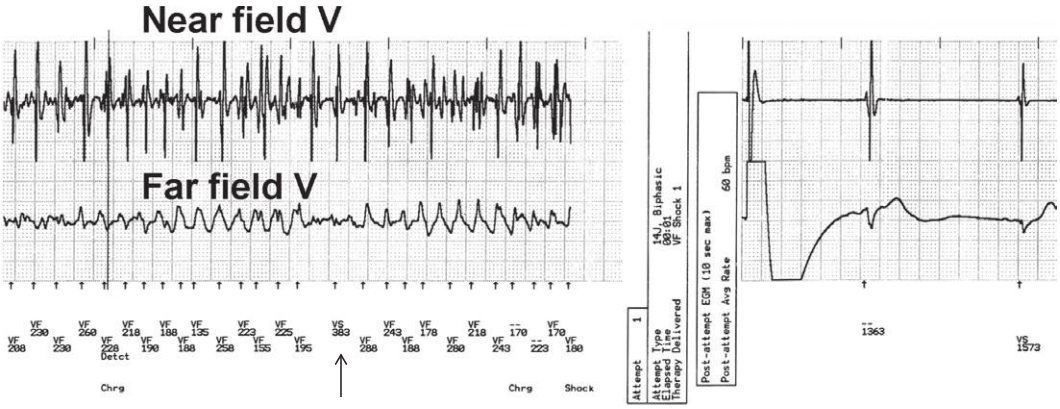


Figure 8.18 Detection of ventricular fibrillation (VF) with undersensing. Near-field and far-field electrograms and ventricular marker channel during induced VF. "VF" and "VS" markers indicate intervals sensed in the VF and sinus rate zones, respectively. VF is detected, and the ICD charges (Chrg) and delivers a shock at the break between the VF and baseline rhythm (shown on the right), despite the fact that not all intervals are classified as VF (arrow). Rapidly varying amplitude on near-field electrograms can contribute to undersensing, but does not contribute in this episode.

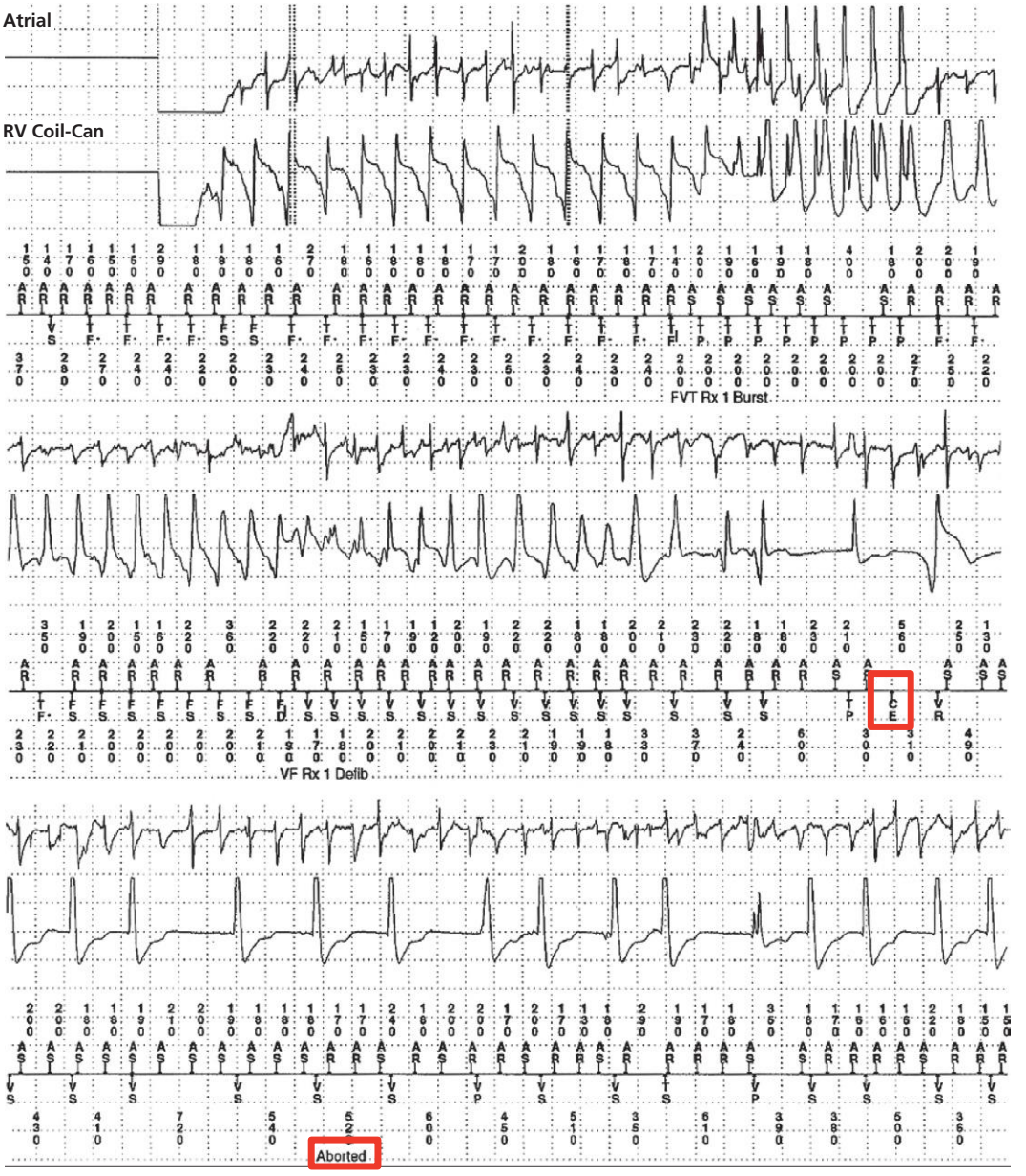


Figure 8.19 Aborted shock for ventricular tachycardia (VT) that terminates after capacitor charging. Continuous tracing of atrial and high-voltage (RV Coil–Can) electrograms and dual chamber markers during an episode detected as fast VT (FVT; cycle length 200–250 ms) during ongoing atrial fibrillation (AF). Atrial markers indicate that the atrial rhythm is AF. Antitachycardia pacing is delivered at the end of the top panel (FVT Rx 1 Burst, TP markers). After antitachycardia pacing, the rhythm accelerates and becomes polymorphic. It is redetected as VF, and the high-voltage capacitor begins to charge (VF Rx 1 defib). Capacitor charging is complete near the end of the middle panel, as indicated by the CE marker in the red rectangle ("charge end"). After a sufficient number of intervals, the shock is aborted in the bottom panel (red rectangle). Antitachycardia pacing (ATP) accelerated the rhythm to VF, which then terminated. This would be classified as successful, but it is not known if the VT would have terminated spontaneously without ATP. (Source: Swerdlow CD, Hayes DL, Zipes DP. Cardiac pacemakers and cardioverter-defibrillators. In *Braunwald's Heart Disease: A Textbook of Cardiovascular Medicine*, 9th Edition, Bonow RO, Libby P, Mann DL, Zipes DP and Braunwald E, eds. Philadelphia: Elsevier Saunders, 2013. Reproduced with permission of Elsevier.)

oversensing). They apply over a range of cycle lengths bounded on the slow end by the VT detection interval and on the fast end by a specific parameter, the SVT limit.

SVT–VT discrimination algorithms operate in a stepwise manner, using a series of logical discriminator "building blocks" (Table 8.3) based on the timing relationships of sensed events and morphology of sensed ventricular EGMs. Algorithms combine complementary discriminators to make a final rhythm classification of VT or SVT. Each discriminator building block has advantages and limitations. Some are redundant and some interact differently depending on the order in which they are applied. We focus on how they are assembled into a comprehensive algorithm rather than on the specifics of implementation in each commercial ICD.

Blocks 1–4 in Table 8.3 apply to single-chamber ICDs or the ventricular component of dual chamber ICDs. Blocks 5–9 combine atrial and ventricular information in dual chamber algorithms. Block 10 incorporates atrial rate into dual chamber algorithms. In contrast to the passive discriminators in blocks 1–10, block 12 is an active discriminator based on response to pacing.

Single chamber ventricular building blocks

Ventricular electrogram morphology

The ventricular EGM morphology discriminator classifies tachycardia as SVT if morphological characteristics of the EGM are similar to those of validated supraventricular beats and as VT if they are not. It is the only single chamber building block that can classify all SVTs correctly, including sudden-onset regular SVT with a 1:1 AV relationship or atrial flutter. Thus, it is the cornerstone of modern single chamber algorithms and the central single chamber component of dual chamber algorithms. It is also the most complex building block.

Common features All morphology discriminators designed for SVT–VT discrimination share common steps (Figure 8.20):

1 Record a template EGM of baseline rhythm.
2 Construct and store a quantitative representation of this template.
3 Record EGMs from an unknown tachycardia.
4 Time-align the template and tachycardia EGMs.
5 Construct a quantitative, normalized representation of each tachycardia EGM.
6 Compare the representation of each tachycardia EGM with that of the template to determine its degree of morphological similarity.
7 Classify each tachycardia EGM as a morphology match or non-match with the template.
8 Classify the tachycardia as VT or SVT based on the fraction of EGMs that match the template.
Steps 3 through 8 are performed in real time.

Morphology discriminators differ according to EGM source, methods of filtering and alignment, and details of quantitative representations. Figure 8.21 provides an example of one such discriminator. The source EGM should be recorded from widely-spaced electrodes, such as the high-voltage electrodes of transvenous ICDs or the sensing electrodes of subcutaneous ICDs (S-ICDs).[56] All contemporary ICDs apply the morphology discriminator to EGMs recorded from widely-spaced electrodes. However, until recently St. Jude Medical ICDs analyzed morphology from the closely-spaced sensing bipoles. EGMs should be aligned using a robust method that is insensitive to minor changes in EGM morphology. Often, the EGM peak is used as a fiducial point. Alignment errors often result in complete failure of template matching. If a tachycardia EGM that is visually indistinguishable from the template has a match score of 0%, an alignment error has occurred.

Limitations of morphology discriminators Morphology discriminators share common failure modes that are summarized in Table 8.4 and illustrated in Figure 8.22.

- *Inaccurate template.* The template may be inaccurate because the baseline EGM has changed (e.g. post-implantation lead maturation, new bundle branch block) or because the template was recorded during intermittent bundle branch block or from an abnormal rhythm (e.g. idioventricular or bigeminal premature ventricular contractions).
- *Electrogram truncation.* EGM truncation ("clipping") occurs when the recorded EGM signal amplitude exceeds the range of the EGM amplifier, often due to postural changes. The maximum absolute peak of the EGM is clipped, removing EGM features for analysis and altering

Table 8.3 Discriminator building blocks for supraventriculat tachtcardia–VT discrimination algorithms

Building block	*Purpose*	*Limitation*	*Role in dual-chamber algorithms*	
			V = A (rate)	*V < A (rate)*
Ventricular (single or dual chamber ICDs)				
1 VV regularity (stability)	Discriminates monomorphic VT (regular) from conducted AF (irregular)	Unreliable at ventricular rates of >170 bpm; under-detection of irregular VT		+
2 VV sudden onset	Discriminates abrupt onset of VT from gradual acceleration of sinus tachycardia	Detects abrupt onset of SVTs; misclassifies VT that starts in sinus zone and accelerates gradually into VT zone or starts in VT zone	+	
3 Ventricular EGM morphology	Discriminates VT based on EGM morphology change vs. baseline	Confounded by aberrant conduction; multiple technical issues Cannot be used in redetection	+	+
4 Ventricular EGM width	Discriminates VT based on EGM width change vs. baseline	Measured EGM width may not be reproducible; patients with bundle branch block may not have width increase in VT	+	+
Atrioventricular (single or dual chamber ICDs)				
5 Comparison of atrial vs. ventricular rate	VT diagnosed if A rate < V rate; cornerstone of dual chamber algorithms	Confounded by atrial under-sensing or far-field R wave over-sensing	+	+
6 AV dissociation	AV dissociation usually indicates VT	VT with 1:1 retrograde conduction; rapidly-conducted AF		+
7 Pattern of A/V events	Discriminates VT based on pattern of AV events	Unreliable for 1:1 tachycardias		+
8 Chamber of origin	Discriminates whether tachycardia initiates in atrium or ventricle	A single oversensed/undersensed event may cause misclassification		+
9 Dual chamber sudden onset	Discriminates VT based on abrupt change in ventricular rate and AV interval	Unreliable if baseline rhythm is ventricular paced		+
Atrial (single or dual chamber ICDs)				
10 Atrial rate	Identifies AF to modify single chamber ventricular discriminators	Atrial under-/over-sensing causes measurement error VT/VF may occur during AF	+	
Active discrimination				
11 A, V, or AV pacing during tachycardia	May terminate tachycardia; discriminates 1:1 tachycardia that persists based on pattern of AV intervals after pacing	Proarrhythmia		+

AF, atrial fibrillation; AV, atrioventricular; EGM, electrogram; SVT, supraventricular tachycardia; VF, ventricular fibrillation; VT, ventricular tachycardia.

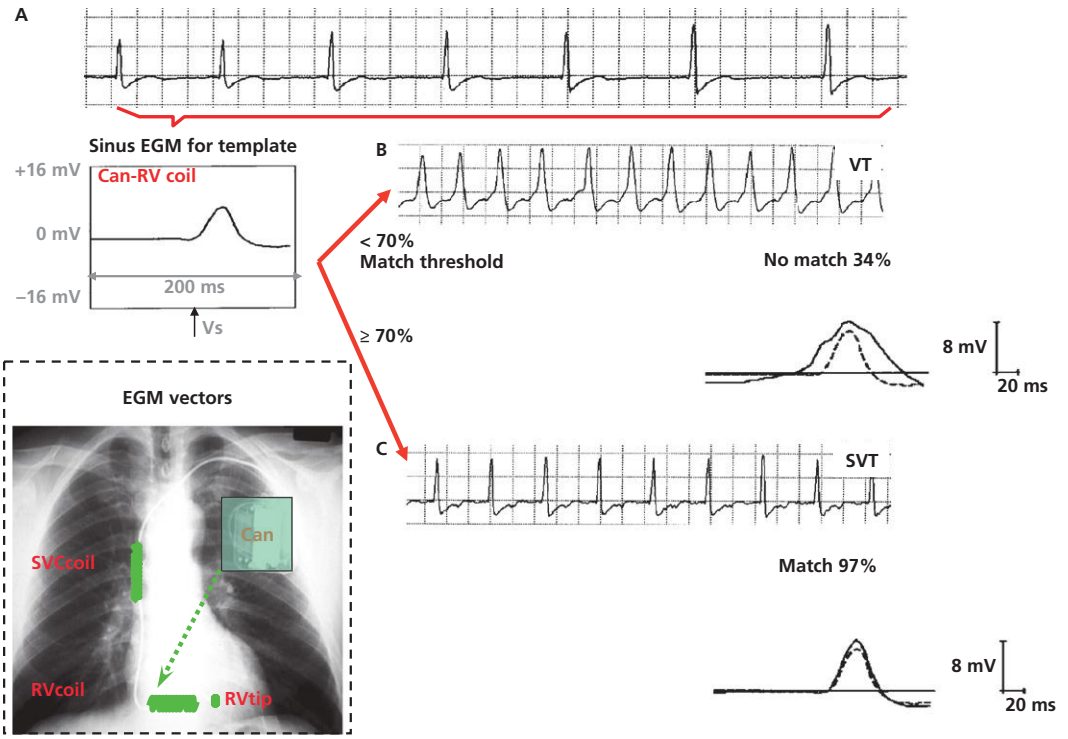


Figure 8.20 Structure of morphology algorithm. (A) The stored template representing the sinus rhythm coil-to-can electrogram (EGM) is stored and compared with real-time EGMs of tachycardia: (B) ventricular tachycardia (VT) and (C) supraventricular tachycardia (SVT). See text for details.

the timing of the tallest peak, which can cause alignment errors.

- *Alignment errors.* Alignment errors occur when one feature of the tachycardia EGM is aligned with a different feature of the template EGM. They prevent match between a tachycardia EGM and a morphologically similar template. The mechanisms depend on the method used for EGM alignment. Usually, tachycardia EGMs are assigned morphology match scores of 0%.
- *Interfering signals during tachycardia.* All modern transvenous ICDs use morphology discriminators that include the "can" electrode in the default EGM. Oversensing of pectoral myopotentials may prevent an SVT from matching the sinus template if the EGM amplitude is small.
- *Rate-related aberrancy.* If complete bundle branch aberrancy occurs reproducibly, the template may be recorded during rapid atrial pacing, but variable aberrancy in rapidly conducted AF is rarely reproducible. If a template is acquired at a fast rate, automatic template updating should be deactivated to prevent subsequent automatic acquisition of a slow baseline template without aberrancy.
- *SVT soon after a shock.* After a shock, ICD detection algorithms reclassify the rhythm as sinus and revert to their initial detection mode within a few seconds, but post-shock distortion of EGM morphology persists for 30 s to several minutes.[57,58] If a supraventricular tachyarrhythmia starts after the rhythm has been classified as sinus, but before post-shock EGM distortion dissipates, morphology discriminators misclassify SVT as VT.[57]

Use of morphology discriminators for other purposes In the subcutaneous ICD (S-ICD), if the tachycardia EGM does not match the template ("static morphology" analysis), then a second "dynamic" morphology analysis is performed to discriminate VT from VF by a beat-to-beat

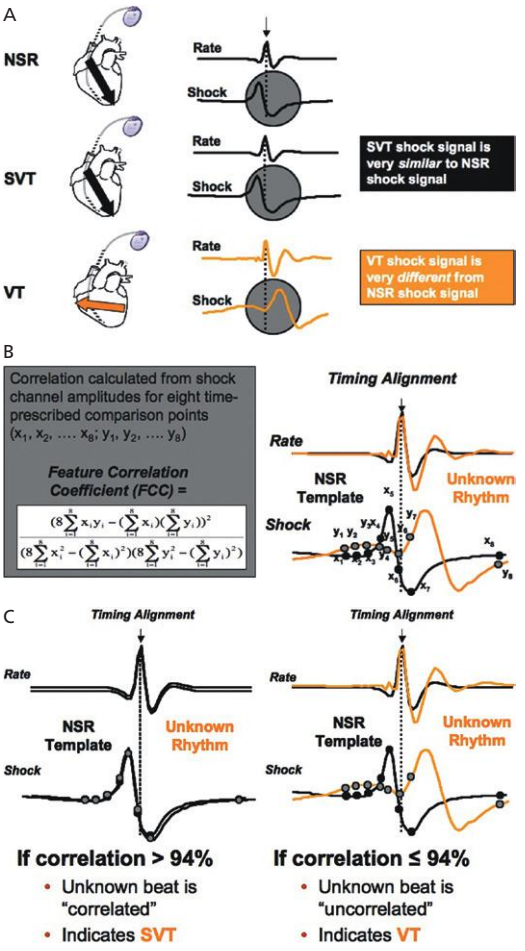


Figure 8.21 A morphology discrimination algorithm. (A) The algorithm works by comparing shock electrogram (EGM) morphology during tachycardia with that obtained and stored during normal sinus rhythm (NSR), under the premise that the morphology and timing relationships between the two EGMs during supraventricular tachycardia (SVT) will be similar to that during NSR (barring any aberrant conduction), whereas the shock EGM will be markedly different during ventricular tachycardia (VT) compared with NSR. (B) The correlation between the shock channel morphologies during NSR and the unknown rhythm is calculated from amplitudes for eight time-prescribed comparison points. (C) If the correlation between the shock channel morphologies during NSR and the unknown rhythm is >94%, the algorithm identifies the beat as supraventricular, otherwise it indicates that it is VT. (Source: Rhythm ID, Boston Scientific Corporation. Reproduced with permission of Boston Scientific.)

comparison of the morphology of tachycardia EGMs to determine their consistency. This step uses morphology to discriminate monomorphic VT from polymorphic VT or VF, rather than to discriminate SVT from VT. A dynamic template match indicates monomorphic VT; mismatch indicates polymorphic VT or VF. Morphology discriminators can also be used to reject T wave oversensing reliably based on the poor match between the activation and repolarization components of the ventricular EGM.

Supplementary use of electrogram width In the S-ICD, an additional, related discriminator, EGM width, supplements the morphology discriminator building block. If the dynamic morphology match indicates monomorphic VT, the algorithm compares EGM width between the tachycardia and stored template. The rhythm is classified as VT if the tachycardia EGM is sufficiently wider than the template and as SVT if it is not. The method for determining EGM width must be insensitive to variations in baseline and early repolarization.

Older discriminators

Interval stability The *VV regularity* building block (VV interval stability or "Stability") discriminates between the regular ventricular intervals usually present in monomorphic VT and the irregular ventricular intervals usually present in rapidly conducted AF. Regularity criteria can reject AF with ventricular rates slower than 170 bpm in the absence of antiarrhythmic drugs. At faster rates, they cannot discriminate AF from VT reliably, because VV intervals in AF become more regular.[59–61] This discriminator may prevent detection of monomorphic VT that becomes irregular after therapy with amiodarone or type Ic antiarrhythmic drugs.[60,61]

Sudden onset The *RR onset* building block discriminates sudden-onset VT from gradual-onset sinus tachycardia. "Onset" has high specificity for rejecting sinus tachycardia,[59,61] providing premature beats do not occur as the sinus rate accelerates across the sinus–VT boundary. But, when used in isolation, it prevents detection of VT that originates during SVT or VT that starts abruptly with an initial rate below the VT detection limit. In the

Table 8.4 Failure modes of the electrogram–morphology discriminator

	Root cause	*Solution or mitigation*
Incorrect classification of VT as SVT		
Inaccurate template	Change in baseline EGM; automatic updating during bigeminy or bundle branch block	Automatic template updating after implant; operator confirmation of template in follow-up
EGM truncation	Inadequate amplifier range	Evaluate baseline EGM amplitude in various postures; adjust dynamic range of amplifier so that EGM amplitude is 50–75% of range
Alignment errors	Failure of alignment procedures	Algorithm specific (reference CDS)
Interfering signal in tachycardia	Superposition of extraneous signal such as pectoral myopotentials on true ventricular EGM degrades % match	Evaluate % match during pectoral muscle exercise Select alternative source EGM if interference is reproducible
Rate-related aberrancy	Alteration of interventricular conduction at rapid rate	Reduce fraction of EGMs (e.g. 5 of 8 to 3 of 8) required to exceed SVT match threshold, if programmable Disable automatic updating if template acquired at fast rate
SVT soon after shock	Post-shock EGM distortion	Program additional single chamber discriminators in patients with repetitive VT
Incorrect classification of SVT as VT		
Analysis of morphology in single lead	Similar VT and SVT morphology in analyzed lead	Change lead if programmable Program other discriminators with "OR" logic for classification of VT Program high-rate time out

EGM, electrogram; SVT, supraventricular tachycardia; VT, ventricular tachycardia.

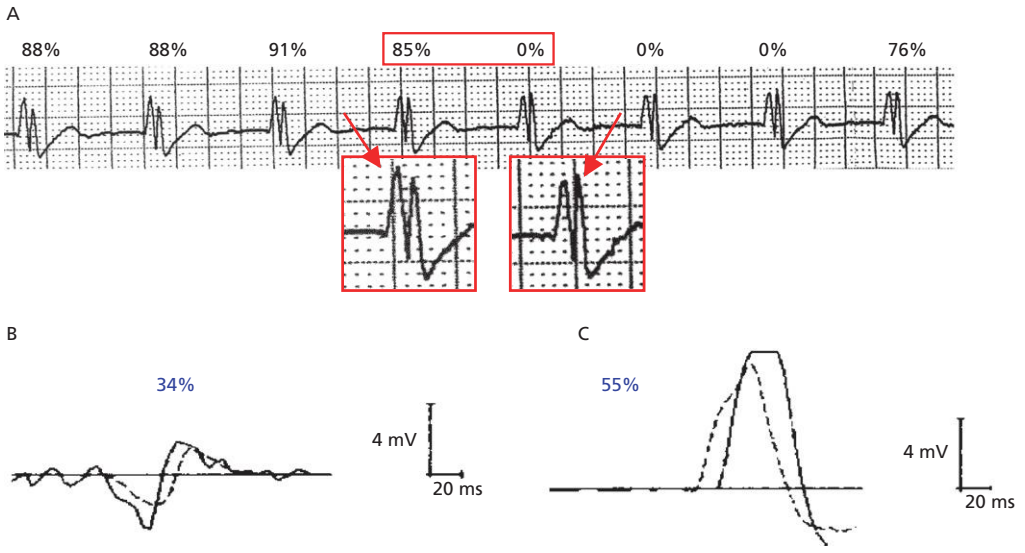


Figure 8.22 Failure modes of morphology algorithms. (A) Alignment error. (B) Interfering baseline myopotentials with low amplitude coil-to-can electrogram (EGM). (C) Truncation of the EGM peak during tachycardia due to postural changes.

latter case, the ICD misclassifies the "onset" of the arrhythmia as the gradual acceleration of the VT rate across the VT rate boundary. Most single and dual chamber discriminators re-evaluate classification of ongoing tachycardias, but Onset only classifies it once as it crosses the sinus–VT boundary. Both for this reason and because the morphology discriminator usually is highly accurate for rejection of sinus tachycardia, onset should not be used as the only discriminator.

Dual chamber ventricular building blocks

Atrial versus ventricular rate

Comparison of atrial and ventricular rates is the cornerstone and first step of most dual chamber algorithms, either explicitly (Boston Scientific Rhythm ID, St. Jude Medical, and Biotronik) or implicitly (Medtronic). The Medtronic algorithm also includes this comparison as an explicit subsequent step. The central role of this discriminator is predicated on accurate atrial sensing during high ventricular rates, which has proved to be the weakest link in performance of dual chamber SVT–VT discrimination algorithms.

Discriminators that evaluate relative timing of atrial/ventricular events The primary role of these building blocks is to discriminate VT with 1:1 ventriculoatrial (VA) conduction from SVT with 1:1 AV conduction. Their two secondary roles are to classify tachycardia with stable 2:1 AV relationships as atrial flutter and to classify dissociated isorhythmic tachycardias (similar atrial and ventricular rates) as VT. The *AV dissociation* building block detects VT during any SVT, but classifies conducted AF as dissociated. The *AV patterns* building block identifies stable associations of atrial and ventricular events. It also identifies tachycardias with stable 2:1 AV patterns as atrial flutter. The *chamber of origin* building block discriminates between VT and SVT with 1:1 AV association by identifying whether the tachycardia originates in the atrium or ventricle. In ICD patients, most AV nodal or AV reciprocating tachycardias are ablated. Abrupt-onset SVTs typically represent atrial tachycardia, which usually begins with an intrinsic atrial event in the interval between the last ventricular event in the sinus rate zone and the first ventricular event in the VT zone. Conversely, at the start of spontaneous VT, there is usually no atrial event in this interval. Dual chamber sudden onset (Sinus Tachycardia Rule, Medtronic) is a substantial refinement of the single chamber rule, applied only to tachycardias with a 1:1 AV association, and based on the observation that sinus tachycardia is characterized by gradual changes in both AV and V–V intervals.[62] Unlike single chamber Onset, dual chamber Onset identifies VT that begins during sinus tachycardia by the change in the expected AV relationship. However, it misclassifies rare VTs with 1:1 VA conduction that begin in the sinus rate zone and accelerate across the VT rate boundary. More problematically, if the baseline rhythm is ventricular paced (e.g. all cardiac resynchronization ICDs), it collapses to single chamber Onset.

Single chamber atrial building blocks in dual chamber algorithms Although atrial correlates of the single chamber ventricular discriminators can be calculated, they are not employed in any current dual chamber algorithm. However, *atrial rate* (A–A interval) is applied to determine the presence or absence of AF/flutter and to invoke or prioritize a single chamber ventricular interval stability only if atrial tachyarrhythmia is present. This prevents underdetection of irregular VT in the absence of AF/flutter.

Importance of accurate atrial sensing Both atrial undersensing or oversensing invalidate comparison of atrial and ventricular rates. Atrial undersensing may be caused by either low amplitude EGMs (especially during AF) or functional interactions with the post-ventricular atrial blanking period (PVAB) triggered by ventricular-sensed or -paced events (Figure 8.23). At high ventricular rates, long PVABs may comprise a sufficient fraction of the cardiac cycle that they blank enough atrial EGMs to prevent correct estimation of atrial rate.

Atrial oversensing is most commonly caused by far-field R waves (FFRWs; Figure 8.24) that are either high in amplitude, comparable in amplitude to small P waves, or sufficiently late relative to the sensed ventricular EGM that they time outside the PVAB. Consistent or inconsistent FFRW oversensing may result in incorrect classification of SVT as VT either by the AV dissociation, AV pattern, or



Figure 8.23 Inappropriate detection of supraventricular tachycardia (SVT) as ventricular tachycardia (VT) due to the post-ventricular atrial blanking period (PVAB). Enlarged panel at right shows that the peak of the atrial electrogram (EGM) times within the 90-ms PVAB after the ventricular EGM (top, dark short line on marker channel). At right of top panel, VT is detected in the V > A rate branch and antitachycardia pacing (ATP) is delivered (V > ATP). Note that there is a good morphology discriminator match (numerical values on marker channel > match threshold of 60%), but this is overridden by incorrect dual chamber determination of V rate > A rate. In the lower panel, the asterisks indicate capacitor charging and (HV) over the lightening symbol indicates an inappropriate 650-V shock.

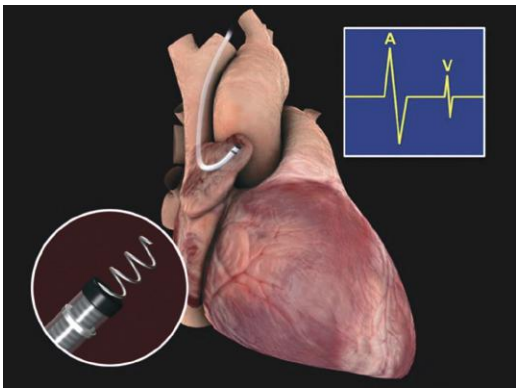


Figure 8.24 Far-field R wave oversensing in a dual chamber ICD. The close proximity between the atrial lead in the right atrial appendage and the right ventricle increases the likelihood of sensing far-field R waves on the atrial channel. (Source: Seet RCS, Friedman PA, Rabinstein AA. Prolonged rhythm monitoring for the detection of occult paroxysmal atrial fibrillation in ischemic stroke of unknown cause. *Circulation* 2011; 124: 477–486. Reproduced with permission of Wolters Kluwer Health.)

chamber-of-origin discriminators. The best way to prevent atrial oversensing of FFRWs is to position the atrial lead where a large atrial EGM is recorded with no or minimal FFRWs.

Active discrimination: response to pacing In the electrophysiology laboratory, the response of the opposite chamber to pacing is commonly used for diagnosing tachycardias with a 1:1 AV relationship. The *response to pacing* building block is conceptually different from others because it requires an active intervention that either terminates a 1:1 tachycardia or discriminates VT from SVT by the pattern of atrial and ventricular events at the end of pacing. One validated algorithm delivers simultaneous atrial and ventricular antitachycardia pacing (ATP).[63] To date, such active discrimination has not been implemented in an ICD.

Operation of complete SVT–VT discrimination algorithms

Single chamber algorithms

The morphology discriminator is the primary single chamber discriminator. In transvenous ICDs it may be linked with Stability to withhold therapy unless both discriminators indicate VT. As noted, it is linked with ventricular EGM width in S-ICD.

Dual chamber algorithms

Dual chamber algorithms are more complex than single chamber ones. Those that apply comparison of atrial and ventricular rates as a first step limit the fraction of VTs to which single chamber discriminators are applied, since the ventricular rate exceeds the atrial rate in more than 80% of VTs in the VT zone of dual chamber ICDs and a higher fraction of VTs in the VF zone.[64,65] Thus, these algorithms apply additional discriminators to fewer than 20% of VTs, reducing the risk of misclassifying VT as SVT by subsequently applied discriminators, provided that the atrial rate is measured accurately. However, they apply additional discriminators to all SVTs. The integration of building blocks into dual chamber algorithms may be considered in terms of relative atrial and ventricular rates.

Operation for atrial rate less than ventricular rate ($V > A$) The rhythm is classified as VT.

Operation for atrial rate equal to ventricular rate ($V = A$) The vast majority of tachycardias with a 1:1 AV relationship are SVTs, primarily sinus tachycardias. The relevant building blocks are shown in Table 8.3. In addition, "Active discrimination" may be used in future devices.

Operation for atrial rate greater than ventricular rate ($V < A$) The building blocks that apply to these challenging rhythms are summarized in Table 8.3. Although various combinations successfully discriminate VT from SVT in VT zones, most VT during AF is sufficiently rapid to be detected in the VF zone,[66] where some discriminators do not apply (e.g. Stability) and others lose specificity for SVT, e.g. morphology templates may misclassify aberrantly conducted beats.

Representative dual chamber algorithms

Figure 8.25 shows representative examples of how the discriminator building blocks are assembled into dual chamber SVT–VT discriminator algorithms. In Figure 8.25A (Boston Scientific), the initial step is comparison of atrial and ventricular rates. If $V \leq A$, the morphology discriminator is

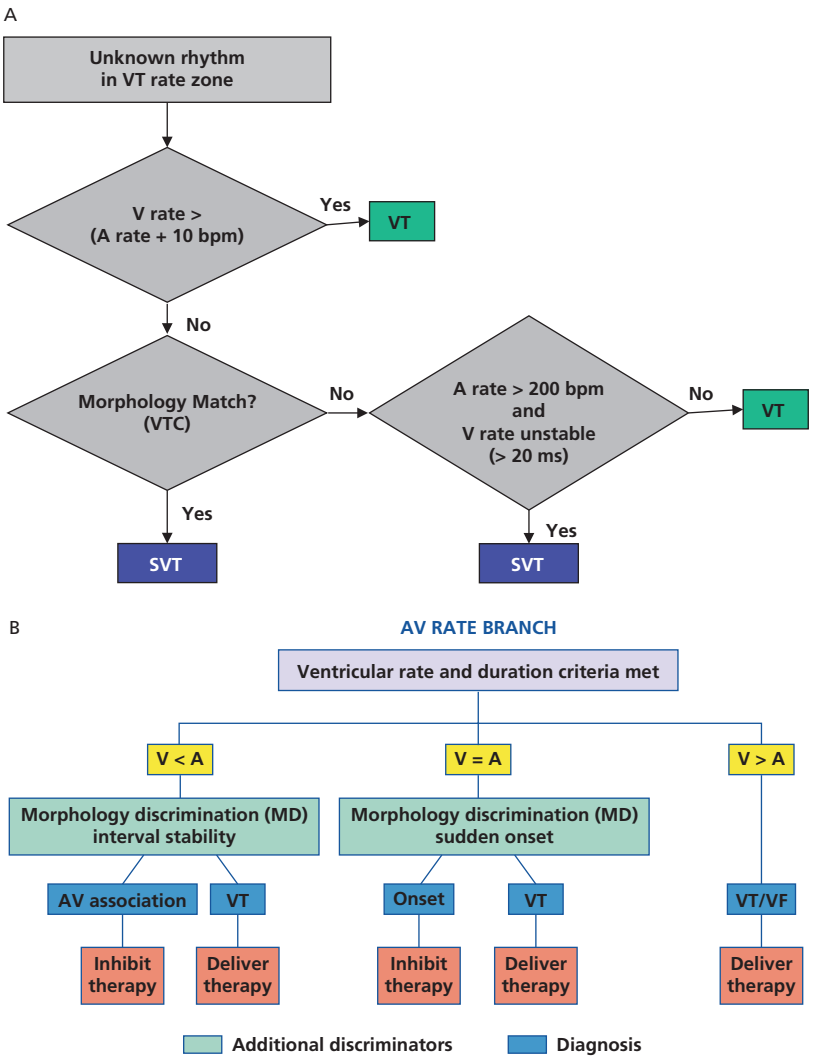


Figure 8.25 Flow chart representations of dual chamber supraventricular tachycardia (SVT)–ventricular tachycardia (VT) detection algorithms: (A) Boston Scientific, (B) St. Jude Medical. See text for details. AV, atrioventricular. (Source: (A) Boston Scientific Corporation. Reproduced with permission of Boston Scientific. (B) St. Jude Medical, Inc. Reproduced with permission of St. Jude Medical, Inc.)

applied. If the morphology discriminator diagnoses VT, an additional step is taken to exclude aberrantly conducted AF. The atrial rate criterion is applied; if it exceeds the threshold for AF, single chamber Stability is applied. At this stage therapy is withheld only if the atrial rate indicates AF and the ventricular rhythm is irregular. In Figure 8.25B (St. Jude Medical) the initial step of comparison of atrial and ventricular rates is the same. This algorithm offers different options for discriminators depending on the A/V rate branch, but both branches offer the morphology discriminator. The V = A branch is concerned with diagnosing 1:1 and isorhythmic tachycardias. It is supplemented by "Arrhythmia Onset," a combination of the Onset (to reject sinus tachycardia) and Chamber of Origin (to discriminate abrupt onset atrial tachycardia from VT). The risk of underdetecting VT using single chamber Onset is substantially reduced because the morphology discriminator will identify the vast

majority of VTs it misclassifies and because it is applied to less than 20% of VTs. The V < A branch is concerned with diagnosing VT during AF/flutter. Again, the morphology discriminator plays a leading role, supplemented by the AV Association discriminator for a 2:1 atrial flutter and the Stability discriminator to reject aberrantly conducted AF.

Duration-based "Safety-Net" features to override discriminators

These programmable features deliver therapy if an arrhythmia satisfies the ventricular rate criterion for an extended duration even if discriminators indicate SVT. The premise is that VT will continue to satisfy the rate criterion, but the ventricular rate during transient sinus tachycardia or AF will decrease below the VT rate boundary before the duration is exceeded. The limitation is delivery of inappropriate therapy when SVT exceeds the programmed duration, which occurs commonly for durations of less than 1 min and in up to 10% of SVTs at 3 min, depending on the VT detection interval and AV conduction.[59] Durations of 5–10 min are required to minimize inappropriate therapy.[67] In some ICDs, override features may be independently programmable in the VT and VF zones. The beneficial effect of these features are limited and we recommend programming them only for specific, individualized indications.

SVT–VT discrimination algorithms: performance and clinical role

Measuring and comparing performance

Clinical comparisons of algorithm performance require the consideration of multiple factors, including tachycardia episodes not stored in ICD memory and those faster than the SVT limit to which discriminators may not apply. Programmed parameters may influence algorithm performance. All algorithm failures do not have equivalent clinical significance. Inappropriate ATP usually is less significant than an inappropriate shock, and failure to detect asymptomatic self-terminating VT is less significant than failure to detect VT that requires resuscitation. Head-to-head comparisons of different SVT–VT discrimination algorithms show that there are substantive differences in performance,[54,68] but it is difficult to be certain which of multiple differences among building blocks account for these findings.

Performance of single chamber versus dual chamber discriminators

When dual chamber ICDs were developed before the advent of single chamber morphology discriminators, there was great optimism that they would provide superior SVT–VT discrimination to single chamber ICDs, both with respect to fewer inappropriate therapies and fewer underdetected VTs. Multiple studies have compared dual versus single chamber SVT–VT discrimination. Despite some variation in results, a few conclusions can be drawn: (1) currently, unselected primary prevention patients do not benefit from dual chamber SVT–VT discrimination; (2) a randomized "bench testing" comparison using pre-recorded, induced SVTs (mostly rapidly-conducted AF) showed no benefit of dual chamber discriminators with devices available in 2009;[54] and (3) currently recommended programming for primary prevention patients (Table 8.5) reduces inappropriate therapy for SVT compared with traditional programming.[69] Additionally, current standard-of-care use of β-blockers may reduce ventricular rates in SVT. The combination of these factors, combined with improved morphology discriminators, makes it unlikely that unselected primary prevention patients will ever benefit from dual chamber SVT–VT discrimination. Dual chamber algorithms have been reported to provide a modest performance improvement over single chamber algorithms in secondary prevention patients who have SVT and slower VT at overlapping ventricular rates.[70–73] Currently, experts disagree about whether or not dual chamber ICDs benefit patients who are likely to have rapidly conducted SVT in the programmed VT detection zone. These conclusions are further complicated by head-to-head comparisons that show that the specificity of device-based algorithms differs among manufacturers, depending on programmed rate and whether single or dual chamber detection is employed.[68]

Additionally, dual chamber ICDs provide other features not available in single chamber ICDs, including dual chamber pacing algorithms that minimize RV pacing in patients with sinus node disease, diagnostics for AF, and stored EGMs that provide higher diagnostic accuracy than single chamber ICDs.[74] Dual chamber ICDs may be considered if the benefits of these features will outweigh the disadvantages of dual chamber ICDs, which include higher cost, more implant complications,

Table 8.5 ICD programming for primary and secondary prevention patients

	Secondary prevention	*Primary prevention*		
		Strategy 1	*Strategy 2*	*Strategy 3*
Zone 1—VT				
Programmed rate (bpm)*	≥20 slower than slowest VT†	170–199	170–199	167–181
Duration for detection (s)	≥9		60	10–12
SVT–VT discrimination	Yes		Yes	
Therapy	ATP × 2–4 shocks: maximum or based on implant testing	Optional monitor only	ATP × 2–4 shocks: maximum or based on implant testing	Optional monitor only
Zone 2—Faster VT				
Programmed rate (bpm)*	188–249	≥200	200–249	182–249
Duration for detection (s)	9	2.5	12	9
SVT–VT discrimination	Yes	No	Yes	Yes
Therapy	ATP × 1–2§ shocks: maximum or based on implant testing	ATP × 1§ shocks: maximum or based on implant testing	ATP × 2–4 shocks: maximum or based on implant testing	ATP × 1–2§ shocks: maximum or based on implant testing
Zone 3—Fastest VT/VF		NA		
Programmed rate (bpm)*	≥250		≥250	≥250
Duration for detection (s)	9		2.5	9
SVT–VT discrimination	No		No	No
Therapy	ATP × 1§ Maximum shocks		ATP × 1§ maximum shocks	ATP × 1§ maximum shocks

*ICD counting methods require about 75% of beats to be faster than this rate.

†If slowest VT is <200 bpm.

§Reduced delay between ATP and first shock.

ATP, antitachycardia pacing; SVT, supraventricular tachycardia; VF, ventricular fibrillation; VT, ventricular tachycardia.

and decreased longevity. Figure 8.26, Figure 8.27, and Figure 8.28 show representative examples.

Clinical role of SVT–VT discriminators

SVT–VT discriminators are only part of the solution to the problem of minimizing inappropriate therapy of SVT. Non-device elements include β-blockers, antiarrhythmic drugs, and catheter ablation. Device elements include appropriate programming of rate and duration.

In clinical trials, approximately 25% of inappropriately treated SVTs are faster than the SVT

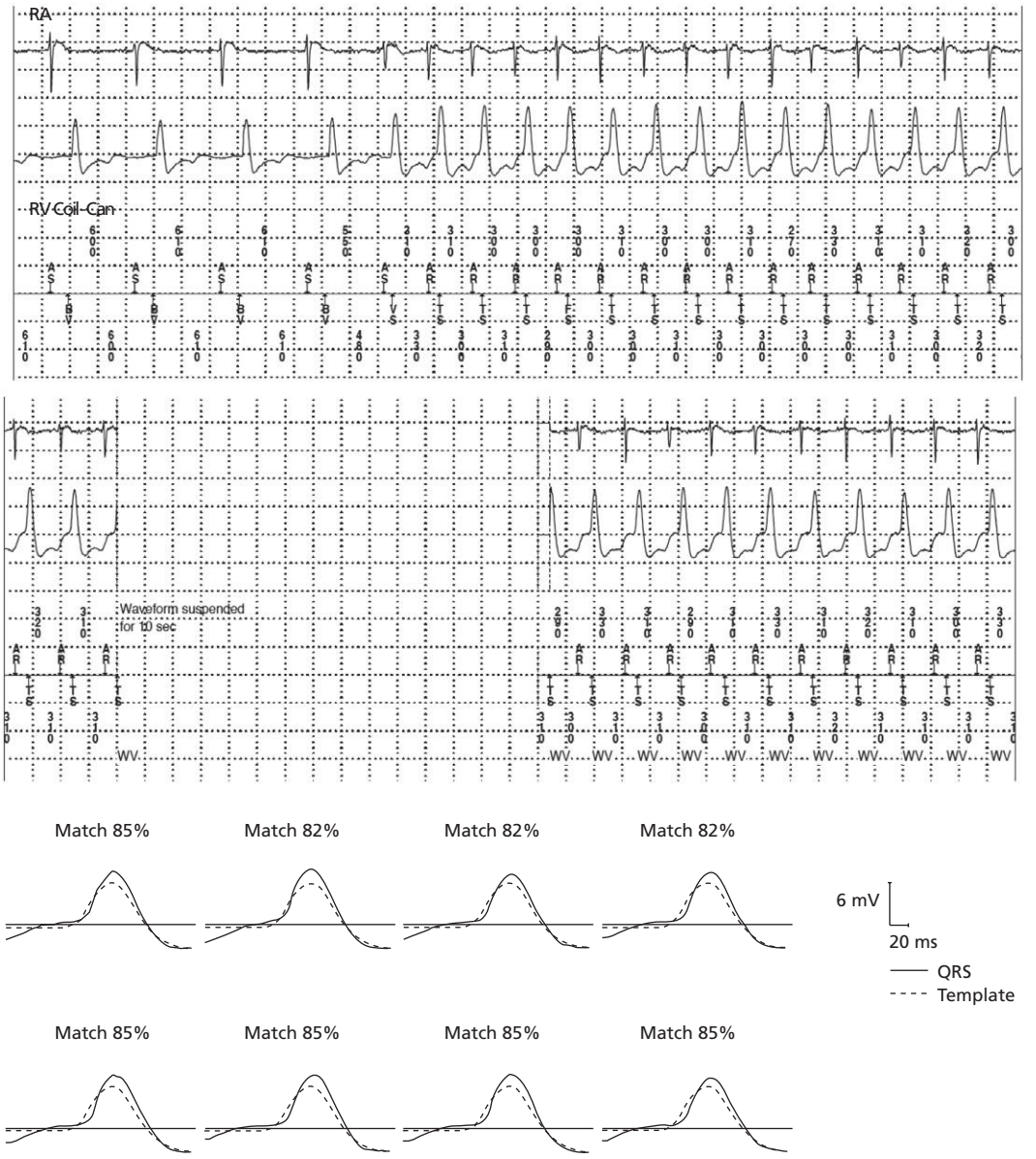


Figure 8.26 Correct classification of abrupt onset supraventricular tachycardia (SVT) by morphology discriminator. Right atrial (RA) and shock (RV coil-to-can) electrograms (EGMs), and dual chamber markers are shown. The fifth atrial EGM in the upper panel initiates SVT. VT detection based on rate alone would have occurred at the third (truncated) ventricular EGM in the lower panel, but the morphology discriminator (Wavelet, WV) classified the rhythm as SVT based on the match percentage being greater than the threshold value of 70% (bottom panel). Note the increase in shock EGM amplitude from sinus to SVT.

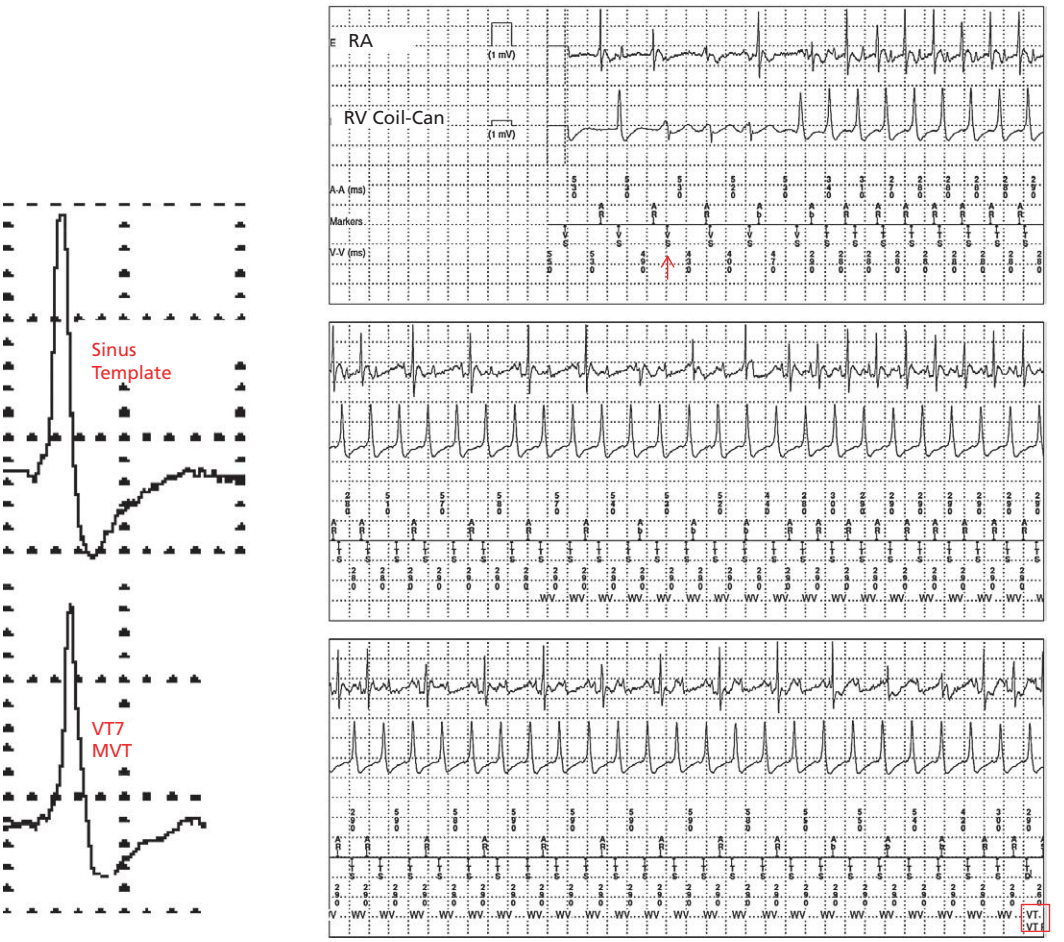


Figure 8.27 Interaction of single chamber and dual chamber algorithms. Right atrial (RA) and shock (RV coil-to-can) EGMs, and dual chamber markers are shown. The left panel compares individual shock electrograms for the sinus template and seventh episode of monomorphic (M) ventricular tachycardia (VT), showing a close match. The red arrow shows onset of VT. The morphology algorithm classified rhythm as SVT (WV). Intermittent 1:1 ventriculoatrial (VA) conduction delays correct rhythm classification by comparison of atrial and ventricular rates, because classification is based on median value. After median ventricular rate exceeds median atrial rate, the algorithm delays for 10 beats before classifying rhythm as VT (bottom right).

limit.[67] The SVT limit must be programmed fast enough to apply to the most rapidly conducted SVT. An SVT–VT discrimination algorithm should be programmed in all patients with normal AV conduction. The algorithm should include a single chamber ventricular morphology discriminator if available. A dual chamber algorithm, usually including comparison of atrial and ventricular rates, should be programmed in patients with a stable, functioning atrial lead. SVT–VT discriminators should be more specific in slower (VT) zones, in which delay in detection of VT is well tolerated and underdetection of VT rarely causes collapse.

Implant procedure

ICD systems are implanted most commonly by electrophysiologists, often without the use of an operating room or general anesthesia. The

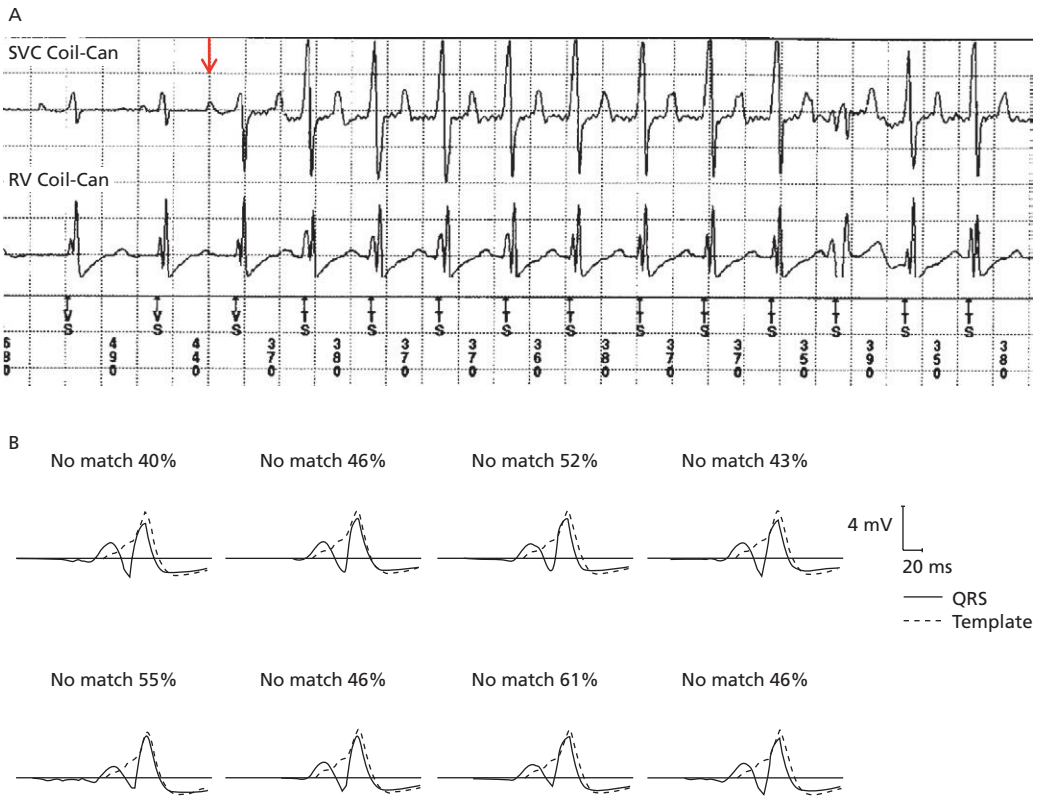


Figure 8.28 Inappropriate detection of abrupt-onset supraventricular tachycardia (SVT) as ventricular tachycardia (VT) in a single chamber ICD that would have been prevented by the dual chamber, chamber-of-onset discriminator. High-voltage electrograms (EGMs) recorded from the superior vena cava (SVC) and right ventricular (RV) coils are shown with single chamber markers. Atrial EGMs are seen clearly on the SVC channel with the appearance of surface P waves. (A) Shows abrupt onset of SVT. Atrial tachycardia begins at third beat (arrow) with a premature atrial EGM wave that has a different morphology from the first two sinus atrial EGMs. (B) Shows that moderate right bundle branch aberrancy results in match percentages between 40% and 60%, below the match threshold of 70%.

downsizing of ICD pulse generators allows for implantation techniques that approach those for a permanent pacemaker; however, the acute testing and management of these devices still require electrophysiology expertise.

Whether implanted in an operating room, a multipurpose procedure room, or an electrophysiology laboratory, and whether general anesthesia or conscious sedation is employed, the basic concepts of ICD surgery are the same. Meticulous sterile technique must be used and patients should receive perioperative intravenous antibiotics. The antibiotics chosen should provide adequate activity against staphylococcal species, as these are the most common bacteria associated with early device infections. Typically, vancomycin or a cephalosporin is used, with vancomycin increasing in use with the emergence of methicillin-resistant *Staphylococcus aureus* as a common bacterium associated with infection.[75] Local irrigation of the pulse generator pocket with antibiotic solution is often performed, although controlled data establishing the efficacy of this additional step are lacking. Meticulous hemostasis is also required to avoid postoperative bleeding and hematoma formation. Heparin products should be avoided in the perioperative period and multiple studies have now demonstrated that performing implantation with

full oral anticoagulation is preferable to a heparin bridging strategy.

A physiological recorder is useful for recording and evaluating electrophysiological signals, and heart rhythm, blood pressure, and respiration must be monitored. This can be performed either invasively with an arterial line and endotracheal intubation or, more commonly, with ECG monitoring, a brachial cuff, and pulse oximetry. Finally, the patient should be connected to a transthoracic defibrillator with skin pads for back-up defibrillation therapy if needed during defibrillation testing or with lead placement.

The sites of venous access and methods of obtaining access are similar to those for permanent pacemakers. Unless contraindicated by an AV fistula, venous anomaly, previous chest surgery (i.e. mastectomy), severe dermatological conditions, or scarring, a left-sided approach is preferred as this is the optimal vector for defibrillation with an active can system. Cut-down to the cephalic vein or percutaneous axillary vein access may be preferable to subclavian puncture to reduce the incidence of subclavian crush observed with these large leads. However, a steep vertical access to the axillary vein should be avoided as this has been associated with lead failures. Leads need to be well secured to the pectoral fascia, because dislodgement of defibrillation leads remains a common perioperative complication.[76] The transvenous defibrillator leads are implanted in the same fashion as pacemaker leads. Attention should be given to insure that the distal coil is entirely within the RV cavity and not straddling the tricuspid valve. Adequate sensing (R waves >5 mV) and pacing (threshold <1.0 V) of the RV lead need to be established. If a dual chamber ICD is implanted, then a separate atrial lead is placed, again with adequate sensing and pacing parameters required. Only bipolar atrial leads are used in ICD systems. Such leads should have closely spaced electrodes to reduce the risk of far-field sensing of ventricular EGMs. For biventricular pacing ICDs (CRT-D), a third lead is implanted, typically in a posterior or lateral branch of the coronary sinus venous system.

Subcutaneous leads have been used in conjunction with transvenous defibrillator systems for patients with very high defibrillation thresholds. An entirely subcutaneous ICD system, avoiding transvenous and intracardiac leads, has recently been developed that mitigates the risk of transvenous leads (Figure 8.29). A major limitation of the S-ICD is the lack of antitachycardia or bradycardia support pacing, except for a brief post-shock period. For patients requiring ICD implantation without a pacing indication, the S-ICD is an attractive option. The generator is placed in the left lateral costal margin and the lead courses subcutaneously to the xiphoid process and then along the left parasternal region. Avoiding transvenous and intracardiac lead placement eliminates the risk of intravascular infections, valvular damage, cardiac perforation, and pneumothorax. The S-ICD is also an alternative to traditional transvenous ICDs for patients with obstructive vascular access, prosthetic tricuspid valves, and high risk of systemic infection, such as dialysis or immunocompromised subjects. Interestingly, the "ultra" far-field EGMs available with subcutaneous electrodes and unique discrimination algorithms has made this device very accurate for discriminating supraventricular and ventricular arrhythmias,[54] although it may be susceptible to T wave oversensing.[77]

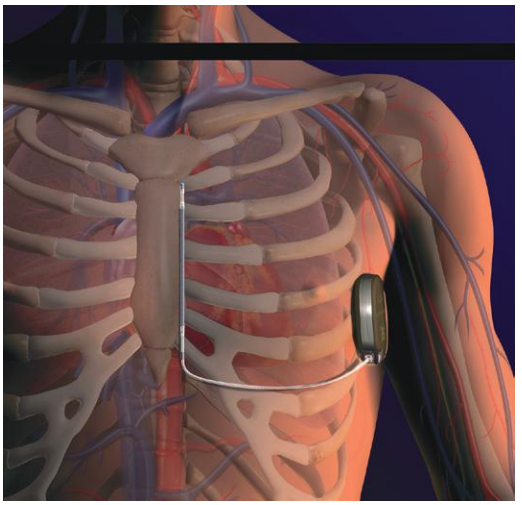


Figure 8.29 Subcutaneous ICD generator and lead *in situ*. The pulse generator is positioned near the left mid-axillary line. Defibrillation occurs between the housing (can) of the generator and an 8-cm long, left parasternal coil electrode. Sensing is performed using one of three pairs of electrodes, chosen among the can and small sensing electrodes proximal and distal to the coil. (Source: Boston Scientific Corporation. Reproduced with permission of Boston Scientific.)

Testing defibrillation efficacy at ICD implant

Fortunately, only the upper portion of the probability-of-success curve is of clinical interest. Implant testing limited to this upper portion compares a measure of defibrillation efficacy with a level of performance (implant criterion) that is expected to result in an acceptable success rate for defibrillation of spontaneous VF. The goal is to efficiently identify a high point on the defibrillation probability-of-success of curve. Limited "patient-specific" and "safety margin" testing strategies have been developed for clinical implant testing.

In clinical research, the principal goal is to determine a patient-specific estimate of defibrillation efficacy so that defibrillation can be compared under different experimental conditions.[78] The objective of *patient-specific strategies* is an accurate estimate of the minimum shock strength that achieves a specific, high probability of success (e.g. DF_{90}). Defibrillation efficacy must be assessed at several shock strengths chosen in relation to an estimate of the probability-of-success curve. Clinically, the advantage of a patient-specific strategy is that it minimizes potential long-term adverse effects of excessive shock strength, such as myocardial depression or rapid battery depletion if frequent delivered or aborted shocks occur.

In clinical practice, the usual goal is to identify those patients in whom ICD shocks are unreliable. *Safety margin strategies* limit testing to the minimum necessary to determine if there is a sufficient margin such that the maximum output of the ICD defibrillates reliably. Defibrillation efficacy is assessed one or more times, usually at only one shock strength chosen in relation to the maximum shock strength of the ICD. The outcome of each assessment is classified as either successful or unsuccessful, and the cumulative result is compared with the implant criterion. Today, most implant testing is performed using a safety margin strategy.

Defibrillation testing

Defibrillation efficacy can be assessed directly by fibrillation–defibrillation ("defibrillation") testing or indirectly by vulnerability testing. Both methods can be used either in a patient-specific strategy or safety margin strategy. DFT testing refers to a group of methods that assess defibrillation efficacy by calculating a shock strength on the sloping portion of the curve based on successes and failures of a few shocks at different strengths (Figure 8.30). Thus, the DFT is based on a limited, discrete sampling of a continuous statistical distribution. Simulations based on clinical data demonstrate that the mean DFT depends on how this sampling is performed, and hence on the specific testing method used (shock protocol, initial shock strength, and shock step size). They also demonstrate that the standard deviation of most clinical methods is wide.[79] Clinical data show that conventional DFT testing has limited reproducibility.[80]

The goal of defibrillation testing is to ensure that the programmed shock strength has an extremely high probability of terminating VF in a given patient (Figure 8.31). Multiple methods for calculating the DFT have been developed (Figure 8.32 and Table 8.6).[81] For patient-specific testing, the most commonly recommended programming of first shock strength is DFT + 10 J. When safety margin testing is used, the first shock is set to maximum output. Recommended safety margin testing includes two of two shock successes at 10 J below the maximum output or one shock success in one trial at 20 J below the maximum output.

Clinically, repeat testing is performed in those ICD patients who do not meet an implant criterion, either to confirm the high DFT prior to system revision or after revision to determine the effect of the intervention on the DFT. Since the DFT is not fixed, but a random variable with a discrete probability distribution, repeating DFT measurements under constant conditions is equivalent to repeated sampling of its probability distribution, resulting in varying values. Any defibrillation failure may be an unlikely event due to chance rather than evidence of an inadequate ICD system. For example, a system with a 90% success rate is expected to fail in 10% of attempts. If a shock at the DF_{90} fails to defibrillate, repeat defibrillation at the same shock strength is likely to succeed, since it has the same 90% probability of success. Generally, when a single defibrillation measurement is an outlier in its statistical distribution, a repeat measurement is likely to be closer to the mean. This behavior, referred to as regression to the mean, predicts that

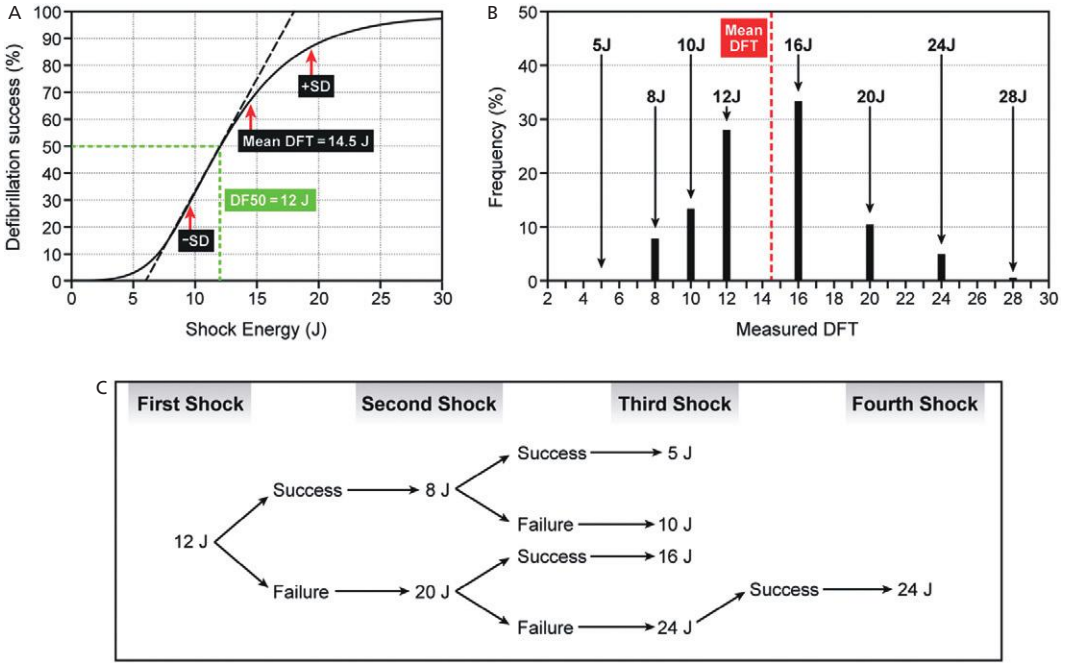


Figure 8.30 Relationship between (A) defibrillation probability of success curve and (B) measured defibrillation threshold (DFT) during repeated testing in an individual patient, using the sequence of three or four test shocks shown in (C). This sequence, known as a binary search protocol, starts at 12 J, the shock strength with a 50% probability of success (DF_{50}). The process, defined by the binary search protocol, results in a single value, which the clinician records as the patient's "DFT." The right upper panel shows the statistical distribution of 50 000 simulated repetitions of this binary search DFT process applied to the defibrillation probability of success curve. Even for the most frequently measured DFT value (16 J), there is only about a one-third chance that repeating the process will yield the same result. The mean measured DFT (14.5 J) corresponds to the DF_{68}. However, one standard deviation of measured DFTs extends from the DF_{30} to the DF_{87}. (Source: Adapted from Smits K, Virag N. Impact of defibrillation test protocol and test repetition on the probability of meeting implant criteria. *Pacing Clin Electrophysiol* 2011; 34: 1515–26. Reproduced with permission of John Wiley & Sons Ltd.)

outlier values are likely to be followed by less extreme ones nearer the subject's true mean. It applies to repeated measurements in the same subject of a variable that follows a statistical distribution.[82] A recent clinical study analyzed the effect of shock waveform on DFT.[46] The authors concluded that individual patient differences were explained better by regression to the mean than by true differences in defibrillation efficacy. This has important implications when interpreting interventions designed to improve defibrillation efficacy.

The first clinical implication of regression to the mean is illustrated in the previous example: a single defibrillation failure may be a low probability outcome of a shock that has a high probability of successful defibrillation. The second clinical implication relates to the clinical practice of repeating defibrillation testing only on patients who fail the implant criterion (conditional retesting). If such conditional re-testing is performed without any change in the defibrillation system, some patients who pass will be those with adequate safety margins as judged by their defibrillation probability-of-success curves. These patients were misclassified by the first test, but classified correctly by the second (regression to the mean). Others will be patients with inadequate safety margins classified correctly by the first test but incorrectly by the repeated test. A third possibility is introduced by conditional re-testing after system revision that shifts the defibrillation probability-of-success

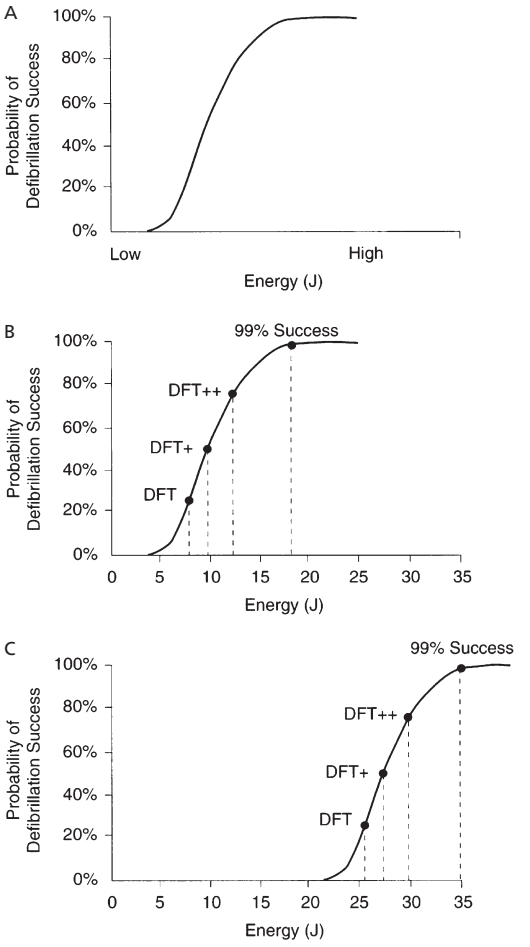


Figure 8.31 Graphical representation of the relationship between probability of successful defibrillation versus energy level of shock. (A) The generalized defibrillation success curve is sigmoidal in shape. (B) The defibrillation success curve for a hypothetical patient. If the defibrillation threshold (DFT) is measured as a single successful defibrillation at a given energy level (DFT), the confidence for repeated success is lower than if an energy level is tested that defibrillates twice (DFT+) or three times (DFT++) without failure. The safety margin for programming is the difference between the measured value of DFT and the energy needed for >99% successful defibrillation. In this case, the safety margins are approximately 10, 8, and 6 J for DFT, DFT+, and DFT++, respectively (see Table 8.3). The energy level for 99% success is never really known for any patient, however. The safety margins for any measure of DFT are estimated empirically based on the assumption that the shape of the DFT curve is relatively consistent between patients. (C) In this hypothetical patient, all measures of DFT are high. Using a safety margin of 10 J added to the DFT+ or DFT++ would require a device with at least a 37-J output to ensure >99% successful defibrillation. This patient would require revision of the lead system to reduce the DFTs or the implantation of a high-output device.

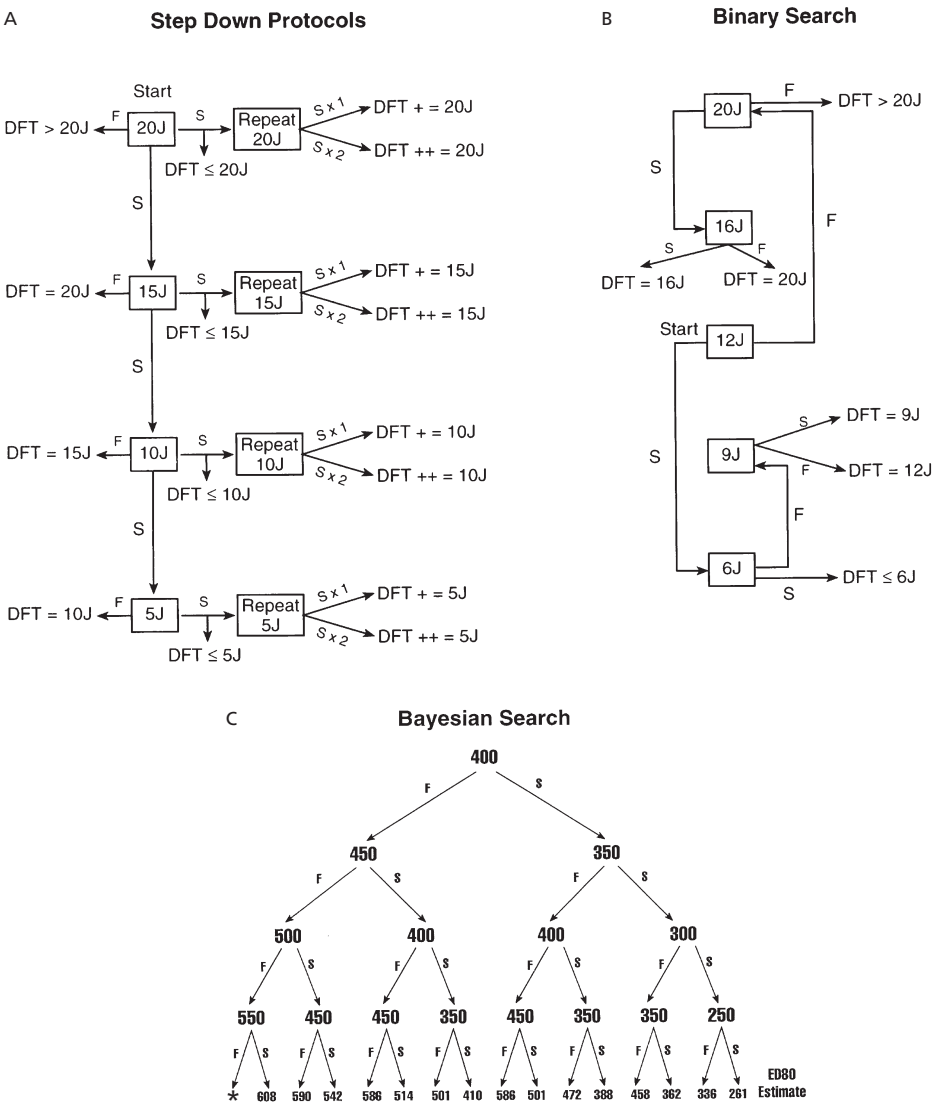


Figure 8.32 Defibrillation threshold (DFT) testing algorithms. (A) The step-down protocol is most commonly used clinically. Starting at 10 J less than the maximal output of the device (20 J in this example), successful defibrillation may either be repeated at this energy (single-energy success protocol) or stepped down incrementally until failure. The lowest energy level to defibrillate successfully is the DFT. By repeating this energy once or twice without failure, the DFT+ and DFT– are defined. J, joules; S, successful defibrillation; F, failed defibrillation. (B) The binary search protocol starts at intermediate energy levels and again the lowest energy level to defibrillate is the DFT. This energy may be repeated for verification. (C) The Bayesian search protocol shown here was developed for use with St. Jude Medical defibrillators. The numerical values represent the voltage output for defibrillation testing using Ventritex devices. The algorithm was constructed mathematically and verified in clinical testing. The voltage output specified by the algorithm after completing the series of four inductions of ventricular fibrillation identifies the ED80 or energy that terminates 80% of fibrillation episodes (*DFT >550 V). (Source: Malkin RA, Herre JM, McGowen L *et al*. A four-shock Bayesian up-down estimator of the 80% effective defibrillation dose. *J Cardiovasc Electrophysiol* 1999; 10: 973–80. Reproduced with permission of John Wiley & Sons Ltd.)

Table 8.6 Safety margins for ICDs based on the defibrillation threshold (DFT) method

Method	*Technique*	*Definition*	*Estimated minimal energy for 99% success*
DFT	Step-down to failure	Lowest energy level yielding a single successful defibrillation	2 DFT
DFT+	Step-down to failure and repeat last successful energy	Lowest energy level yielding two successful defibrillations without a failure	1.5 DFT
DFT++	Step-down to failure and repeat last successful energy twice	Lowest energy level yielding three successful defibrillations without a failure	1.2 DFT or 5 J
Bayesian	Testing in up or down increments based on response to previous attempt	Completion of a four-shock algorithm	Bayesian DFT + 100 V
Single energy, two successes	Single energy level tested twice	Two successful defibrillations without failure at the same energy level	2 DFT
Single energy, three successes	Single energy level tested three times	Three successful defibrillations without failure at the same energy level	1.7 DFT

Recommendations are based on extensive animal studies and mathematical modeling; appropriate testing in each patient is mandatory. (Source: Singer I, Lang D. 1996.[81] Reproduced with permission of Springer.)

curve to the left: improvement in defibrillation efficacy. In any individual patient, the specific reason for passing re-testing cannot be determined with certainty, but a population-based simulation can provide a quantitative estimate of the likelihood of each outcome. Considering a population of patients, the greatest benefit in minimizing the fraction of patients with truly inadequate defibrillation is achieved by revising any system that fails the implant criterion. However, this approach will subject patients who had outlier results on the first test to the risk of unnecessary system revision. A stepwise approach to patients with high DFTs is summarized in Figure 8.33.

Vulnerability testing

This method is based on the close relationship between the ULV and minimum shock strength that defibrillates reliably (Figure 8.2). Unlike the DFT, the ULV is highly reproducible because it depends on predictable patterns of activation and repolarization during normal rhythm. In contrast, the less reproducible DFT depends on unpredictable patterns during VF. Mechanistically linked to re-initiation of VF after a shock, the ULV corresponds to a high and highly reproducible point on the defibrillation probability-of-success curve, approaching 85–90%. The principal advantage of vulnerability testing is that, when applied in a safety margin strategy, it can determine that defibrillation is reliable without inducing VF in 80–95% of patients. In contrast, fibrillation–defibrillation testing requires inducing VF with the attendant risks of circulatory arrest in all patients.[83] To the best of our knowledge, cardiac arrest due to post-shock pulseless electrical activity has not been reported after T wave shocks that do not induce VF. However, vulnerability testing does not reduce the thromboembolic risks associated with shocks in patients with AF. Until recently, the principal disadvantage of vulnerability testing was that it required accurate, operator-performed timing measurement using multiple surface leads to ensure that the T wave shock is delivered at the most vulnerable interval. However, this interval can now be determined automatically using intracardiac EGMs available in ICDs.[84] When a patient-specific strategy is used, first shock strength may be programmed safely at ULV + 5J.[85] When a safety margin strategy is used, testing may be

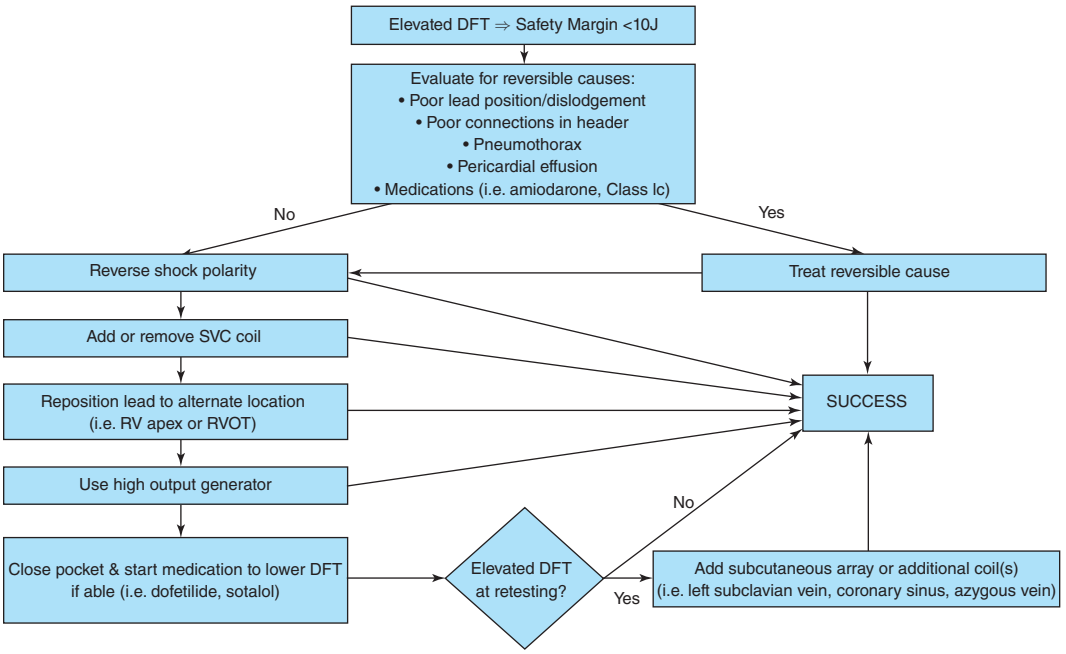


Figure 8.33 Suggested algorithm for management of the patient with an elevated defibrillation threshold (DFT), defined as a safety margin of <10 J below the maximal device output. The implanter should first rule out and treat reversible causes of elevated DFTs, and then attempt further modifications to the configurations and/or treatment regimen as illustrated. RV, right ventricular; RVOT, right ventricular outflow tract; SVC, superior vena cava.

performed 10–15 J below the maximum output of the ICD.

Implantation without assessing defibrillation efficacy

An obviously appealing approach would be to identify clinical correlates of high DFTs or failure to meet the implant criterion so that testing is limited to those at high risk for unsuccessful defibrillation. Multiple retrospective studies have analyzed such clinical correlates. Table 8.7 summarizes their results, which have not been entirely consistent. Further, the effect size of each correlate is small. Over a population, they identify patients with DFTs that are statistically higher than average, but differences are too small to be clinically meaningful. To date there is no practical algorithm based on clinical data that provides reliable guidance on whether or not to test an individual patient. This is in part due to the probabilistic nature of defibrillation as discussed previously, which introduces an obligatory degree of randomness into the outcome of any defibrillation testing strategy.

A strategy of no testing or selective testing of certain patients has become increasingly popular. For ICDs implanted in the left pectoral position, the probability of passing defibrillation safety margin testing is high enough (>90%) that testing provides limited incremental information. A "no testing" strategy is based on this presumption of dependable defibrillation, consistent use of ATP to terminate VT, primary prevention ICD recipients who have a low rate of shocks for VT/VF (~5%/year), and programming first shocks to maximum output. Both simulations[86] and retrospective data[87] suggest that limited safety margin testing neither increases risk nor decreases total mortality in such patients, and a prospective clinical trial is in progress.[88]

In considering the balance between implant safety and long-term benefit, a no-testing strategy increases implant efficiency and prevents rare

Table 8.7 Causes and corrections for high defibrillation thresholds (DFTs) at implant

Cause of elevated DFT	*Diagnosis*	*Correction*
Poor lead position	On fluoroscopy distal coil out of RV, proximal coil low in atrium	Reposition lead
Increased high-voltage impedance	Data from defibrillation attempt, commanded determination of impedance	Check header connections, reposition lead and/or coils, add SVC to single-coil system, add SQ array, relieve pneumothorax
Pneumothorax	High shock impedance, fluoroscopy, dyspnea	Relieve pneumothorax
Hypoxia	Low oxygen saturation	Lighten sedation, assist ventilation
Ischemia	Chest pain, ECG changes, hypotension	Anti-ischemic therapy
Multiple defibrillations	Numerous previous defibrillation attempts	Implant device in best configuration and retest
Antiarrhythmic drugs or anesthetics	Exclude other etiologies	Retest after stopping drugs, stop inhaled anesthetics
Poor current distributions	High or low shocking impedance, poor lead positions	Reposition coil, add SVC coil to single-coil system, add SQ array or azygous lead
Shunting current through guidewires or retained leads	Retained guidewires, temporary or permanent pacing leads	Retest after removing wires or leads
Poor myocardial substrate	Exclusion of other causes, failure of multiple lead configurations and polarity	Add coils, SQ array, azygous lead, epicardial patches to circuit, use high-output device, add class III antiarrhythmic drugs that reduce DFTs

RV, right ventricle; SQ, subcutaneous; SVC, superior vena cava.

deaths due to fibrillation–defibrillation testing,[83] although it probably does not increase safety in comparison with vulnerability testing. Overall, sensing issues require induction of VF in about 5% of primary prevention ICD recipients because of marginal R waves, device–device interactions, or intra-device interactions. Testing is contraindicated in about 5% because of conditions such as left atrial appendage thrombus, inadequate anesthesia, suspected poor hemodynamic tolerance of testing, and unreliable external rescue shocks. In the remaining majority of primary prevention ICD recipients, there is no consensus on the overall risk–benefit of testing, but testing remains the recommendation of the Heart Rhythm Society.

The postoperative management of patients includes monitoring of vital signs and heart rhythm during the recovery from anesthesia or conscious sedation, as well as the completion of a course of perioperative antibiotics. A chest radiograph is performed to document lead position and to rule out complications from the implantation such as a pneumothorax. Typically, the lead function is assessed non-invasively before the patient is discharged from hospital. The duration of postoperative hospitalization has decreased remarkably with modern ICD technology. Often patients are discharged less than 24 h after surgery, and some implants can be performed on an out-patient basis for primary prevention indications.

The follow-up of patients after ICD implantation usually consists of an early evaluation of wound healing and lead integrity. This is often performed approximately 2–4 weeks after implantation. At that visit, pacing outputs can be reprogrammed and lead function can be assessed non-invasively. Traditionally, ICD patients are evaluated with device interrogation and pacing threshold testing every 3 months. However, given the reliability of modern pulse generators and leads, follow-up

every 6 months among clinically stable patients is now standard, with even less frequent visits common among subjects whose systems are followed with remote monitoring.

For dual chamber systems, a separate atrial lead is used. Typically this is a simple bipolar pacemaker lead, with no unique design for being part of an ICD. Despite the rapid acceptance of this technology, all of the early large studies establishing ICD indications evaluated only single chamber systems. The first large study to evaluate directly the impact of dual chamber pacing among ICD patients was the DAVID trial.[89] This was a single-blind, randomized trial of 506 subjects with standard indications for ICDs. Patients underwent implantation with a dual chamber ICD and were randomized to ventricular back-up pacing (VVI at 40 bpm) or dual chamber rate-modulated pacing (DDDR at 70 bpm). Surprisingly, dual chamber pacing was associated with worse clinical outcomes. The results of this study have challenged the approach of indiscriminate use of dual chamber pacing among ICD patients. Subsequent studies showed that the deleterious effects of dual chamber ICDs could be avoided with algorithms or pacing modes to minimize right ventricular pacing.[90] As noted above, the discrimination of dual chamber devices has not been shown to be superior to that of single chamber devices for most primary prevention patients. Accordingly, dual chamber ICDs can be used safely when clinically indicated, but they should not be used indiscriminately. They have a role in patients with sinus bradycardia where atrial support pacing is desirable, patients with atrial arrhythmias where the diagnostic value of atrial sensing will be potentially useful, and patients with high burdens of arrhythmias where dual chamber EGMs can facilitate the interpretation and classification of arrhythmias.

ICD therapy and programming

High-rate, overdrive pacing is very effective for terminating VT. Adaptive algorithms are used in which the pacing rate is programmed based upon the tachycardia cycle length of each episode of tachycardia (Figure 8.34). Randomized studies have shown similar efficacy of burst (constant cycle length in the train) and ramp (decremental cycle lengths in the train) pacing when applied to slower VTs, but greater efficacy for burst pacing when applied to VTs faster than 187 bpm. Figure 8.35 shows an example of ATP for fast VT in the VF zone. It also highlights several interpretive issues in analyzing ICD-stored EGMs. Early studies of ATP in ICDs reported high rates for pace termination of spontaneous episodes of relatively slow VT, typically approximately 90%, with low rates of arrhythmia acceleration (1–3%). More recent data indicate that many of these episodes would likely have terminated spontaneously. Recent data indicate success rates of 45–50% for episodes of VT faster than 182 bpm and lasting longer than 30 beats. These observations support a strategy of empiric programming of ATP in patients with the underlying substrate for monomorphic VT (Table 8.5).[91]

A series of clinical trials has helped determine programming parameters to optimize therapy and minimize unnecessary shocks, particularly in the primary prevention population. The PainFree trials showed that empiric programming of ATP was effective and reduced inappropriate shocks. Moreover, antitachycardia pacing for arrhythmias at rates as high as 250 bpm was shown to be safe.[92] The Comparison of Empiric to Physician-Tailored Programming of Implantable Cardioverter-Defibrillators (EMPIRIC) study demonstrated that standard algorithms, including antitachycardia pacing for rapid arrhythmias, was preferable to individualized programming based on patient or arrhythmia characteristics.[93] An analysis of these early studies showed that many arrhythmias self-terminated, indicating that detection times were too short. This led to studies of both prolonged detection time and increased rate cut-off for therapy. The Primary Prevention Parameters Evaluation (PREPARE) study was one such study where arrhythmias at rates of less than 182 bpm were not treated and detection intervals were prolonged.[94] This programming strategy results in fewer appropriate as well as inappropriate shocks. It also reduces shocks for lead malfunctions and extraneous noise. An even more dramatic approach to ICD programming was employed in the MADIT-RIT trial where separate arms of the study had devices programmed to withhold therapy for 60 s at rates less than 200 bpm or to deliver no therapy for any arrhythmia of less than 200 bpm.[95] These arms were

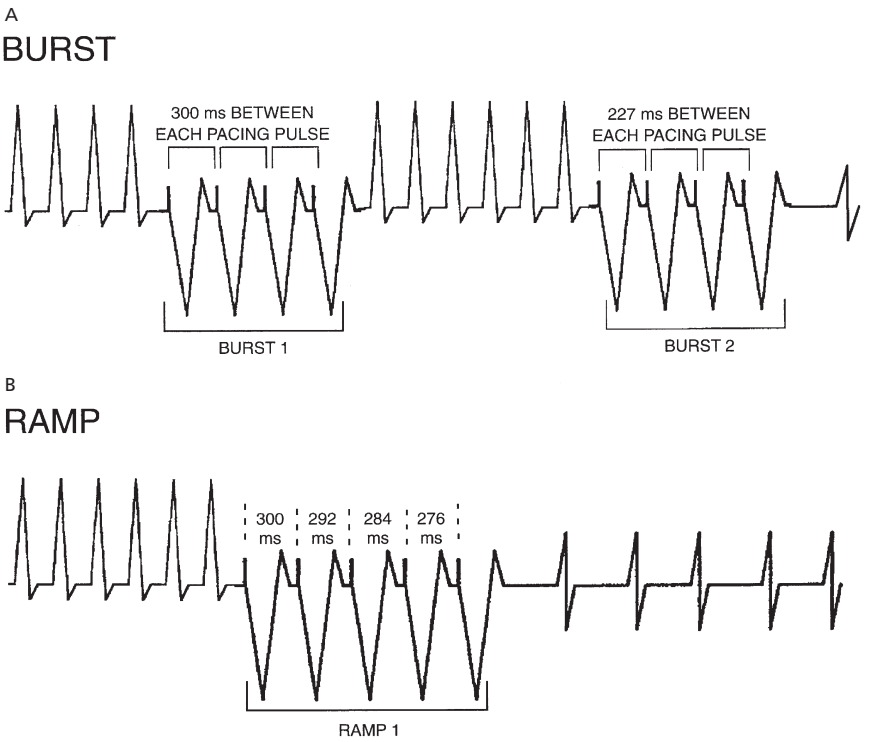


Figure 8.34 Schematic of burst and ramp antitachycardia pacing (ATP). (A) Four beats of ventricular tachycardia are followed by the first burst of ATP at 300 ms for four beats. The rate for this burst is determined as a programmable percentage of the tachycardia cycle length. Tachycardia continues after burst 1, so after redetection burst 2 is delivered at a programmable rate faster than burst 1 (227 ms in this example). The pacing interval for subsequent bursts will decrement further until a minimum pacing cycle length is reached, all ATP attempts are delivered, or the tachycardia terminates. (B) In ramp ATP there is a decrement in the pacing interval between consecutive stimuli. The initial pacing rate starts as a percentage of the tachycardia cycle length. Multiple ramp attempts can be programmed with shorter intervals in each subsequent attempt. (Source: Boston Scientific Corporation. Reproduced with permission of Boston Scientific.)

associated with fewer inappropriate therapies and lower mortality, without an increase in the rate of syncope. The link between inappropriate therapies and mortality is less clear from this study, as most therapies were ATP and not shocks. Table 8.5 and Table 8.8 summarize the considerations and suggested ICD programming for primary and secondary prevention patients.

Summary

ICD therapy has undergone a remarkable transformation in the 25 years since the devices were first approved for human use. Modern devices provide detailed information about the rate and morphology of ECG signals, as well as physiological parameters that help manage patients remotely. The simplicity of defibrillator implantation now approaches that of pacemakers and more patients have been identified who can benefit from this therapy. However, the reliability of transvenous leads and the incidence and impact of unnecessary shocks are problems that have blunted full adoption of this therapy. Improvement in lead design, including subcutaneous systems, newer programming strategies, and better patient selection will hopefully contribute to improved outcomes and further reductions of SCD.

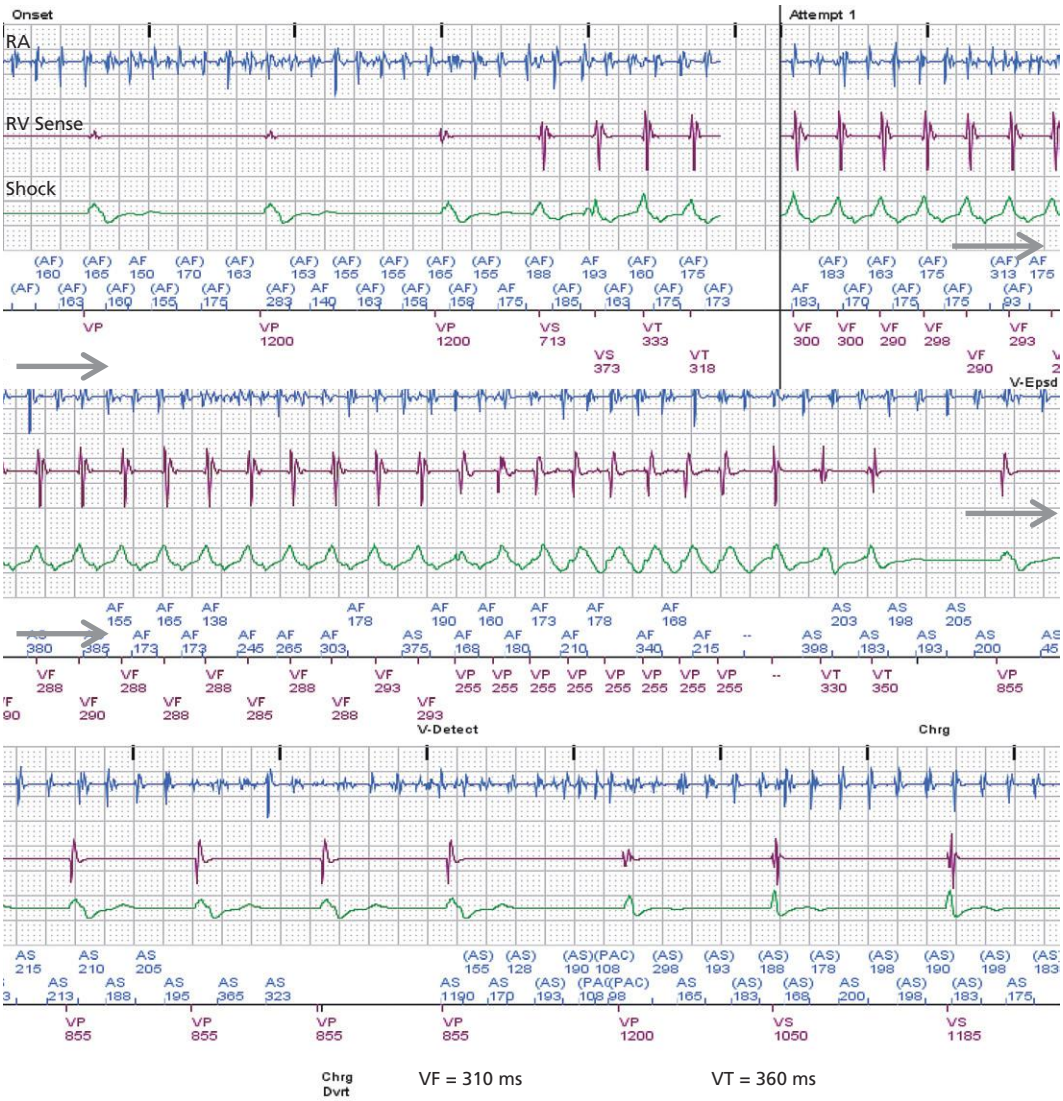


Figure 8.35 The continuous stored electrogram (EGM) shows atrial (RA), near-field integrated-bipolar (RV Sense), and far-field (Shock) EGMs. The dual chamber marker channel displays atrial intervals above and ventricular intervals below the line. The atrial rhythm throughout is atrial fibrillation (AF, marker channel). (A) The first three ventricular intervals are paced at 1200 ms (50 bpm). The fourth beat shows onset of regular tachycardia that accelerates to a cycle length of 300–290 ms. The vertical line denotes interruption of recording after onset of tachycardia and just before VF is detected initially (V-Epsd at end of panel). (B) Persistence of device-detected "ventricular fibrillation (VF)" is confirmed in the middle of the panel (V-Detect), followed by antitachycardia pacing (ATP) in the VF zone that terminates tachycardia. Because ATP was delivered in the VF zone, the ICD does not undergo a full redetection process, but rather a more limited reconfirmation process. It begins to charge (Chrg) when two of three ventricular intervals after ATP are classified in the ventricular tachycardia (VT) zone. ATP is followed by post-therapy pacing for five beats at 855 ms (70 bpm). (C) "Chrg Dvrt" indicates that the ICD classifies the tachycardia episode as completed so that the charge on the high-voltage capacitors is dissipated. Thus, the patient is spared a shock, but the battery loses the corresponding energy. The last two ventricular EGMs represent slowly-conducted AF and differ markedly in morphology from tachycardia EGMs. The ICD's classification of this rhythm based on rate alone is "VF." It does not apply supraventricular tachycardia (SVT)–VT discriminators in the VF zone. The physician's classification is monomorphic VT during AF based on the abrupt onset of rapid, regular tachycardia with morphology different from the conducted beats during AF that terminates distinctly with ATP. The ICD may be reprogrammed so that this tachycardia is classified in a VT zone to increase the likelihood that ATP will be delivered without charging.

Table 8.8 Considerations for ICD programming

Use of β-blockers
Heart rate during exercise
Rate of prior documented clinical sustained ventricular tachycardia (VT)
Antiarrhythmic drugs that may slow VT rate
Rate and duration of prior documented non-sustained VTs
Rate of prior documented supraventricular tachycardias (SVTs) and likely effectiveness of SVT–VT discriminators in rejecting SVT

References

1 Mirowski M, Mower MM, Gott VL, *et al*. Feasibility and effectiveness of low-energy catheter defibrillation in man. *Circulation* 1973; 47: 79–85.

2 Epstein AE, Dimarco JP, Ellenbogen KA, *et al*. ACC/AHA/HRS 2008 Guidelines for Device-Based Therapy of Cardiac Rhythm Abnormalities. *Circulation* 2008; 117: 2820–2840.

3 Tracy CM, Epstein AE, Darbar D, *et al*. 2012 ACCF/AHA/HRS focused update of the 2008 guidelines for device-based therapy of cardiac rhythm abnormalities: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines. *Circulation* 2012; 126: 1784–1800.

4 The Antiarrhythmic Versus Implantable Defibrillator (AVID) Investigators. A comparison of antiarrhythmic-drug therapy with implantable defibrillators in patients resuscitated from near-fatal ventricular arrhythmias. *N Engl J Med* 1997; 337: 1576–1583.

5 Sheldon R, Connolly S, Krahn A, *et al*. Identification of patients most likely to benefit from implantable cardioverter-defibrillator therapy: the Canadian Implantable Defibrillator Study. *Circulation* 2000; 101: 1660–1664.

6 Kuck K-H, Cappato R, Siebels J, *et al*. Randomized comparison of antiarrhythmic drug therapy with implantable defibrillators in patients resuscitated from cardiac arrest: the Cardiac Arrest Study Hamburg (CASH). *Circulation* 2000; 102: 748–754.

7 Moss A, Hall J, Cannom D, *et al*. Improved survival with an implanted defibrillator in patients with coronary disease at high risk of ventricular arrhythmias. *N Engl J Med* 1997; 335: 1933–1940.

8 Buxton AE, Lee DL, Fisher JD, *et al*. A randomized study of the prevention of sudden death in patients with coronary artery disease. *N Engl J Med* 1999; 341: 1882–1890.

9 Gold MR, Nisam S. Primary prevention of sudden cardiac death with implantable cardioverter defibrillators: Lessons learned from MADIT and MUSTT. *Pacing Clin Electrophysiol* 2000; 23: 1981–1985.

10 Buxton AE, Lee KL, DiCarlo L, *et al*. Electrophysiologic testing to identify patients with coronary artery disease who are at risk for sudden death. *N Engl J Med* 2000; 342: 1937–1945.

11 Moss AJ, Zareba W, Hall WJ, *et al*. Prophylactic implantation of a defibrillator in patients with myocardial infarction and reduced ejection fraction. *N Engl J Med* 2002; 346: 877–883.

12 Bardy GH, Lee KL, Mark DB, *et al*. Amiodarone or an implantable cardioverter-defibrillator for congestive heart failure. *N Engl J Med* 2005; 352: 225–237.

13 Kadish A, Dyer A, Daubert JP, *et al*. Prophylactic defibrillator implantation in patients with nonischemic dilated cardiomyopathy. *N Engl J Med* 2004; 350: 2151–2158.

14 Maron BJ, Spirito P, Shen WK, *et al*. Implantable cardioverter-defibrillators and prevention of sudden cardiac death in hypertrophic cardiomyopathy. *JAMA* 2007; 298: 405–412.

15 Nademanee K, Veerakul G, Mower M, *et al*. Defibrillator versus β-blockers for unexplained death in Thailand (DEBUT): A randomized clinical trial. *Circulation* 2003; 107: 2221–2226.

16 Schwartz PJ, Spazzolini C, Priori SG, *et al*. Who are the long-QT syndrome patients who receive an implantable cardioverter-defibrillator and what happens to them?: data from the European Long-QT Syndrome Implantable Cardioverter-Defibrillator (LQTS ICD) Registry. *Circulation* 2010; 122: 1272–1282.

17 Bigger JT. Prophylactic use of implanted cardiac defibrillators in patients at high risk for ventricular arrhythmias after coronary-artery bypass graft surgery. Coronary Artery Bypass Graft (CABG) Patch Trial Investigators. *N Engl J Med* 1997; 337: 1569–1575.

18 Hohnloser SH, Kuck KH, Dorian P, *et al*. Prophylactic use of an implantable cardioverter-defibrillator after acute myocardial infarction. *N Engl J Med* 2004; 351(24): 2481–2488.

19 Steinbeck G, Andresen D, Seidl K, *et al*. Defibrillator implantation early after myocardial infarction. *N Engl J Med* 2009; 361(15): 1427–1436.

20 Dorian P, Hohnloser SH, Thorpe KE, *et al*. Mechanisms underlying the lack of effect of implantable cardioverter-defibrillator therapy on mortality in high-risk patients with recent myocardial infarction: insights from the Defibrillation in Acute Myocardial Infarction Trial (DINAMIT). *Circulation* 2010; 122: 2645–2652.

21 Goldenberg I, Vyas AK, Hall WJ, *et al*. Risk stratification for primary implantation of a cardioverter-defibrillator

in patients with ischemic left ventricular dysfunction. *J Am Coll Cardiol* 2008; 51: 288–296.
22 Gold MR, Ensley D, Chilson D, *et al*. T-wave alternans SCD HeFT study: primary endpoint analysis. *Circulation* 2006; 114(18): 2113.
23 de Vreede-Swagemakers JJ, Gorgels AP, Dubois-Arbouw WI, *et al*. Out-of-hospital cardiac arrest in the 1990's: a population-based study in the Maastricht area on incidence, characteristics and survival. *J Am Coll Cardiol* 1997; 30: 1500–1505.
24 Stecker EC, Vickers C, Waltz J, *et al*. Population-based analysis of sudden cardiac death with and without left ventricular systolic dysfunction: two-year findings from the Oregon Sudden Unexpected Death Study. *J Am Coll Cardiol* 2006; 47: 1161–1166.
25 Efimov IR, Cheng Y, Van Wagoner DR, Mazgalev T, Tchou PJ. Virtual electrode-induced phase singularity: A basic mechanism of defibrillation failure. *Circ Res* 1998; 82: 918–925.
26 Swerdlow CD, Shehata M, Chen PS. Using the upper limit of vulnerability to assess defibrillation efficacy at implantation of ICDs. *Pacing Clin Electrophysiol.* 2007; 30: 258–270.
27 Winfree AT. Sudden cardia death: A problem in topology. *Sci Am* 1983; 248: 144–149.
28 Yamanouchi Y, Cheng Y, Tchou PJ, Efimov IR. The mechanisms of the vulnerable window: The role of virtual electrodes and shock polarity. *Can J Physiol Pharmacol* 2001; 79: 25–33.
29 Efimov IR, Gray RA, Roth BJ. Virtual electrodes and deexcitation: New insights into fibrillation induction and defibrillation. *J Cardiovasc Electrophysiol* 2000; 11: 339–353.
30 Chattipakorn N, Ideker RE. Delayed afterdepolarization inhibitor: A potential pharmacologic intervention to improve defibrillation efficacy. *J Cardiovasc Electrophysiol* 2003; 14: 72–75.
31 Weiss JN, Qu Z, Chen PS, *et al*. The dynamics of cardiac fibrillation. *Circulation* 2005; 112: 1232–1240.
32 Choi BR, Liu T, Salama G. Ventricular fibrillation: Mother rotor or multiple wavelets? *Circ Res* 2001; 89: E30.
33 Norton J, Anderson C. Energy management in aluminum electrolytic capacitors. *Proceedings of the 23rd Capacitor and Resistor Technology Symposium* 2003: 269–277.
34 Root M. *The Tab Battery Book : An In-depth Guide to Construction, Design, and Use*. New York, NY: McGraw-Hill/TAB Electronics, 2010.
35 Kaiser C. *The Capacitor Handbook: A Comprehensive Guide for Correct Component Selection in All Circuit Applications. Know What to Use When and Where*. Minneapolis, MN: C J Publishing; 2011.
36 Baura G. *Medical Device Technologies; A System Based Overview using EngineeringS*. Oxford: Academic Press, 2012.
37 Kleemann T, Becker T, Doenges K, *et al*. Annual rate of transvenous defibrillation lead defects in implantable cardioverter-defibrillators over a period of >10 years. *Circulation* 2007; 115: 2474–2480.
38 Maisel WH, Kramer DB. Implantable cardioverter-defibrillator lead performance. *Circulation* 2008; 117: 2721–2723.
39 Ellenbogen KA, Wook MA, Shepard RK, *et al*. Detection and management of an implantable cardioverter defibrillator lead failure: incidence and clinical implications. *J Am Coll Cardiol* 2003; 41: 73–80.
40 Wilkoff BL, Belott PH, Love CJ, *et al*. Improved extraction of ePTFE and medical adhesive modified defibrillation leads from the coronary sinus and great cardiac vein. *Pacing Clin Electrophysiol* 2005; 28: 205–211.
41 Kroll MW. A minimal model of the monophasic defibrillation pulse. *Pacing and clinical electrophysiology. Pacing Clin Electrophysiol* 1993; 16: 769–777.
42 Kroll MW. A minimal model of the single capacitor biphasic defibrillation waveform. *Pacing Clin Electrophysiol* 1994; 17: 1782–1792.
43 Walcott GP, Walker RG, Cates AW, Krassowska W, Smith WM, Ideker RE. Choosing the optimal monophasic and biphasic waveforms for ventricular defibrillation. *J Cardiovasc Electrophysiol* 1995; 6: 737–750.
44 Fishler MG. Theoretical predictions of the optimal monophasic and biphasic defibrillation waveshapes. *IEEE Trans Biomed Eng* 2000; 47: 59–67.
45 Schuder J, Stoeckle H, West JA. Transthoracic ventricular defibrillation in the dog with truncated exponential stimuli. *IEEE Trans Biomed Eng BME* 1971; 18: 410–415.
46 Gold M, Val-Mejias J, Cuoco F, Siddiqui M. Comparison of fixed tilt and tuned defibrillation waveforms: The promise study. *J Cardiovasc Electrophysiol* 2013; 24: 323–327.
47 Blair H. On the intensity-time relations for stimulation by electric currents, i. *J Gen Physiol* 1932; 15: 709–729.
48 Cleland B. A conceptual basis for defibrillation waveforms. *Pacing Clin Electrophysiol* 1996; 19: 1186–1195.
49 Swerdlow C, Ahern T, Chen P-S. Comparative reproducibility of defibrillation threshold and upper limit of vulnerability. *Pacing Clin Electrophysiol* 1996; 19: 2103–2111.
50 Swerdlow CD, Brewer JE, Kass RM, Kroll MW. Application of models of defibrillation to human defibrillation data: Implications for optimizing implantable defibrillator capacitance. *Circulation* 1997; 96: 2813–2822.
51 Efimov IR, Cheng Y, Yamanouchi Y, Tchou PJ. Direct evidence of the role of virtual electrode-induced phase

singularity in success and failure of defibrillation. *J Cardiovasc Electrophysiol* 2000; 11: 861–868.

52 Yamanouchi Y, Cheng Y, Tchou PJ, Efimov IR. The mechanisms of the vulnerable window: The role of virtual electrodes and shock polarity. *Can J Physiol Pharmacol* 2001; 79: 25–33.

53 Gold MR, Shorofsky SR. Transvenous defibrillation lead systems. *J Cardiovasc Electrophysiol* 1996; 7: 570–580.

54 Gold MR, Theuns DA, Knight BP, *et al*. Head-to-head comparison of arrhythmia discrimination performance of subcutaneous and transvenous icd arrhythmia detection algorithms: The start study. *J Cardiovasc Electrophysiol* 2012; 23: 359–366.

55 Marchlinski FE, Callans DJ, Gottlieb CD, *et al*. Benefits and lessons learned from stored electrogram information in implantable defibrillators. *J Cardiovasc Electrophysiol* 1995; 6: 832–851.

56 Requena-Carrion J, Vaisanen J, Alonso-Atienza F, Garcia-Alberola A, Ramos-Lopez FJ, Rojo-Alvarez JL. Sensitivity and spatial resolution of transvenous leads in implantable cardioverter defibrillator. *IEEE Trans Bio-Med Eng* 2009; 56: 2773–2781.

57 Swerdlow CD, Brown ML, Lurie K, *et al*. Discrimination of ventricular tachycardia from supraventricular tachycardia by a downloaded wavelet-transform morphology algorithm: A paradigm for development of implantable cardioverter defibrillator detection algorithms. *J Cardiovasc Electrophysiol* 2002; 13: 432–441.

58 Khalighi K, Florin TJ, Peters RW, Shorofsky SR, Gold MR. Distortion of intracardiac electrograms following defibrillator shocks for atrial tachyarrhythmias. *Pacing Clin Electrophysiol* 1997; 20: 1682–1685.

59 Brugada J, Mont L, Figueiredo M, Valentino M, Matas M, Navarro-Lopez F. Enhanced detection criteria in implantable defibrillators. *J Cardiovasc Electrophysiol* 1998; 9: 261–268.

60 Le Franc P, Kus T, Vinet A, Rocque P, Molin F, Costi P. Underdetection of ventricular tachycardia using a 40 ms stability criterion: Effect of antiarrythmic therapy. *Pacing Clini Electrophysiol* 1997; 20: 2882–2892.

61 Swerdlow CD, Chen P-S, Kass RM, Allard JR, Peter CT. Discrimination of ventricular tachycardia from sinus tachycardia and atrial fibrillation in a tiered-therapy cardioverter-defibrillator. *J Am Coll Cardiol* 1994; 23: 1342–1355.

62 Stadler RW, Gunderson BD, Gillberg JM. An adaptive interval-based algorithm for withholding icd therapy during sinus tachycardia. *Pacing Clin Electrophysiol* 2003; 26: 1189–1201.

63 Saba S, Volosin K, Yee R, Swerdlow C, Brown M. Combined atrial and ventricular antitachycardia pacing as a novel method of rhythm discrimination: The dynamic discrimination download study. *Circulation* 2010; 121: 487–497.

64 Wilkoff BL, Kuhlkamp V, Volosin K, *et al*. Critical analysis of dual-chamber implantable cardioverter-defibrillator arrhythmia detection: Results and technical considerations. *Circulation* 2001; 103: 381–386.

65 Glikson M, Swerdlow CD, Gurevitz OT, *et al*. Optimal combination of discriminators for differentiating ventricular from supraventricular tachycardia by dual-chamber defibrillators. *J Cardiovasc Electrophysiol* 2005; 16: 732–739.

66 Stein KM, Euler DE, Mehra R, Seidl K, Slotwiner DJ, Mittal S, Markowitz SM, Lerman BB. Do atrial tachyarrhythmias beget ventricular tachyarrhythmias in defibrillator recipients? *J Am Coll Cardiol* 2002; 40: 335–340.

67 Klein GJ, Gillberg JM, Tang A, *et al*. Improving svt discrimination in single-chamber icds: A new electrogram morphology-based algorithm. *J Cardiovasc Electrophysiol* 2006; 17: 1310–1319.

68 Gold MR, Ahmad S, Browne K, Berg KC, Thackeray L, Berger RD. Prospective comparison of discrimination algorithms to prevent inappropriate icd therapy: Primary results of the rhythm id going head to head trial. *Heart Rhythm* 2012; 9: 370–377.

69 Moss AJ, Schuger C, Beck CA, *et al*. Reduction in inappropriate therapy and mortality through icd programming. *N Engl J Med* 2012; 367(24): 2275–2283.

70 Almendral J, Arribas F, Wolpert C, *et al*. Dual-chamber defibrillators reduce clinically significant adverse events compared with single-chamber devices: Results from the datas (dual chamber and atrial tachyarrhythmias adverse events study) trial. *Europace* 2008; 10: 528–535.

71 Theuns DAMJ, Rivero-Ayerza M, Boersma E, Jordaens L. Prevention of inappropriate therapy in implantable defibrillators: A meta-analysis of clinical trials comparing single-chamber and dual-chamber arrhythmia discrimination algorithms. *Int J Cardiol* 2008; 125: 352–357.

72 Ricci RP, Quesada A, Almendral J, *et al*. Dual-chamber implantable cardioverter defibrillators reduce clinical adverse events related to atrial fibrillation when compared with single-chamber defibrillators: A subanalysis of the datas trial. *Europace* 2009; 11: 587–593.

73 Friedman PA, McClelland RL, Bamlet WR, *et al*. Dual-chamber versus single-chamber detection enhancements for implantable defibrillator rhythm diagnosis: The detect supraventricular tachycardia study. *Circulation* 2006; 113: 2871–2879.

74 Powell BD, Cha YM, Asirvatham SJ, *et al*. Implantable cardioverter defibrillator electrogram adjudication for device registries: Methodology and observations from altitude. *Pacing Clin Electrophysiol* 2011; 34: 1003–1012.

75 Baddour LM, Epstein AE, Erickson CC, *et al*. Update on cardiovascular implantable electronic device infections and their management. *Circulation* 2010; 121: 458–477.
76 Gold MR, Peters RW, Johnson JW, Shorofsky SR. Complications associated with pectoral implantation of cardioverter-defibrillators. *Pacing Clin Electrophysiol* 1997; 20: 208–211.
77 Bardy GH, Smith WM, Hood MA, *et al*. An entirely subcutaneous implantable cardioverter-defibrillator. *N Engl J Med* 2010; 363: 36–44.
78 Doshi S, Pittaro M, Reeves R, *et al*. Efficacy of tuned waveforms based on different membrane time constants on defibrillation thresholds: Primary results from the power trial. *Pacing Clin Electrophysiol* 2012; 35: 1253–1261.
79 Smits K, Virag N. Estimating the parameter distributions of defibrillation shock efficacy curves in a large population. *Ann Biomed Eng* 2010; 38: 1314–1325.
80 Swerdlow CD, Davie S, Ahern T, Chen PS. Comparative reproducibility of defibrillation threshold and upper limit of vulnerability. *Pacing Clin Electrophysiol* 1996; 19: 2103–2111.
81 Singer I, Lang D. The defibrillation threshold. In: Kroll MW, Lehmann MH, eds. *Implantable Cardioverter Defibrillator Therapy. The Engineering Clinical Interface*. Norwell: Kluwer Academic, 1996: 89–129.
82 Barnett AG, van der Pols JC, Dobson AJ. Regression to the mean: What it is and how to deal with it. *Int J Epidemiol* 2005; 34: 215–220.
83 Birnie D, Tung S, Simpson C, *et al*. Complications associated with defibrillation threshold testing: The canadian experience. *Heart Rhythm* 2008; 5: 387–390.
84 Birgersdotter-Green U, Ruetz LL, Anand K, *et al*. Automated vulnerability testing identifies patients with inadequate defibrillation safety margin. *Circ Arrhythm Electrophysiol* 2012; 5(6): 1073–1080.
85 Swerdlow CD. Implantation of cardioverter defibrillators without induction of ventricular fibrillation. *Circulation* 2001; 103: 2159–2164.
86 Gula LJ, Massel D, Krahn AD, *et al*. Is defibrillation testing still necessary? A decision analysis and markov model. *J Cardiovasc Electrophysiol* 2008; 19: 400–405.
87 Blatt JA, Poole JE, Johnson GW, *et al*. No benefit from defibrillation threshold testing in the scd-heft (sudden cardiac death in heart failure trial). *J Am Coll Cardiol* 2008; 52: 551–556.
88 Healey JS, Hohnloser SH, Glikson M, *et al*. The rationale and design of the shockless implant evaluation (simple) trial: A randomized, controlled trial of defibrillation testing at the time of defibrillator implantation. *Am Heart J* 2012; 164: 146–152.
89 The DAVID Investigators. Dual-chamber pacing or ventricular backup pacing in patients with an implantable defibrillator: the dual chamber and VVI implantable defibrillator (DAVID) trial. *JAMA* 2002; 288: 3115–3123.
90 Olshansky B, Day JD, Moore S, *et al*. Is dual-chamber programming inferior to single-chamber programming in an implantable cardioverter defibrillator? Result of the INTRINSIC RV (Inhibition of Innecessary RV Pacing With AVSH in ICDs) study. *Circulation* 2007; 115: 9–16.
91 Schaumann A, Muhlen FVZ, Herse B, *et al*. Empirical versus tested antitachycardia pacing in implanted cardioverter defibrillators: a prospective study including 200 patients. *Circulation* 1998; 97: 66–74.
92 Wathen MS, Sweeney MO, DeGroot PJ *et al*. Shock reduction using antitachycardia pacing for spontaneous rapid ventricular tachycardia in patients with coronary artery disease. *Circulation* 2001; 104: 796–801.
93 Wilkoff BL, Ousdigian KT, Sterns LD, *et al*. A Comparison of Empiric to Physician-Tailored Programming of Implantable Cardioverter-Defibrillators: Results From the Prospective Randomized Multicenter EMPIRIC Trial. *J Am Coll Cardiol* 2006; 48: 330–339.
94 Wilkoff BL, Williamson BD, Stern RS, *et al*. Strategic programming of detection and therapy parameters in implantable cardioverter-defibrillators reduces shocks in primary prevention patients: Results from the PREPARE (Primary Prevention Parameters Evaluation) study. *J Am Coll Cardiol* 2008; 52: 541–550.
95 Moss AJ, Schuger C, Beck CA, *et al*. Reduction in inappropriate therapy and mortality through ICD programming. *N Engl J Med* 2012; 367: 2275–2283.

9

CHAPTER 9

Cardiac resynchronization therapy

Yong-Mei Cha
Mayo Clinic, Rochester, MN, USA

Heart failure and mechanisms of cardiac resynchronization therapy

Chronic heart failure (HF) is one of the leading epidemics in the US, affecting 5 million patients overall and claiming nearly 300 000 lives annually. In the Framingham study, total mortality was 24% in women and 55% in men within 4 years of developing symptomatic HF.[1] Contemporary pharmacological therapies (β-blockers, angiotensin-converting enzyme inhibitors, angiotensin receptor blockers, mineralocorticoid receptor antagonists, and statins) have yielded substantial reductions in mortality from progressive HF. Despite these advances in medical therapy, HF still carries high morbidity and mortality. The rates of rehospitalization have remained unchanged over the past decade. Each year, more than 1 million hospitalizations with a primary diagnosis of HF occur in the US and contribute more than $34 billion to medical costs for HF.[2]

The fundamental pathophysiology is impaired myocardial contractility in systolic HF, leading to ventricular hypertrophy and dilation. Disordered electromechanical coupling at multiple levels contributes to reduced ventricular pump function. Left bundle branch block (LBBB) is frequently accompanied by progression of left ventricular (LV) systolic dysfunction, with the consequence of delayed electrical conduction to the LV lateral wall. The loss of normal interventricular (VV) and intraventricular conduction via the His–Purkinje conduction system results in dyssynchronous ventricular excitation and contraction (Figure 9.1, left).[3] This recognized ventricular dyssynchrony further reduces myocardial efficiency and cardiac output, worsening cardiac performance.

Cardiac resynchronization therapy (CRT), a non-pharmacological therapeutic approach developed more than a decade ago, resynchronizes electrical and mechanical coupling by placing leads to the right and left ventricles [via the coronary sinus (CS)] to excite the right ventricle (RV), and the LV lateral wall simultaneously (Figure 9.1, right). The acute hemodynamic benefit is apparent, including improvement in ventricular contractility and cardiac output, and reduction in mitral regurgitation and LV filling pressure. It has now been clearly proven that CRT can improve chronic LV systolic dysfunction with evidence of reverse LV remodeling.[4–6] These remodeling effects include reduction in LV volumes and chamber size[7] and improvement in LV ejection fraction (LVEF). At the cellular level, CRT may up-regulate β-adrenergic responses to signaling changes at the receptor and post-receptor levels, improve ion-channel function, and promote mitochondrial energy production.[8–10]

Indications and patient selection

CRT has been shown in numerous clinical trials to be an effective therapy for select HF patients. The American Heart Association/American College of

Cardiac Pacing and ICDs, Sixth Edition. Edited by Kenneth A. Ellenbogen and Karoly Kaszala.
© 2014 John Wiley & Sons, Ltd. Published 2014 by John Wiley & Sons, Ltd.

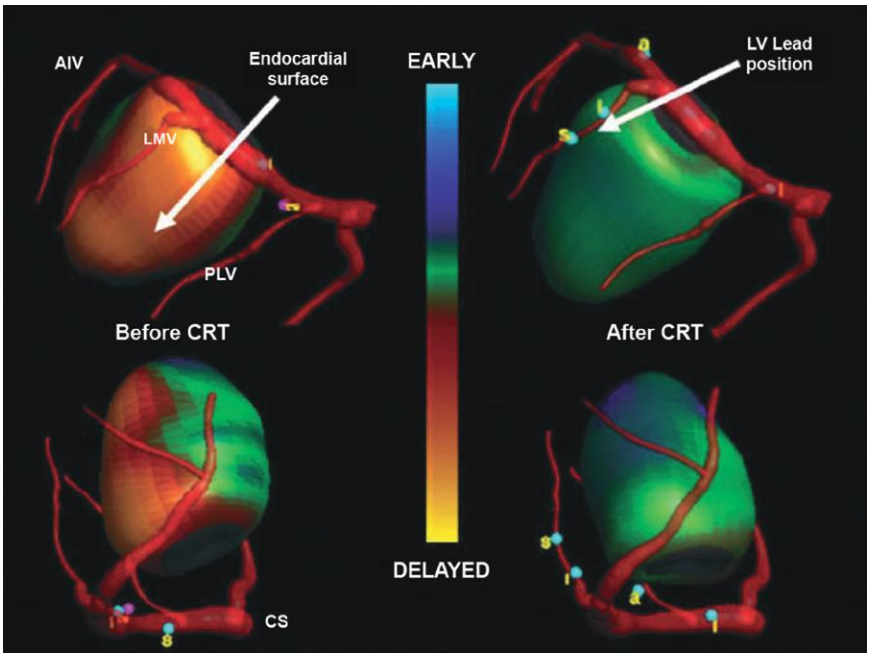


Figure 9.1 Image integration of functional (mechanical dyssynchrony) and anatomical (coronary venous anatomy) information before and after cardiac resynchronization therapy (CRT) at end systole. The branches of the coronary venous tree are displayed in the red reconstruction model. AIV, anterior interventricular vein; CS, coronary sinus; LMV, lateral marginal vein; PLV, posterolateral vein. (Source: Tournoux *et al.* 2007.[3] Reproduced with permission of John Wiley & Sons Ltd.)

Cardiology/Heart Rhythm Society (AHA/ACC/HRS) 2008 guidelines recommended CRT in patients with advanced HF [New York Heart Association (NYHA) class III or IV], evidence of severe LV systolic dysfunction (LVEF $\leq$35%) and evidence of ventricular conduction delay (QRS duration $\geq$120 ms) after failing optimal medical therapy.[11] Based on recently published evidence that CRT also provides benefit to those with mild-to-moderate HF symptoms, the 2012 ACCF/AHA/HRS Focused Update of the 2008 Guidelines for Device-Based Therapy of Cardiac Rhythm Abnormalities was published in September 2012.[12]

The Focused Update document further stratified the class indication by using QRS duration and morphology. Among those who meet the CRT criteria for the 2008 guidelines (NYHA class III or IV, LVEF $\leq$35%, QRS duration $\geq$120 ms), patients are considered class I with a QRS duration of 150 ms or longer and LBBB; and class IIA with a QRS duration of 120–149 ms and LBBB or with a QRS duration of 150 ms or longer and no LBBB (Table 9.1). As mentioned, this modification is based on sufficient evidence that CRT is most beneficial to those with a QRS duration of 150 ms or longer and LBBB morphology, in that up to 70% of these patients may have LV electrical and mechanical delay that can be corrected by the addition of LV pacing.[4,6, 13–15]

In patients with atrial fibrillation (AF) and LVEF of 35% or less, atrioventricular node (AVN) ablation or adequate drug suppression of the ventricular rate to achieve near 100% biventricular pacing is recommended. Anticipated ventricular pacing of 40% or more may be detrimental and could be amended by CRT.[16,17]

The new Focused Update of the guideline recommends CRT for those with NYHA functional class II HF, i.e. mild-to-moderate HF symptoms. Patients with LVEF of 35% or less, a QRS duration of 150 ms or longer, and LBBB are class I candidates for CRT. Patients with a QRS duration of

Table 9.1 Recommendations for cardiac resynchronization therapy (CRT) in patients with systolic heart failure

Patient population	*Class*	*Level*
NYHA class II, III, or ambulatory NYHA class IV, LVEF ≤35%, sinus rhythm QRS duration ≥150 ms, LBBB	I	A/B
NYHA class II, III, or ambulatory class IV, LVEF ≤35%, sinus rhythm QRS duration 120–149 ms, LBBB	IIA	B
NYHA class III or ambulatory class IV, LVEF ≤35%, sinus rhythm QRS duration ≥150 ms, non-LBBB	IIA	A
LVEF ≤35%, AF AVN ablation or medical rate control to allow 100% pacing Anticipated device pacing >40%	IIA	B/C
NYHA class I, ischemic cardiomyopathy, LVEF ≤30%, sinus rhythm QRS duration ≥150 ms, LBBB	IIB	C
NYHA class III or ambulatory class IV, LVEF ≤35%, sinus rhythm QRS duration 120–149 ms, non-LBBB	IIB	B
NYHA class II, LVEF ≤35%, sinus rhythm QRS duration ≥150 ms, non-LBBB	IIB	B
NYHA class I or II QRS duration ≤150 ms, non-LBBB	III	B
Co-morbidities and/or frailty limit survival to ≤1 year	III	C

AF, atrial fibrillation; AVN, atrioventricular node; CRT, cardiac resynchronization therapy; LBBB, left bundle branch block; LVEF, left ventricular ejection fraction; NYHA, New York Heart Association.

120–149 ms with LBBB (class IIA) or those with a QRS duration of 150 ms or longer without LBBB (class IIB) are also potential candidates for CRT.[5,6]

In patients with asymptomatic LV systolic dysfunction (NYHA functional class I), LVEF of 30% or less, a QRS duration of 150 ms or longer, LBBB, and ischemic etiology of HF, CRT may be considered at the physician's discretion as a class IIB indication.[6]

CRT has no benefit in those with mild HF symptoms (NYHA class I or II), with a QRS duration of less than 150 ms and no LBBB, and those with multiple co-morbid conditions and/or expected survival of less than 1 year.[5,6,18,19]

An algorithm of indications for CRT is outlined in the Focused Update document (Figure 9.2).[12] The Focused Update is essentially in agreement with the Heart Failure Society of America CRT Guideline Update published in 2012.[20] The latter document states that to be candidates for CRT, NYHA functional class IV patients should be ambulatory.

Patient selection criteria for CRT are summarized in Table 9.2.

CRT implantation

There are currently three approaches to achieving LV pacing. The most commonly used is the transvenous approach, which utilizes a specially designed delivery system for cannulating the CS to permit delivery of pacing leads into the branches of the epicardial venous trees. When the transvenous approach has failed or is not available, an LV pacing lead can also be placed into the epicardial myocardium under direct visualization by using a left thoracotomy. Finally, transvenous LV endocardial pacing via trans-septal puncture has been described in limited circumstances. The hemodynamic benefit favors endocardial LV pacing; its clinical application is limited however, because chronic anticoagulation is required.[21,22]

Coronary vein anatomy

Coronary venous blood returns to the CS, which opens to the posterior septum of the right atrium. The number of coronary veins and where these veins drain into the CS differ in each patient. From the proximal to the distal CS, the coronary veins

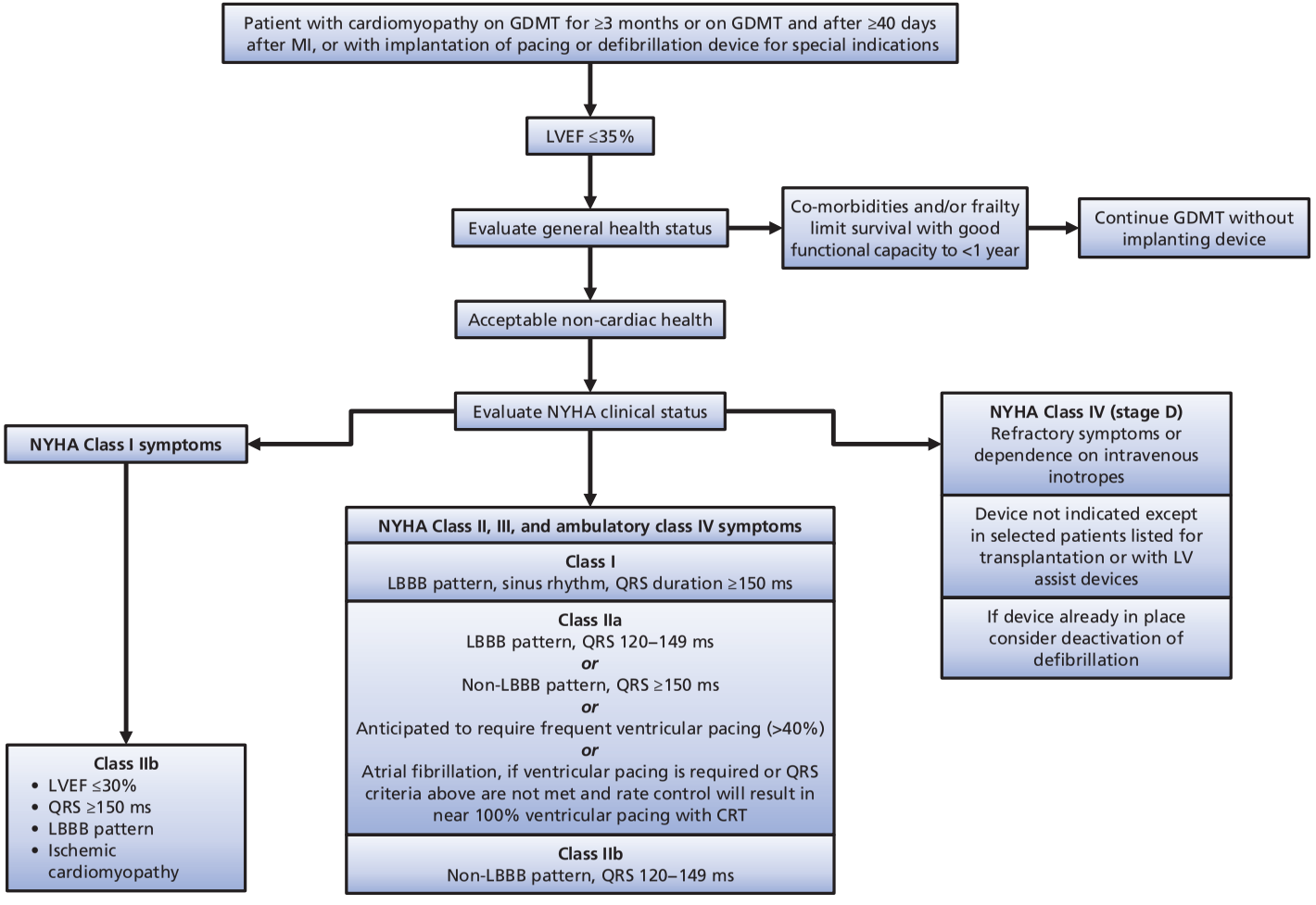


Figure 9.2 Algorithm of indications for cardiac resynchronization therapy (CRT). Benefit for NYHA class I and II patients has been shown in CRT with defibrillation (CRT-D) trials. While patients may not experience immediate symptomatic benefit, late remodeling may be avoided along with long-term heart failure (HF) consequences. No trials have been done that support cardiac resynchronization therapy with pacing (CRT-P) without an ICD in NYHA class I and II patients. Thus, it is anticipated these patients would receive CRT-D unless clinical reasons or personal wishes make CRT-P more appropriate. In patients who are NYHA class III and ambulatory class IV, CRT-D may be chosen, but clinical reasons and personal wishes may make CRT-P appropriate to improve symptoms and quality of life when an ICD is not expected to produce meaningful benefit in terms of survival. GDMT, guideline-directed medical therapy; ICD, implantable cardioverter–defibrillator; LV, left ventricular; LBBB, left bundle branch block; LVEF, left ventricular ejection fraction; MI, myocardial infarction; NYHA, New York Heart Association.

are the middle cardiac, posterior, posterolateral, lateral, anterolateral, and anterointerventricular veins, as shown in Figure 9.3. These coronary venous trees serve as the vehicle and host for LV lead placement. Most coronary veins do not exclusively collect venous return from the LV region after which they are named. The anterolateral or lateral vein may have the branches that are tributaries to the posterolateral, lateral, and anterolateral walls (Figure 9.4A,B). Approximately 60% of LV leads placed in the middle cardiac vein can be navigated to the posterolateral wall of the LV (Figure 9.4C). Overall, lateral lead position can be accomplished through multiple venous distribution, including anterolateral, lateral, posterolateral, and middle cardiac veins.[23] The LV free wall is the most common region of delayed electrical activation and mechanical contraction in HF. It is critical to place the LV lead to the lateral, anterolateral, or posterolateral position to achieve biventricular synchrony. Septal lead location has been considered an unfavorable location for resynchronization.[6,23] In some instances, target veins are present, but they are too small to host an LV lead or, paradoxically, are too large to achieve lead stability in the lateral location.

Table 9.2 Patient selection criteria for cardiac resynchronization therapy (CRT)

- Patients who benefit the most from CRT have a left ventricular ejection fraction (LVEF) of 35% or lower, a QRS duration of 150 ms or longer, and left bundle branch block (LBBB), across NYHA classes I–IV
- CRT may not be as effective, but remains beneficial, in those without LBBB if QRS duration is 150 ms or longer or with LBBB if QRS duration is 120–149 ms, in NYHA classes II–IV
- CRT is not recommended in those without LBBB and with a QRS duration shorter than 120 ms, in any NYHA class

Coronary sinus cannulation

The first step is to identity a fat pad in the atrioventricular (AV) groove where the CS is located (Figure 9.5A). The fat pad appears more lucent than muscle on fluoroscopy (Figure 9.5B). There are a few ways to engage the CS:

- A 0.035-Fr guidewire, such as the SafeSheath® CSG® Worley guidewire (Pressure Products) or Radiofocus Angled Glidewire® (Terumo), can be

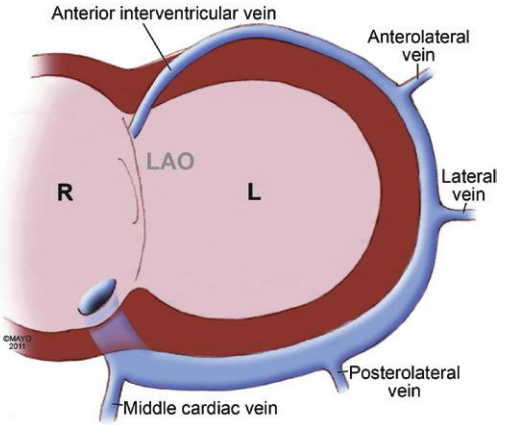


Figure 9.3 Coronary vein anatomy. The venous branches are named. LAO, left anterior oblique.

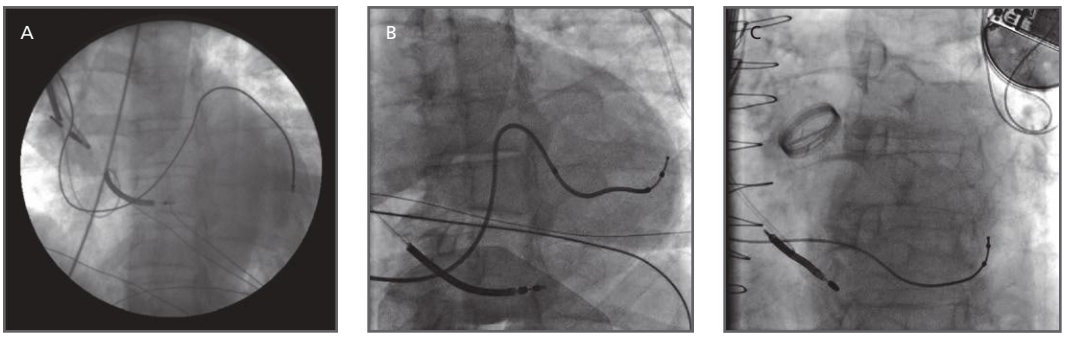


Figure 9.4 Fluoroscopy showing placement of the LV lead at the left ventricular lateral wall via (A) anterolateral, (B) lateral, and (C) middle cardiac veins in left anterior oblique review.

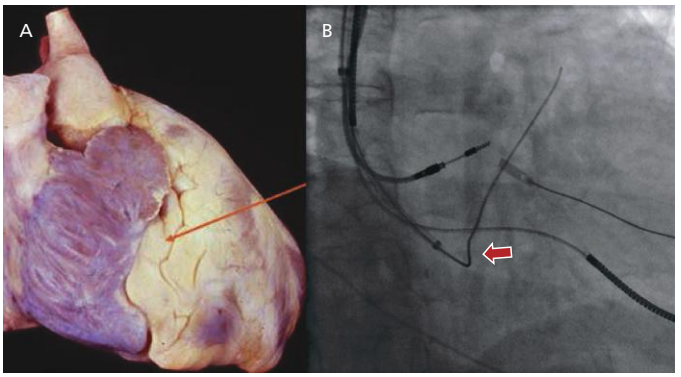


Figure 9.5 (A) Gross right anterior oblique heart anatomy showing the fat pad in the atrioventricular groove (arrow). (B) The fat pad is more lucent than the myocardium on fluoroscopy (arrow). The guidewire is placed into the coronary sinus as shown in this fluoroscopy RAO view.

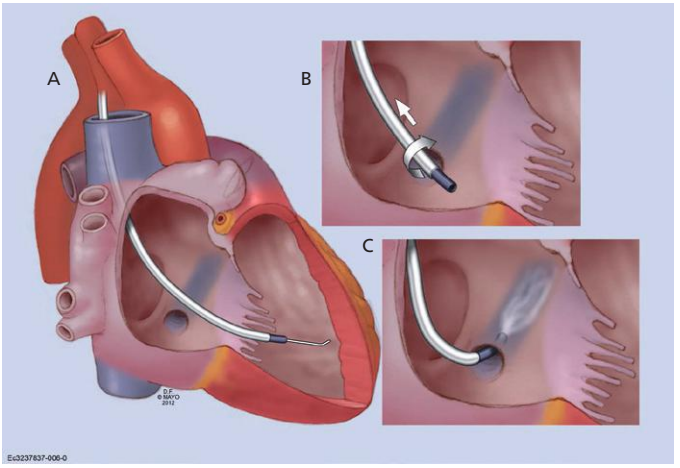


Figure 9.6 Engaging the coronary sinus using a long sheath and sub-selecting catheter. (A) The delivery set is first placed into the right ventricle over the wire. (B) The sheath and catheter are slowly pulled back with counter-clockwise rotation, and fall into the coronary sinus ostium. (C) Contract injection confirms the catheter is in the coronary sinus.

used to engage the CS (Figure 9.5B). The wire with the angled tip (not the J tip) can be successfully placed into the CS without difficulty in some cases.

- Often, a long sheath with a sub-selecting catheter is used to engage the CS. First, the delivery set (sheath and sub-selecting catheter) is placed in the RV over the guidewire. After removing the guidewire, the delivery set is pulled back toward the CS with a counter-clockwise rotation. The sub-selecting catheter often falls into the CS ostium where a small amount of contrast injection can confirm the anatomy (Figure 9.6A–C). The sheath is then advanced into the CS over the soft sub-selecting catheter. Contrast injection, without or with a balloon obstructing the CS backflow, helps to determine the options for selecting a target vein for LV lead placement.
- When the guidewire or sub-selecting catheter is not rigid enough to support or has difficulty advancing the sheath, in some instances, a steerable ablation catheter can be used to engage the CS and support advancement along the long sheath (Figure 9.7). In this case, a straight Attain®

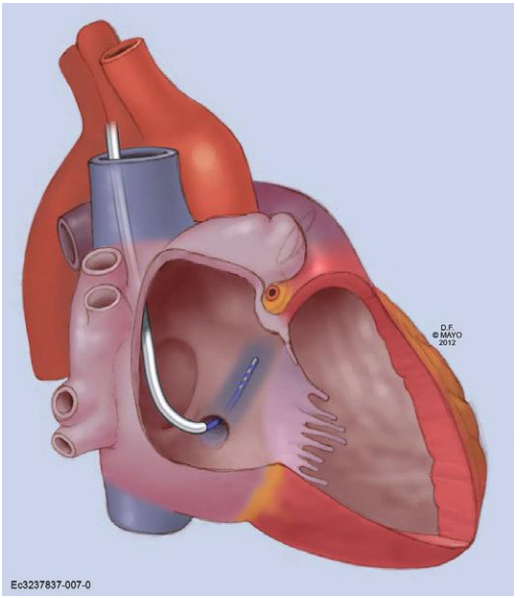


Figure 9.7 The mapping and ablation catheter is used to engage into coronary sinus. The sheath is advanced over the catheter.

sheath (Medtronic) or another preformed sheath may be used with the steerable catheter.

When the CS cannot be accessed despite these efforts, contrast hand injection into the right atrium or coronary angiography may be considered to facilitate visualization of the presence and location of the CS ostium in the contrast venous phase. The presence of a prominent Thabesian valve, a narrowed CS, or an obstructive valve of Vieussens may require coronary venoplasty to obtain venous access.

Figure 9.8 shows the variety of commercially available LV lead delivery systems. The Attain® LV lead delivery set (Medtronic; Figure 9.8A) is 8 Fr in size and available in straight and curved shapes. Various sub-selecting 7-Fr catheters are available in different shapes and angles at the tip. The Rapido® (Boston Scientific; Figure 9.8B) LV lead delivery set comes with braided catheters of various shapes and lengths, with a breakable hub that allows for simplified cutting. The CPS Direct SL® slittable outer guide catheter (St. Jude Medical; Figure 9.8C) is designed for CS access and left heart lead delivery. It is compatible with CPS Aim® inner catheters (cannulators) and the CPS Luminary® bideflectable catheter with lumen. The soft tip, which is braid re-enforced, provides torque transfer ability. Seven curve options meet the needs of various anatomies and different implanter techniques. The inner catheters have acute, 90°, and obtuse angles for selection. The SafeSheath® CSG® Worley (Pressure Product; Figure 9.8D) is designed specifically for ventricular resynchronization therapy where the right-sided chamber is considerably dilated. It has a larger lumen (9 Fr) and is available in standard, long, and jumbo sizes. The braided core provides improved torque control and its tip is radio-opaque for better fluoroscopic visualization. The long gentle throw of the Worley causes its tip to virtually fall into the CS ostium while it is being pulled back from the RV to the right atrium in counter-clockwise rotation. The sheath can be peeled away easily after the LV lead is placed. When a right-sided CRT implant is planned, the appropriate choices are right-sided delivery systems available from the Attain®, Rapido®, CPS Direct® SL, and Worley families.

Coronary vein navigation and left ventricular lead selection

Once the CS is successfully cannulated, coronary venography may be performed to delineate the coronary venous anatomy. This is done with a standard balloon occlusion catheter and hand injection of contrast. Care must be taken to achieve a good seal within the main body of the CS in order to obtain maximal opacification of the distal vasculature. Underfilling the coronary venous system is a common mistake that may result in failure to identify potentially suitable targets for LV pacing lead placement. Occasionally, the inflated balloon occludes the ostium of a suitable branch vessel for LV lead placement; therefore, occlusive venography at multiple levels within the main CS may be needed. If complete balloon occlusion of a large CS cannot be achieved, distal occlusion with prolonged imaging may help to identify more proximal vessels by filling via collaterals. Most operators use both right anterior oblique (RAO) and left anterior oblique (LAO) views to image the CS and its branches.

Transvenous LV pacing leads may be either stylet driven or placed with the use of an over-the-wire delivery system, similar to that used for percutaneous coronary intervention. In general,

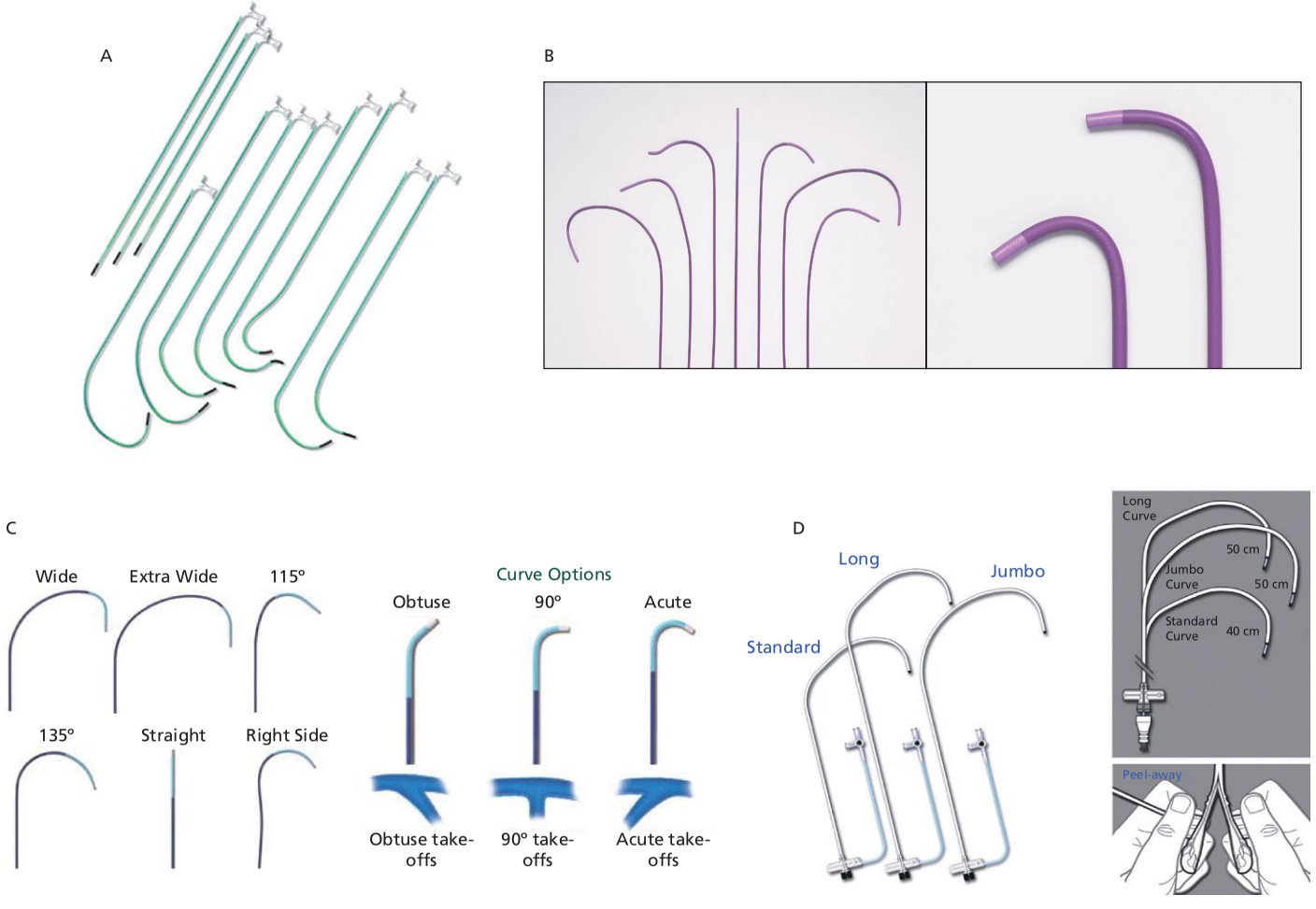


Figure 9.8 Available left ventricular lead delivery systems: outer sheath and sub-selecting catheter from (A) Medtronic; (B) Boston Scientific; (C); St. Jude Medical; and (D) Pressure Product. (Source: (A) Medtronic, Inc. Reproduced with permission of Medtronic, Inc. (B) Boston Scientific Corporation. Reproduced with permission of Boston Scientific. (C) St. Jude Medical, Inc. Reproduced with permission of St. Jude Medical, Inc. (D) Pressure Products Medical Supplies, Inc. Reproduced with permission of Pressure Products Medical Supplies, Inc.)

the leads are delivered most commonly over a 0.014-Fr guidewire. Larger diameter leads may accommodate a conventional stylet or a 0.014-Fr guidewire. With sheath support, the LV lead can negotiate within the target vein, as it is advanced to more distal branches. Overall, the success of LV lead placement is approximately 95%.[24] Lateral veins, including the posterolateral, lateral, and anterolateral veins, are prioritized to host the LV lead. The size and length of these venous branches are usually suitable for the available types of LV leads. Most commercially available LV leads are 2.6–6.0 Fr in size (tip or body) and shaped in straight, canted, spiral, or S curve forms. A straight LV lead is usually universal, such as EASYTRAK® 2 (Boston Scientific), and is easily handled. It navigates curvature well and is suitable for torturous venous anatomy. It uses tines for fixation in the coronary veins. A canted-shape LV lead, such as Attain® Ability (Medtronic), enables the lead to be wedged in a stable position. A spiral curved LV lead, such as EASYTRAK® 3 (Boston Scientific), is often selected for a large, long venous branch. It increases the lead stability and provides good contact with the epicardium (Figure 9.9). The caveat is that the lead may be retracted and dislodged into the CS when the entire spiral segment is not well situated in the vein branch. The proximal end of the spiral curve should be anchored in the branch, not in the CS, as indicated by the arrow in Figure 9.9. The majority of available LV leads are bipolar, providing more choices for a biventricular pacing configuration. It is worth mentioning that lead stability (wedging into the distal tributary of the vein) and non-apical location need to be balanced for the final lead position. Several studies have shown that an apical LV lead location has a higher non-responder rate and less favorable CRT outcome.[6,23]

Figure 9.10A shows the Attain® LV lead family from Medtronic. Attain® Ability is 4 Fr with a canted tip, and suitable for a small venous structure. The Attain® StarFix lead has three soft lobes that can be folded to improve its stability. Figure 9.10B shows the LV leads from Boston Scientific. EASYTRAK® 3 is a bipolar lead with spiral fixation for larger vessels, while the EASYTRAK® 2 lead with tined fixation is made for smaller vessels. ACUITY™ Spiral is a small (2.6-Fr tip, 4.5-Fr body) unipolar lead with three-dimensional (3D) helical bias designed for smaller tortuous vessels. ACUITY™ Steerable LV leads have a self-retaining cant at the tip that is able to unfold within the target vein, simultaneously compressing the distal segment of the lead against the outer wall of the vein, improving fixation, and forcing the tip electrode against the epicardium, thus improving

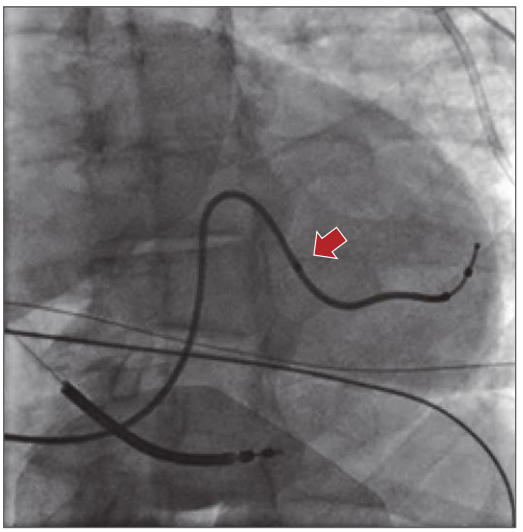
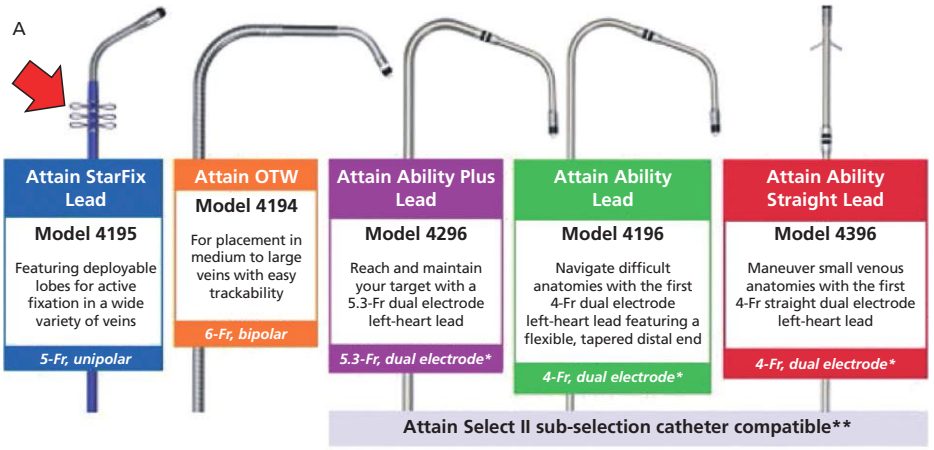


Figure 9.9 Spiral EASYTRAK® 3 left ventricular lead (Boston Scientific) is placed in the lateral vein. The arrow indicates the proximal end of the spiral curve.

Figure 9.10 (A) Attain® left ventricular (LV) lead family from Medtronic. The red arrow indicates the deployed lobes in the Starfix LV lead. *Dual cathode; **leads ≥88 cm in length. (B) Boston Scientific LV lead sections. The ACUITY™ Steerable is a bipolar, steerable, and over-the-wire lead with a canted fixation for various sizes of vessels. EASYTRAK® 3 is a bipolar, over-the-wire lead with a spiral fixation for larger vessels. EASYTRAK® 2 is a bipolar, over-the-wire lead with tined fixation for smaller vessels. The ACUITY™ Spiral is a small, unipolar over-the-wire lead with three-dimensional helical bias designed for smaller tortuous vessels. (C) The St. Jude Medical Quartet™ LV pacing lead: QuickFlex Micro™ Model 1258 LV Lead, and the Quartet™ IS4 Quadripolar LV pacing lead, with a schematic showing options for pacing configuration. (Source: (B) Boston Scientific Corporation. Reproduced with permission of Boston Scientific.)

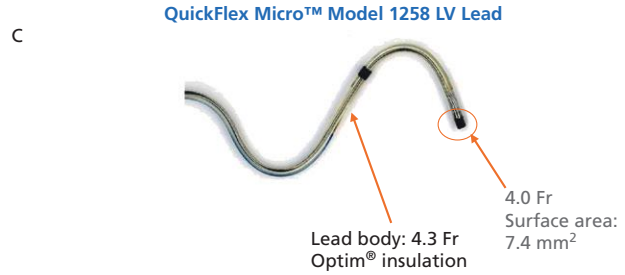
A



B



C

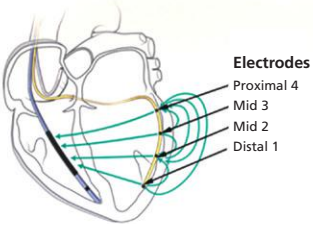




Quartet™ Quad Electrode Model 1458 LV Lead

Revolutionizing CRT Pacing Options

4 electrodes and 10 pacing configurations offer more patient management options



Vector	Cathode to Anode
Vector 1	Distal 1 to Mid 2
Vector 2	Distal 1 to Proximal 4
Vector 3	Distal 1 to RV Coil
Vector 4	Mid 2 to Proximal 4
Vector 5	Mid 2 to RV Coil
Vector 6	Mid 3 to Mid 2
Vector 7	Mid 3 to Proximal 4
Vector 8	Mid 3 to RV Coil
Vector 9	Proximal 4 to Mid 2
Vector 10	Proximal 4 to RV Coil

electrical contact for pacing. Figure 9.10C shows the St. Jude Medical QuickFlex Micro™ Model 1258 LV lead (4.3-Fr lead body, 4.0-Fr tip) and Quartet™ IS4 Quadripolar LV pacing lead (4.7-Fr lead body, 4.0-Fr tip, "S" curve fixation) with four electrodes and 10 potential pacing configurations. The latter provides more options to overcome phrenic nerve stimulation and high pacing thresholds, potentially resulting in less need for lead repositioning and fewer surgical revisions. It is compatible only with the Quadra Assura™ CRT-D generator.

Assessment of optimal left ventricular lead position

Placement of LV leads is prioritized in the lateral veins, including the posterolateral, lateral, or anterolateral veins, and the middle cardiac veins, which have tributary branches in the LV free wall, whereas the anterior interventricular vein in general is not optimal for LV pacing. At the time of lead placement, fluoroscopy is often used to assess the position of the LV lead tip, such as anterior or posterior, basal or apical location in the RAO view, or lateral versus septal location in the LAO view, as shown in Figure 9.11A,B. A greater RV–LV lead tip separation is preferred. Improved clinical outcomes are associated with LV leads positioned at the basal or mid LV lateral wall instead of the apex. Figure 9.12A–D illustrates four examples of the final LV lead position at the anterolateral, lateral and posterolateral wall, and septum (interventricular groove via interventricular vein) in the LAO view, respectively. The septal lead location is considered an unfavorable pacing site under most circumstances.

Electrocardiography (ECG) is a useful tool to assess whether LV free wall pacing is achieved. In RV pacing, ventricular depolarization propagates from right to left, commonly resulting in positive forces in lead I. In LV free wall pacing, the depolarizing vector is in the opposite direction, resulting in a negative QS morphology in lead I (Figure 9.13).[25] Lead III indicates whether the pacing vector is toward an inferior (pacing from the anterior wall) or anterior (pacing from the inferior wall) direction. The RV lead is often placed at the septal apex, resulting in QS in lead III, whereas the LV pacing vector usually directs inferiorly if the lead is situated at the anterolateral or lateral wall. Yet, QS morphology in lead III may be seen when the LV lead is located posteriorly. Biventricular pacing (RV apex + LV lateral wall) produces a right superior axis as a result of fusion of RV and LV

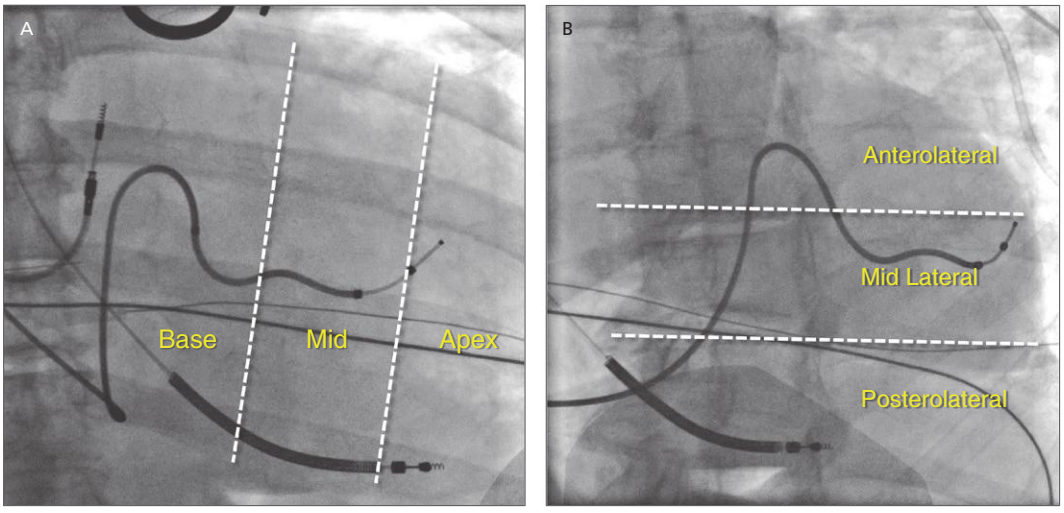


Figure 9.11 Assessment of left ventricular (LV) lead location using fluoroscopy. (A) The right anterior oblique view divides the left ventricle into three segments: basal, mid, and apical. (B) The left anterior oblique view separates the LV lateral wall from the septal position.

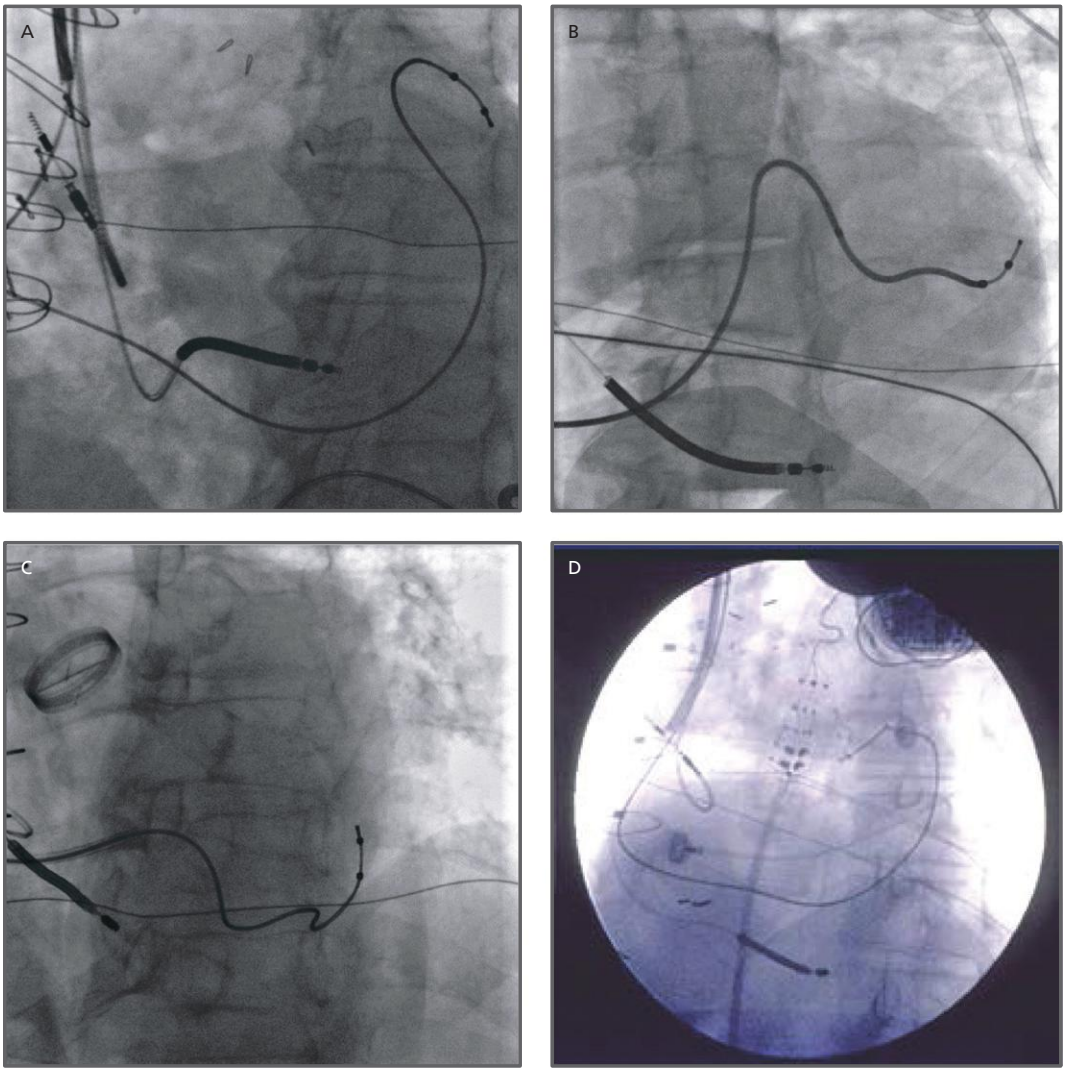


Figure 9.12 Examples of the final LV lead position at the (A) anterolateral, (B) lateral, and (C) posterolateral wall, and (D) septum (interventricular groove) in the LAO view.

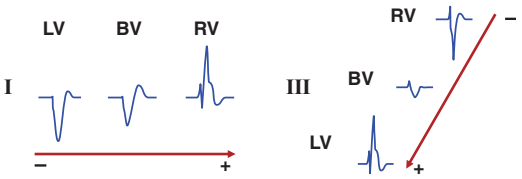


Figure 9.13 Mean QRS axis in the frontal plane during ventricular pacing. In right ventricular apical pacing, ventricular depolarization occurs from right to left; lead I is positive. In left ventricular (LV) free wall pacing, the depolarizing vector is in the opposite direction, resulting in a negative QS morphology in lead I. Lead III indicates the pacing vector is toward the inferior wall (pacing from the anterior wall) or anterior wall (pacing from the inferior wall). AV, atrioventricular; BV, biventricular.

electrical axes. A qR or Qr complex in lead I is present in 90% of cases of biventricular pacing. In biventricular pacing, loss of the q or Q wave in lead I is predictive of loss of LV capture. Figure 9.14A shows an example of ECG QRS morphologies during RV, LV, and biventricular pacing with the corresponding lead positions shown in Figure 9.14B (RAO view and LAO view). The LV lead is located at the LV basal lateral wall. RV apical pacing alone has a LBBB-type and superior axis morphology (QRS duration 160 ms), whereas LV anterior free wall pacing gives rise to a RBBB-type morphology (QRS 180 ms). Biventricular pacing (QRS 150 ms, VV delay 0 ms) has an appearance of RBBB and Qr in lead I.

Assessment of optimal LV lead position is summarized in Table 9.3.

Management of difficulties in placing left ventricular leads

(Table 9.4)

Venous anatomy

Multiple factors may limit placement of LV leads at ideal pacing locations. In the coronary venous anatomy, target veins may be absent, inaccessible, or obstructed. The coronary venous circulation demonstrates considerably more variability than the parallel arterial circulation (Figure 9.15). Anterolateral, posterolateral, and lateral coronary veins serve the LV free wall, while none of the anterointerventricular and only some of the middle cardiac venous branches contribute to the lateral wall.[23] Up to 20% of patients may not have a vein that reaches the optimal LV free wall site for delivery of CRT. In some instances, target veins are present but too small for cannulation with existing lead systems or, paradoxically, too large to achieve mechanical fixation. Currently available leads may navigate small tortuosities impassable to larger leads.

Another commonly encountered difficulty in transvenous LV lead placement is tortuosity of the target vessel take-off or main segment. These anatomical constraints can be extremely difficult to overcome and often require the use of multiple LV lead designs and delivery systems (Figure 9.16A,B). Tortuous take-offs may be overcome with the use of firm guidewires or double guidewires to straighten the vessel. Another technique is to use a sub-selecting catheter with the guide sheath, such as Renal Telescopic Braided Series (Pressure Product). The guide sheath can be advanced into the branch over the sub-selecting catheter and is able to overcome acute-angle take-off and curvature (Figure 9.16C). Thereafter, the guide sheath supports the LV lead engagement (double sheaths provide support, with the outer sheath at the CS and the guide sheath at the proximal vein take-off).

It is not uncommon that the target vein is found to be stenotic, preventing advancement of the LV lead. Venoplasty may be considered to open the area of stenosis. An angioplasty wire can be advanced distally against the resistance of the stenosis and the venous structures. With the wire support, the balloon is advanced over the firm segment of the wire. The balloon measures 3–4 mm in diameter and is relatively pliable [Maverick® Monorail Balloon Catheter (Boston Scientific) or VOYAGER™ RX Coronary Dilatation Catheter (Abbott Vascular)]. Figure 9.17 shows a venoplasty procedure performed in a patient with a left persistent superior vena cava (SVC). By means of a telescoping sheath system composed of a 5-Fr vein selector supported by a 7-Fr renal catheter and Worley sheath, 0.014-Fr Whisper wires were advanced to a desirable location in the middle cardiac vein. The small target tributary would not accommodate the lead system. Venoplasty of the distal middle cardiac vein was performed using a 3.0 × 20-mm VOYAGER balloon to facilitate LV lead placement. Venoplasty should be performed by an experienced vascular interventionist teamed with a device implanter. Vein rupture or vein laceration may occur when the anchoring balloon exceeds the ability of the vein to expand. Choosing the optimal balloon size reduces the possibility of this complication. Although the CS has a low-pressure venous system, vein rupture may result in tamponade. Stand-by equipment for urgent echocardiography and pericardiocentesis should be available at the time of coronary venoplasty.

High left ventricular stimulation thresholds

The principal limitation of the transvenous approach is that the selection of sites for pacing is

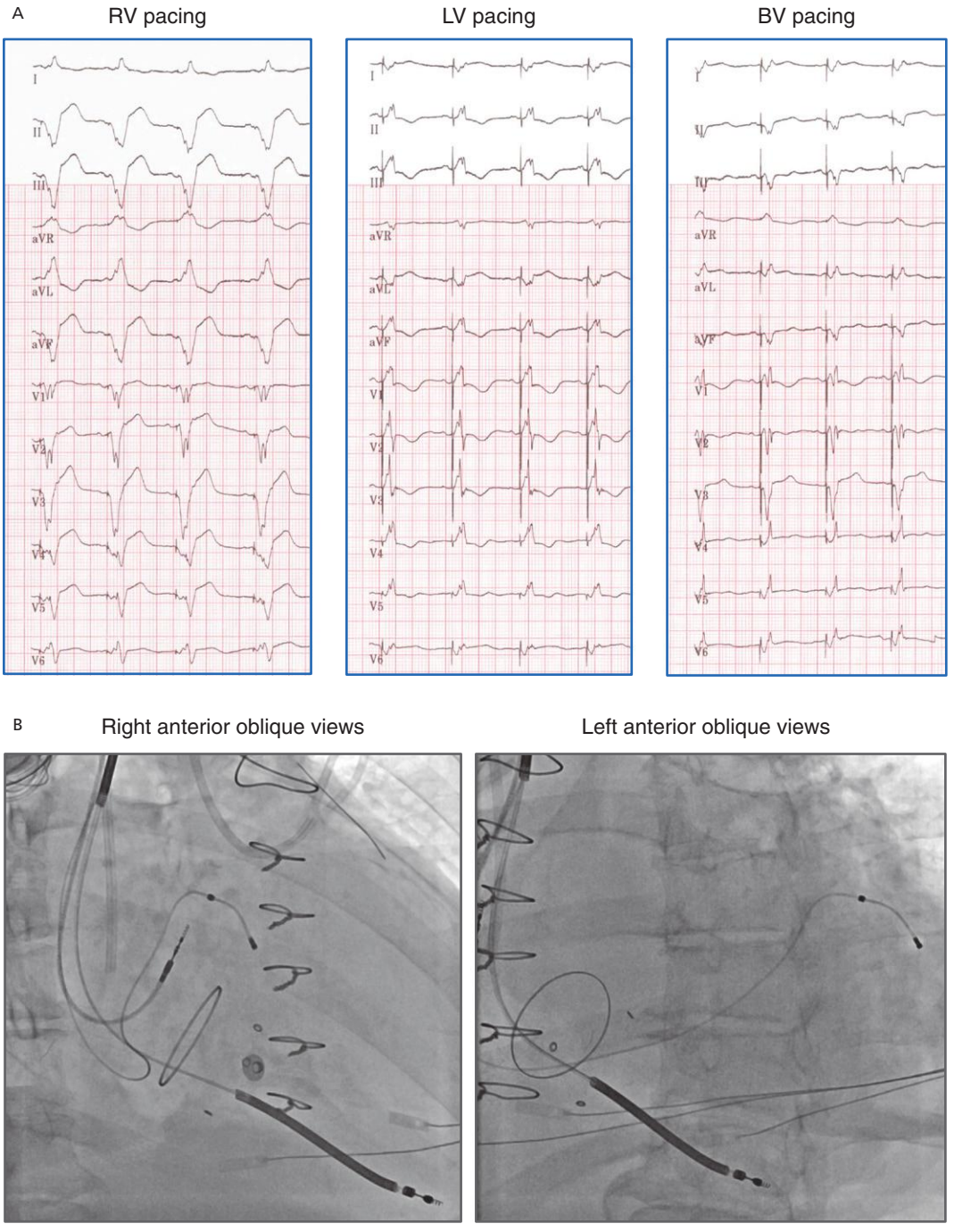


Figure 9.14 (A) ECG QRS morphologies during right ventricular (RV), left ventricular (LV), and biventricular (B) pacing. (B) Corresponding lead positions in right and left anterior oblique views. The LV lead is located at the LV basal lateral wall. RV apical pacing alone gives rise to left bundle branch block and superior axis morphology, whereas LV anterior free wall pacing gives rise to a right bundle branch block (RBBB) morphology. Biventricular pacing has the appearance of RBBB and Qr in lead I.

Table 9.3 Assessment of optimal left ventricular (LV) lead position

- Occlusive coronary venography is helpful to select the optimal vein for LV lead placement
- LV lead placement in the lateral wall can be achieved via lateral, posterolateral, anterolateral, and even middle cardiac veins
- Fluoroscopy LAO view and QS morphology in lead I are quick ways to assess whether the LV lead is placed at a lateral location

Table 9.4 Management of difficulties placing a left ventricular (LV) lead

- When a preferred left ventricular (LV) lead location is not accessible, such as with a high pacing threshold or extracardiac pacing, venoplasty or repositioning the lead to an alternative lateral location should be considered
- Surgical placement of epicardial LV pacing leads or endocardial LV stimulation are options when the coronary venous anatomy precludes successful transvenous implant

dictated entirely by navigable coronary venous anatomy. A commonly encountered problem is that an apparently suitable target vein delivers the lead to a site where ventricular capture can be achieved only at very high-output voltages or not at all. This presumably relates to the presence of scarring on the epicardial surface of the heart underlying the target vein or the presence of epicardial fat that prevents the electrical stimulation from capturing the myocardium. Alternative tributary branches in the same vein or in a different coronary vein may be approached when the pacing threshold is not acceptable. Fortunately, most myocardial scars, often from previous myocardial infarct, are located in the LV anterior, septal, or inferior wall or apex, sparing the free wall where the LV lead is the preferred target.

Phrenic nerve stimulation

The left and right sides of the diaphragm are innervated by the ipsilateral phrenic nerves, which derive from the third, fourth, and fifth cervical nerve roots.[26] The left phrenic nerve (Figure 9.18) passes over the pericardium of the LV free wall, supplying motor fibers to the diaphragm and sensory fibers to the fibrous pericardium,

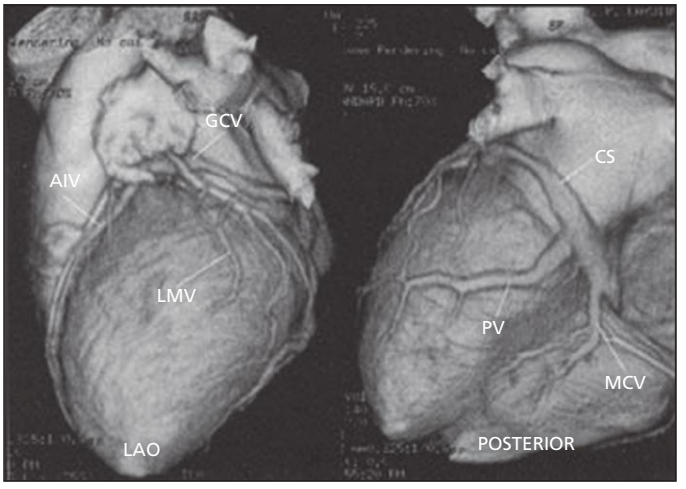


Figure 9.15 Three-dimensional reconstruction of the epicardial coronary venous anatomy using computed tomography. AIV, anterior interventricular vein; CS, coronary sinus; GCV, great cardiac vein; LAO, left anterior oblique; LMV, lateral marginal vein; MCV, middle cardiac vein; PV, posterior vein. (Source: Tada H. Three-dimensional computed tomography of the coronary venous system. *J Cardiovasc Electrophysiol* 2003; 14: 1385. Reproduced with permission of John Wiley & Sons Ltd.)

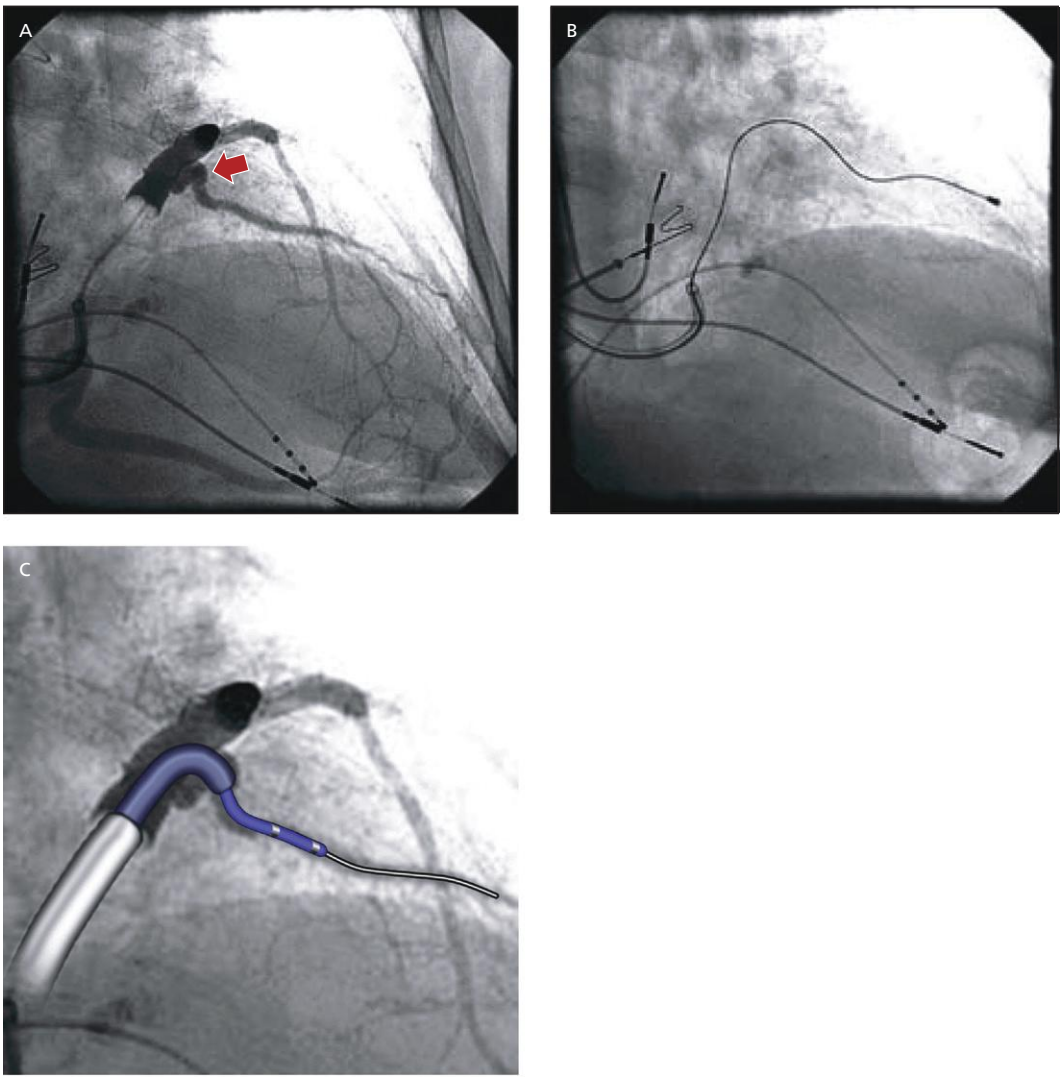


Figure 9.16 (A) "Shepherd's crook" take-off of the lateral marginal vein, with a kink just beyond the second bend (arrow). A 4-Fr over-the-wire left ventricular lead cannot navigate venous kinking. (B) Same patient as shown in Figure 9.16A. Alternate 4-Fr over-the-wire lead successfully navigated the kinked portion of the vein. (C) Schematic illustrating the alternative approach using the Renal Telescopic Braided Series. The Worley outer sheath is in the coronary sinus, the telescoping guide sheath is advanced into the proximal vein branch to overcome the kink, and the lead can be delivered to the destination.

mediastinal pleura, and diaphragmatic peritoneum. The target vein may deliver the lead to a site at or near the left phrenic nerve, resulting in diaphragmatic pacing. High-output pacing to provoke phrenic stimulation is a routine test during the procedure. A significant difference in the capture thresholds for phrenic nerve stimulation versus LV capture can be overcome by manipulation of LV voltage output. An increase in the chronic LV capture threshold may eliminate this safety gap and should be kept in mind during the implant procedure before final lead position is accepted at a site with phrenic nerve capture. Often, an alternative site for LV pacing is sought by repositioning the LV

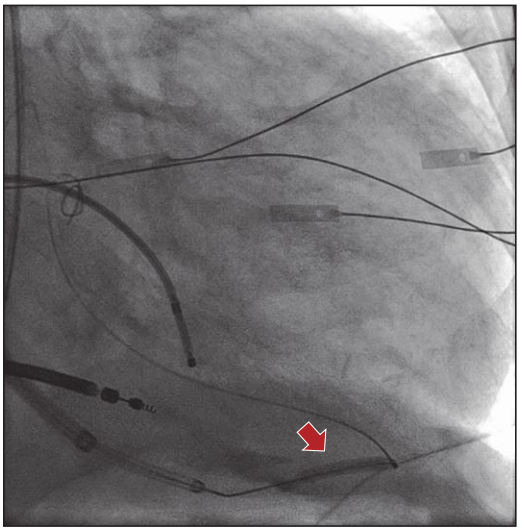


Figure 9.17 A venoplasty procedure performed in a patient with a left persistent superior vena cava (SVC). A telescoping sheath system composed of a 5-Fr vein selector supported by a 7-Fr renal catheter and Worley sheath, and 0.014-Fr Whisper wires was placed in the middle cardiac vein. The small target tributary would not accommodate the lead system. Venoplasty of the distal middle cardiac vein was performed using a 3.0 × 20 mm VOYAGER balloon to facilitate LV lead placement. The arrow shows the balloon inflation.

lead more proximally within the target vein or finding a different vein branch. A small change of lead position may eliminate the issue. Use of bipolar or quadripolar leads and/or pulse generators with multiple programmable LV pacing lead configurations may have advantages in overcoming phrenic stimulation. As there may be significant body positional changes in the anatomical proximity of the phrenic nerve and coronary veins, lack of phrenic nerve capture in the supine position during the implant procedure may not predict future lack of diaphragmatic capture even in the absence of lead dislodgement.

Most often, reprogramming of pacing output or pacing configurations corrects phrenic nerve stimulation. When the threshold causing diaphragmatic stimulation is lower than the minimal LV capture, revision of the LV lead becomes necessary.

Complications related to left ventricular lead placement and management

Complications related to LV lead placement include coronary vein dissection, vein perforation, and lead dislodgement after successful implant.

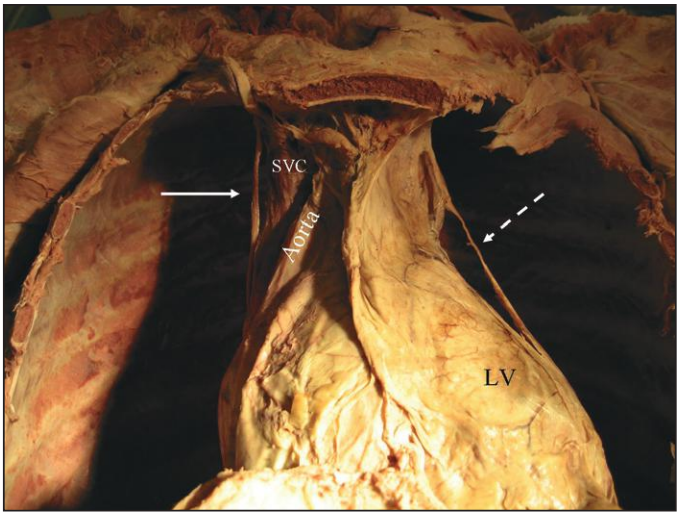


Figure 9.18 Right (solid arrow) and left (dashed arrow) phrenic nerves. LV, left ventricle; SVC, superior vena cava.

Table 9.5 Complications related to coronary sinus in recipients of a non-thoracotomy cardiac resynchronization therapy (CRT) device with or without defibrillation

Trial	*Year*	*Number of patients undergoing implantation*	*Coronary vein dissection, perforation or tamponade [% (SD)]*	*Coronary vein dissection [% (SD)]*	*Coronary vein perforation [% (SD)]*	*Coronary vein tamponade [% (SD)]*
MIRACLE[13]	2002	568	35 (6.2)	23 (4.0)	12 (2.0)	NR
COMPANION[14]	2004	1212	22 (1.8)	5 (0.4)	12 (1.0)	5 (0.4)
CARE-HF[15]	2005	404	6 (1.5)	5 (1.2)	NR	2 (0.5)
MIRACLE ICD[76]	2006	421	19 (4.5)	15 (3.6)	4 (1.0)	NR
RethinQ[77]	2007	176	1 (0.6)	1 (0.6)	NR	NR
REVERSE[4]	2008	642	3 (0.5)	3 (0.5)	NR	NR
MADIT-CRT[6]	2009	1089	5 (0.5)	5 (0.5)	NR	NR
Total		**4512**	**91 (2.0)**	**57 (1.3)**	**28 (1.3)**	**7 (0.4)**

RethinQ, Resynchronization Therapy in Narrow QRS. Other trial names are defined in the text.

Coronary vein dissection/perforation

In a meta-analysis of randomized clinical trials, the event rates for coronary vein dissection and for perforation were both 1.3%, and tamponade occurred in 0.4% of CRT recipients (Table 9.5).[27] Of note, more recent studies have reported lower incidences of coronary vein-related complications than earlier studies. The growing experience of implanters combined with the technical improvement in the LV lead and lead delivery tools may have contributed to this trend.

A coronary vein intimal tear with dissection can be associated with wire engagement or advancement of the sub-selecting catheter and sheath to the CS. The wire and sheath advancement must be gentle and stop when resistance is encountered. Contrast injection helps to assess the presence of dissection. Pushing a delivery sheath alone without an accompanying guidewire, sub-selecting catheter, or lead poses the risk of vein dissection. Another common reason for CS dissection is related to the handling of the occlusion balloon. Advancement of the catheter without a guidewire, over-inflation of the balloon, cannulation of the vein of Marshall, and inadvertent inflation in a side branch are common avoidable technical problems. Gentle contrast injection before inflation of the balloon is helpful to avoid these problems. Figure 9.19 shows an occlusive CS venogram that reveals a true CS lumen (red arrow) and a false lumen (blue arrow) with contrast staining. The guidewire or catheter may be trapped in the false lumen of the venous wall when dissection occurs. Coronary vein staining by contrast often resolves. A guidewire with a soft tip can be used to identify the true lumen of the coronary vein and the procedure can proceed. Coronary vein perforation may or may not cause tamponade as a result of low pressure

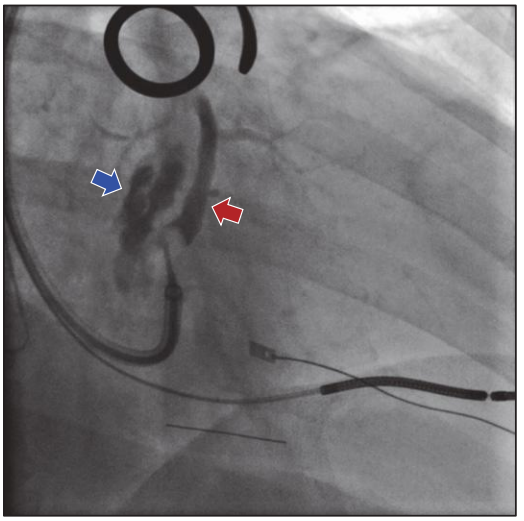


Figure 9.19 Coronary sinus (CS) dissection. An occlusive CS venogram that reveals a true CS lumen (red arrow) and a false lumen (blue arrow) with contrast staining.

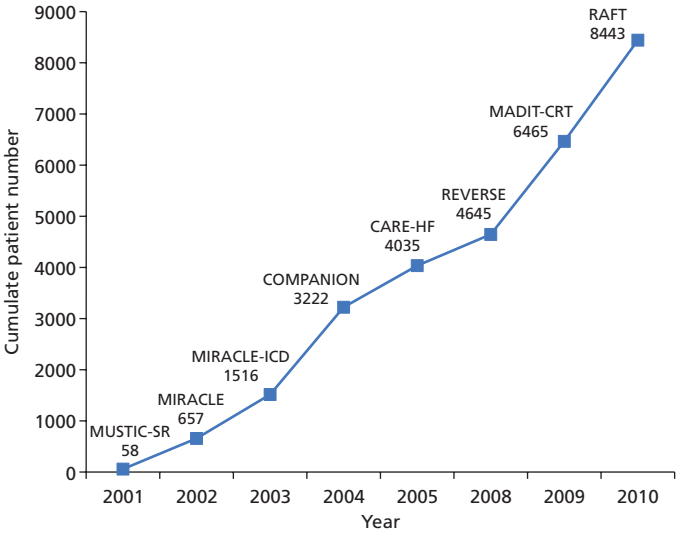


Figure 9.20 Cumulative enrollment in cardiac resynchronization therapy randomized trials. Trial names are defined in the text.

circulation itself. When it occurs, pericardiocentesis is required to restore hemodynamic stability. LV lead placement can be re-attempted in a separate procedure. On occasion, an angioplasty guidewire may perforate distal venous branches into the pericardial space. Wire perforation rarely results in any hemodynamic consequences.

Left ventricular lead dislodgement

The incidence of LV lead dislodgement is clearly higher than dislodgement of a right-side lead, ranging from 2.8% to 10.6% in large clinical trials. The causes of LV lead dislodgement include not enough redundancy of the lead in the right atrium, unstable lead location, too proximal a position of the lead in relation to the CS, placement of a spiral lead in a short vein branch, and others. The National Cardiovascular Data Registry records indicate that among 79 909 patients who underwent CRT-D implantation, acute LV lead dislodgement occurred with a frequency of 1.8%.[28] Hence, device interrogation and reviewing chest X-ray films within 24 h of implant are recommended. Macro-dislodgement with loss of lead capture prompts lead revision. During LV lead revision, alternative vein branches and/or leads with different features are often used. In some instances, an acceptable pacing threshold may be achieved by device reprogramming to adjust the pacing output, pacing configurations, or both.

Clinical outcomes

The aggregate experience with CRT in more than 10 clinical trials involving more than 8000 patients has demonstrated undisputable proof that CRT is an effective therapy for patients with HF, regardless of the severity of HF symptoms (Figure 9.20). The magnitude of the benefit is concordant, although the effects are heterogeneously distributed among different patient subtypes. These include improvement in NYHA class, quality-of-life measures, peak VO_2, 6-min hall walk distance, HF hospitalization, and death. The favorable outcome may, in part, be attributable to improved volumetric remodeling and function of the failing LV.

Severe heart failure

In the first decade of the 21st century, the application of CRT was aimed at those patients with severe symptoms and an advanced stage of HF. The Multisite Stimulation in Cardiomyopathies (MUSTIC), Multicenter InSync Randomized Clinical Evaluation (MIRACLE), Comparison of Medical Therapy, Pacing, and Defibrillation in Heart Failure (COMPANION), and Cardiac Resynchronization in

Heart Failure (CARE-HF) studies were prominent stepping-stone trials of CRT use (Table 9.6).

The MUSTIC trial was one of the first studies. This single-blind, randomized, cross-over study compared a 3-month trial of active CRT with inactive CRT in 58 subjects with severe HF and a QRS duration of longer than 150 ms. Biventricular pacing improved exercise tolerance and quality of life, and reduced hospitalizations for HF.[29]

The MIRACLE study was the first randomized controlled trial without cross-over. It randomized 453 subjects with an LVEF of 35% or less and a QRS duration of 130 ms or longer to CRT with pacemaker capability (CRTP-P) or control arms. The CRT-P arm showed significant symptomatic and functional (6-min walk distance) improvement.[13] These improvements translated into a 40% reduction in death and HF hospitalization, a composite end-point.

The COMPANION trial enrolled 1520 subjects with either ischemic or non-ischemic cardiomyopathy, NYHA class III or IV, LVEF of less than 35%, and a QRS duration of longer than 120 ms. Patients were randomly assigned to one of three arms: optimal medical therapy alone, CRT-P, or CRT with defibrillation capability (CRT-D). Both CRT-P and CRT-D significantly reduced hospitalizations for HF, while mortality reduction was seen only in the CRT-D group.[14]

The CARE-HF trial was the next landmark study that randomized 813 patients with LVEF of less than 35%, NYHA class III or IV, a QRS duration of longer than 150 ms or QRS of 120–150 ms plus echocardiographic evidence of dyssynchrony to optimal medical therapy or CRT-P. The device therapy reduced the composite end-point of hospitalization for HF and all-cause mortality by 37%.[15] This was the first trial showing that stand-alone CRT, without an ICD, improves survival in subjects with severe HF.

These clinical trials have consistently shown clear and continuous improvement in LVEF in both short-term and longer-term follow-up, as shown in Figure 9.21.[30] Of note, extended improvement was observed even at 12 months after CRT implant. Concomitant reduction of LV volumetrics, an index of reverse structural remodeling, was seen in the MIRACLE-ICD, Resynchronization Reverses Remodeling in Systolic Left Ventricular Dysfunction (REVERSE), and Multicenter Automatic Defibrillator Implantation Trial with Cardiac Resynchronization Therapy (MADIT-CRT) trials (Figure 9.22).[4,6,31] The cardiac hemodynamic and structural benefit from CRT may have translated into the reduction of hospitalization for HF and cardiac mortality.

From a functional standpoint, CRT improves HF symptoms, NYHA class, overall wellness, exercise tolerance, and quality of life. Figure 9.23 summarizes the changes in 6-min walk distance in the control and CRT subjects after therapy from published clinical trials. Placebo effect was apparent in the two MIRACLE-ICD trials; there was a similar (30–50 m) gain in walking distance in both control and CRT subjects. However, a greater improvement in walking distance was found in the MIRACLE, CONTAK-CD, and COMPANION trials.[13,14,32]

The quality of life was assessed in three MIRACLE and CONTAK-CD trials. All three MIRACLE trials consistently showed greater changes in Minnesota Living With Heart Failure scores, although CONTAK-CD did not, as shown in Figure 9.24.

Table 9.6 summarizes the outcomes in these clinical trials.

Mild-to-moderate heart failure

All the above-mentioned trials have investigated CRT outcomes in subjects with severe HF and ventricular conduction delay. May CRT benefits extend to patients with less severe HF symptoms? The most recent MADIT-CRT trial was expanded to enroll CRT candidates with mild-to-moderate HF. The study enrolled 1820 subjects who had NYHA class I (20%) and II (80%), an LVEF of less than 30%, and a QRS duration of longer than 130 ms (80% having a QRS >150 ms). Subjects were randomly assigned to either CRT-D (the therapeutic group) or an ICD (the control group). The CRT-D group had a substantially lower combined end-point of death and HF hospitalization than the ICD-alone group (17.2% vs. 25.3%; Figure 9.25).[6] Furthermore, reverse LV remodeling with a reduction of LV end-systolic volume by 57 mL was seen in the CRT-D group compared with 18 mL in the ICD-alone group at 1-year follow-up (Figure 9.22).

Table 9.6 Outcomes of randomized trials in cardiac rehabilitation therapy

Study	*Year*	*Design*	*Total number*	*Group*	*NYHA class*	*EF [% (SD])*	*QRS Interval, mean [ms (SD)]*	*HF Improvement*	*HF admission*	*All-cause death*
									CRT control n/n n/n RR (95% CI)	*CRT control n/n n/n RR (95% CI)*
CONTAK-CD[78]	2000	Parallel open	490	CRT-ICD vs ICD	II–IV	21.5 (7)	158 (26)	Peak VO_2 6MWT NYHA QOL LVEF LV volume	32/245 39/245 0.82 (0.53–1.26)	11/245 16/245 0.69 (0.33–1.45)
MIRACLE[13]	2002	Parallel double blind	453	CRT vs. OMT	III–IV	22 (6)	166 (20)	6MWT NYHA QOL LVEF LVEDD MR	18/228 34/225 0.52 (0.3–0.9)	12/228 16/225 0.73 (0.34–1.54)
MIRACLE-ICD[31]	2003	Parallel double blind	369	CRT-ICD vs. ICD	III–IV	24 (6.2)	163 (22)	NYHA QOL	85/187 78/182 1.06 (0.84–1.33)	14/187 15/182 0.91 (0.45–1.83)
MIRACLE-ICD II[79]	2004	Parallel double blind	186	CRT-ICD vs. ICD	I–II	24.5 (6.7)	165 (24)	NYHA LVEF LVEDV LVESV	_	2/85 2/101 1.19 (0.17–8.26)

COMPANION[14]	2004	Parallel open	1520	CRT-ICD vs. CRT vs. OMT	III–IV	22	160	6MWT QOL NYHA	_	131/617 77/308 0.76 (0.58–1.01)
CARE-HF[15]	2005	Parallel open	813	CRT vs. OMT	III–IV	25	160	NYHA QOL LVEF LVESV	72/409 133/404 0.48 (0.36–0.64)	82/409 120/401 0.64 (0.48–0.85)
REVERSE[4]	2008	Parallel double blind	610	CRT vs. OMT	I–II	27 (7)	153 (21)	LVEF LVEDV LVESV	12/419 14/191 0.47 (0.18–0.83)	9/419 3/191 1.37 (0.37–4.99)
MADIT-CRT[6]	2009	Parallel blinded	1820	CRT-ICD vs. ICD	I–II	24 (5)	65% >150	LVEF LVEDV LVESV	151/1089 167/731 0.59 (0.47–0.74)	74/1089 53/731 1.00 (0.69–1.44)
RAFT[5]	2010	Parallel double blind	1798	CRT-ICD vs. ICD	II–III	23 (5)	158 (24)	_	174/894 236/904 0.68 (0.56–0.83)	186/894 236/904 0.75(0.62–0.91)

CI, confidence interval; EF, ejection fraction; ICD, implantable cardioverter–defibrillator; LVEDD, left ventricular end-diastolic diameter; LVEDV, left ventricular end-diastolic volume; LVEF, left ventricular ejection fraction; LVESV, left ventricular end-systolic volume; MR, mitral regurgitation; NYHA, New York Heart Association; OMT, optimal medical therapy; QOL, quality of life; RR, relative risk; SD, standard deviation; 6MWT, 6-min walk test. The study names are defined in the text.

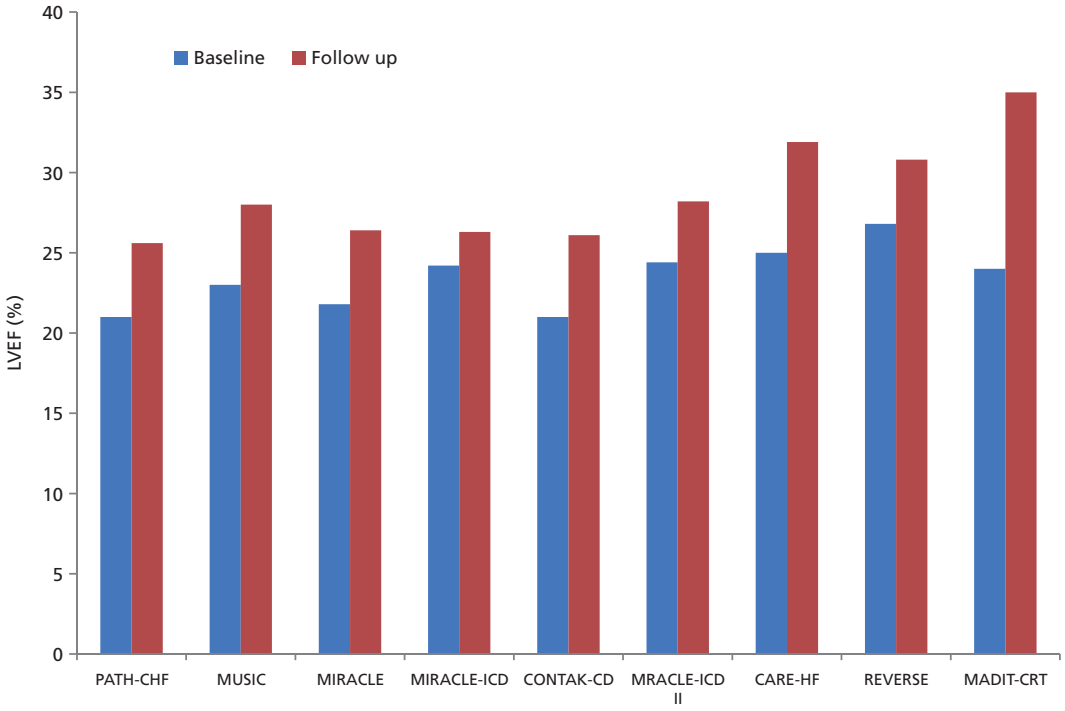


Figure 9.21 Change in left ventricular ejection fraction (LVEF) after cardiac resynchronization therapy (CRT) in heart failure patients with different New York Heart Association (NYHA) functional classes. In comparison to LVEF before CRT (blue bar), there was a statistically significant increase of LVEF in all studies after CRT (red bar). Trial names are defined in the text.

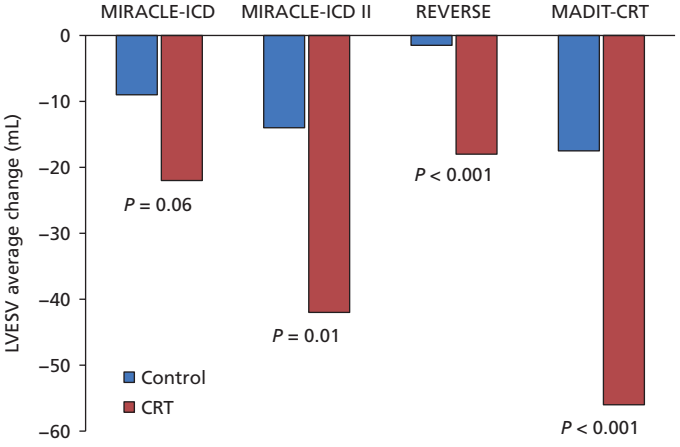


Figure 9.22 Changes in left ventricular end-systolic volume (LVESV) after cardiac resynchronization therapy (CRT) in control (blue bar) and CRT (red bar) groups from clinical trials. Trial names are defined in the text.

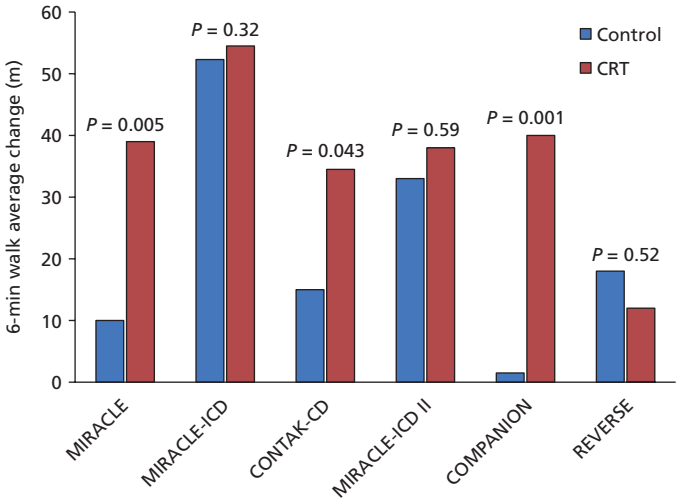


Figure 9.23 Changes in 6-min walk distance after cardiac resynchronization therapy (CRT) in control (blue bar) and CRT (red bar) groups from clinical trials. Trial names are defined in the text.

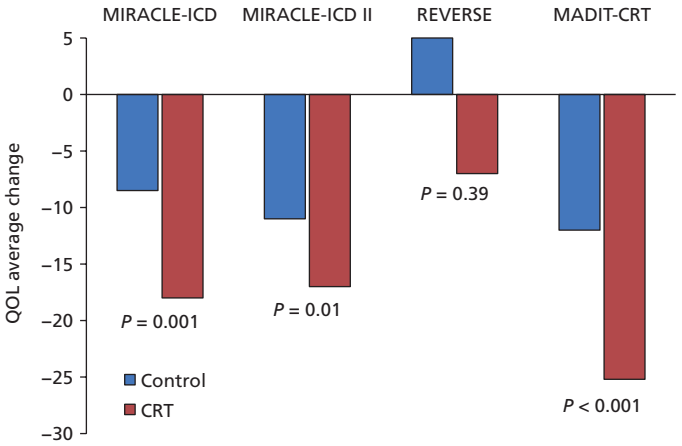
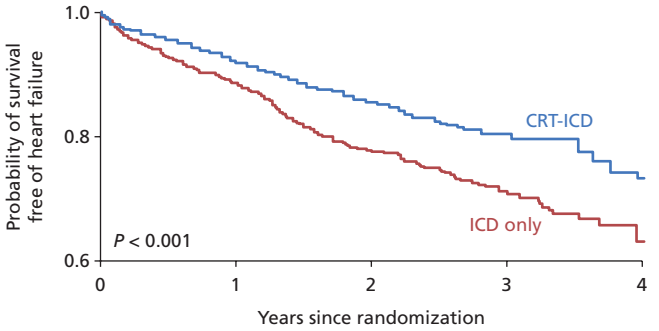


Figure 9.24 Changes in Minnesota Living With Heart Failure scores after cardiac resynchronization therapy (CRT) in control (blue bar) and CRT (red bar) groups from clinical trials. QOL, quality of life. Trial names are defined in the text.



No. at risk (probability of survival)

ICD only	731	621 (0.89)	379 (0.78)	173 (0.71)	43 (0.63)
CRT-ICD	1089	985 (0.92)	651 (0.86)	279 (0.80)	58 (0.73)

Figure 9.25 Kaplan–Meier estimates of the probability of survival free of heart failure from the MADIT-CRT trial. CRT, cardiac resynchronization therapy; ICD, implantable cardioverter–defibrillator. Trial name is defined in the text. (Source: Moss *et al*. 2009.[6] Reproduced with permission of the Massachusetts Medical Society.)

Results from the REVERSE-HF trial[4] concurred with those from the MADIT-CRT trial, observing a substantial reduction in the LV end-systolic volume in the CRT-on group compared with the CRT-off group (average 27.5 mL/m^2 vs. 2.7 mL/m^2) in 610 patients with NYHA class I or II, an LVEF of less than 40%, and a QRS duration of 120 ms or longer.

Similarly, the Resynchronization–Defibrillation for Ambulatory Heart Failure Trial (RAFT)[5] randomly assigned 1798 patients with NYHA class II or III HF, a LVEF of 30% or less and an intrinsic QRS duration of 120 ms or more or a paced QRS duration of 200 ms or more to receive either an ICD alone (control) or an ICD plus CRT. The trial showed the relative risk reduction in HF and mortality from CRT to be comparable in patients with severe and mild-to-moderate HF.

These trials consistently confirmed the benefit of CRT in patients with mild-to-moderate HF symptoms and LVEF of 30% or 40% or less. The vast majority of these patients were in NYHA class II. Reduction of the LV volumetric, evidence of reverse LV structural remodeling, and improved LVEF are apparent, and this has been translated into a decrease in rates of hospitalization for HF. The mortality benefit has been shown in patients with NYHA class II and III (in RAFT), but not in those with NYHA class I and II (in MADIT-CRT and REVERSE) within the studies' follow-up periods. A meta-analysis of five clinical trials showed that among mildly symptomatic patients (NYHA class II), CRT was associated with significantly lower all-cause mortality and HF hospitalization. In asymptomatic patients (NYHA class I), HF hospitalization risk was lower; however, there was no difference in mortality (Table 9.7).[33] Mortality reduction was demonstrated in the RAFT study, which included patients with NYHA class II and III, and LVEF of 30% or less.

QRS duration

To date, QRS duration determined from the surface ECG has been the most extensively evaluated selection criterion for CRT on the premise that ventricular electrical delay is a reliable marker for spatially dispersed mechanical activation. Numerous studies have reproducibly demonstrated that a baseline QRS duration of longer than 150 ms is predictive of acute and/or chronic hemodynamic improvement with CRT, whereas patients with a QRS duration of shorter than 150 ms are less likely to respond.[6,5,14,15] Prediction curves for contractile function response using a baseline QRS duration derived from the Pacing Therapies for Congestive Heart Failure (PATH-CHF and PATH-CHF-II) studies are shown in Figure 9.26.[34] The overlap between these QRS duration ranges was populated with CRT responders and non-responders. The predictive accuracy of a QRS duration to separate responders from non-responders is fairly constant at about 80%,

Table 9.7 Pooled mortality and heart failure (HF) events/hospitalizations with cardiac resynchronization therapy (CRT) among asymptomatic or mildly symptomatic patients with HF (Source: Adabag S *et al.* 2011.[34] Reproduced with permission of Elsevier.)

Events/hospitalizations by NYHA class	*CRT (%)*	*ICD (%)*	*RR*	*95% CI*	*P value*	*NNT*
Class I–II						
Mortality	8.0	11.5	0.81	0.65–0.99	.04	29
HF hospitalization	11.6	18.2	0.68	0.59–0.79	<.001	15
Combined	17.5	26.4	0.72	0.65–0.81	<.001	
Class II						
Mortality	9.6	13.1	0.78	0.65–0.95	.01	28
HF hospitalization	14.6	21.5	0.67	0.57–0.79	<.001	14
Combined	20.7	29.3	0.73	0.64–0.83	<.001	
Class I						
Mortality	6.0	7.1	0.85	0.36–2.01	.71	88
HF hospitalization	11.9	20.5	0.57	0.34–0.97	.04	12
Combined	15.5	22.1	0.70	0.44–1.13	.14	

CI, confidence interval; ICD, implantable cardioverter–defibrillator; NNT, number needed to treat; NYHA, New York Heart Association; RR, relative risk.

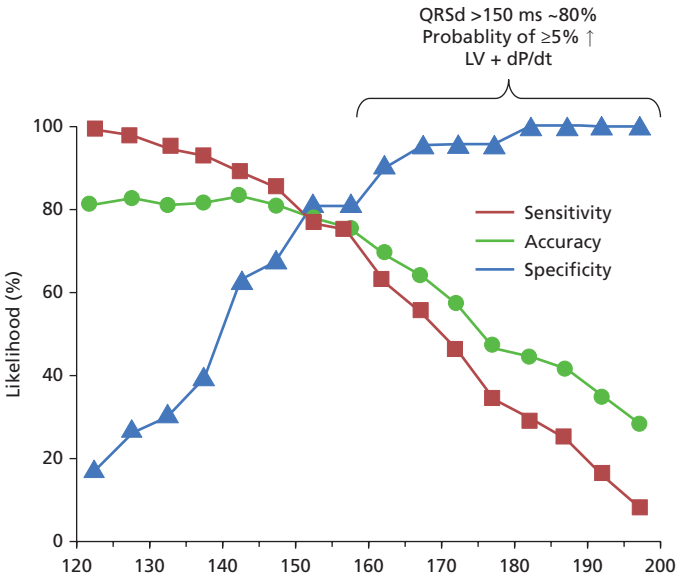


Figure 9.26 Sensitivity, specificity, and accuracy likelihoods are plotted for different QRS thresholds between 120 and 200 ms using acute hemodynamic data from PATH-CHF and PATH-CHF-II. The specificity curve indicates that there is 80% chance of non-response in the presence of QRS duration of less than 150 ms. The sensitivity curve indicates there is 80% chance of response if the QRS duration is more than 150 ms. Cardiac resynchronization therapy response is defined as more than a 5% acute increase in left ventricular (LV) dP/dt.

with a threshold cut-off between 120 and 150 ms. An important qualification is that this analysis is based on acute hemodynamic response to CRT. Consistently, these observations appear to be corroborated by the COMPANION, CARE-HF, MADIT-CRT, RAFT, and REVERSE clinical trials across individuals with mild, moderate, and severe HF;[4–6,14,15] a significant clinical benefit from CRT was observed among patients with a QRS duration of longer than 150 ms, whereas little or no benefit from CRT or CRT-D on death or HF hospitalization was observed among patients with a baseline QRS duration of shorter than 150 ms. Meta-regression analysis[35] showed a statistically significant relationship between the QRS duration at baseline and the log risk ratio of clinical events; a greater risk reduction occurred with a QRS duration of longer than 150 ms. Subgroup analyses from several studies have suggested that a QRS duration of shorter than 150 ms is a risk factor for failure to respond to CRT therapy.[36]

Prolonged QRS duration may not always be accompanied by dyssynchronous mechanical activation. In this situation, despite electrically delayed ventricular activation, CRT would not be anticipated to modify mechanical performance. Conversely, patients with narrow QRS complexes can demonstrate echocardiographic evidence of dyssynchrony. CRT is likely to be of utility in only a minority of these patients.[37]

QRS morphology

The vast majority of candidates for CRT have either intrinsic LBBB or paced LBBB (pacemaker dependent). The presence of LBBB confers a favorable response to CRT, independently and in addition to the QRS duration. Typically, LBBB is associated with delayed depolarization of the LV lateral wall, coupled with delayed mechanical activation in the same territory. It is intuitive that pre-excitation of the delayed LV lateral wall would resynchronize physiologically balanced ventricular activation.[38]. The study by Wokhlu *et al.*[39] showed that survival was similar in patients who underwent *de-novo* implantation or upgrading from an existing pacemaker or ICD. Patients with LBBB achieved more favorable survival and greater improvement in NYHA class and LVEF than those with RBBB.

A meta-analysis of four clinical trials showed that in patients with LBBB, CRT significantly reduced composite adverse clinical events [relative risk (RR), 0.64; 95% confidence interval (CI), 0.52–0.77; $P < .001$]. No benefit was observed for patients with non-LBBB conduction abnormalities (RR, 0.97; 95% CI, 0.69–1.20; $P = .49$).[35] An analysis of the benefit of CRT in subjects with RBBB from five randomized controlled trials (MIRACLE, CONTAK-CD, CARE-HF, MADIT-CRT, and RAFT) compared 259 patients randomly assigned to undergo CRT (4.3–12.5% of trial participants) versus 226 randomly assigned to medical therapy. The available data showed no favorable outcome with CRT in this subgroup.[40] However, the presence of RBBB does not preclude a co-existing LV conduction delay; rather it represents a greater severity of right bundle or RV conduction abnormality than on the contralateral side. Electrical 3D mapping of both the LV and RV in patients with RBBB shows a quarter may have LV conduction delays comparable to LBBB; nearly 50% have some delay that may be amenable to resynchronization.[41]

The key features of clinical outcomes are summarized in Table 9.8.

Approach to CRT non-responders

The majority of eligible CRT recipients respond to CRT. However, approximately 30% of patients fail to respond clinically to CRT, the so-called non-responders.[42,43] The non-response rate varies, depending on the criteria used for defining

Table 9.8 Key features of clinical outcomes

- A QRS duration of longer than 150 ms and/or left bundle branch block are favorable predictors of response to cardiac resynchronization therapy (CRT)
- CRT is an effective therapy across patients with mild-to-severe heart failure (HF)
- CRT improves HF symptoms, exercise effort, and quality of life
- CRT enhances LV systolic function and benefits structural remodeling
- CRT reduces hospitalization for HF
- CRT improves survival rate

non-response. Echocardiographic response is typically assessed by quantifying the change in LVEF or LV end-systolic volume 3–6 months after CRT. The clinical measures for CRT response include improvement in NYHA class by one or more classes, in 6-min walk distance by more than 10% or 50 m, or composite echocardiographic and clinical scores. Although the reduction of LV end-volume by 10% or 15% is the most often used objective evidence of LV reverse remodeling and the criterion for CRT response, the agreement between different methods to define response to CRT is inconsistent.[44] Multiple factors may contribute to the failure of this therapy. Some factors are related to pre-implant patient clinical characteristics, including the nature of cardiomyopathy, width of the QRS interval, type of ventricular conduction delay, extent of LV scar burden, and presence of non-cardiac co-morbidities. Other factors are related to post-implant elements that may be modifiable, such as LV lead position, percentage of biventricular pacing, and optimal AV and VV electrical coupling. The characteristics of CRT responders and non-responders are summarized in Table 9.9.

Etiology of underlying cardiomyopathy

In clinical practice, ischemic cardiomyopathy is more common than non-ischemic cardiomyopathy.[6,45] Conflicting data exist on the role of the underlying etiology of ventricular dysfunction and its impact on response.[14,15,46,47] Randomized clinical trials and cohort studies have shown CRT to be associated with a greater improvement in LVEF and reduced LV volume in patients who present with non-ischemic cardiomyopathy than in those with a predominant ischemic cardiomyopathy, in spite of similar LVEF in both groups before CRT (Figure 9.27).[6,15,45,48] This preferential structural and hemodynamic response may be associated with the more frequent presence of LBBB and less co-morbidity in this entity. Higher mortality has been found among patients with an ischemic cause of HF than among patients with a non-ischemic cause.[6,49,50] In the MADIT-CRT trial, Kaplan–Meier event analysis demonstrated significantly higher rates of HF or death at 3 years in the ischemic cardiomyopathy group compared with rates of HF or death in the non-ischemic group (Figure 9.28A,B), reflecting a poorer prognosis in the ischemic pathophysiological entity.[48] The

Table 9.9 Factors affecting the outcomes of cardiac resynchronization therapy

Factor	*Response more likely*	*Non-response more likely*
Patient clinical characteristics		
Cardiomyopathy	Non-ischemic	Ischemic
Sex	Female	Male
QRS duration	>150 ms	<150 ms
QRS morphology	Left bundle branch block	Right bundle branch block, intraventricular conduction delay
LV end-diastolic volume	180–240 mL	>240 mL
Ventricular dyssynchrony	Present	Not present
Scar burden	Low, not transmural	High, transmural
Right ventricular enlargement, dvsfunction	Not present	Present
Device-modifiable factors		
LV lead position	Lateral, base-mid LV	Anterior or inferior septum, apex
Percentage of biventricular pacing	99–100%	<99%, atrial fibrillation, PVCs
AV and VV optimization	Optimal	Not optimal

AV, atrioventricular; LV, left ventricular; PVC, premature ventricular contraction; VV, interventricular.

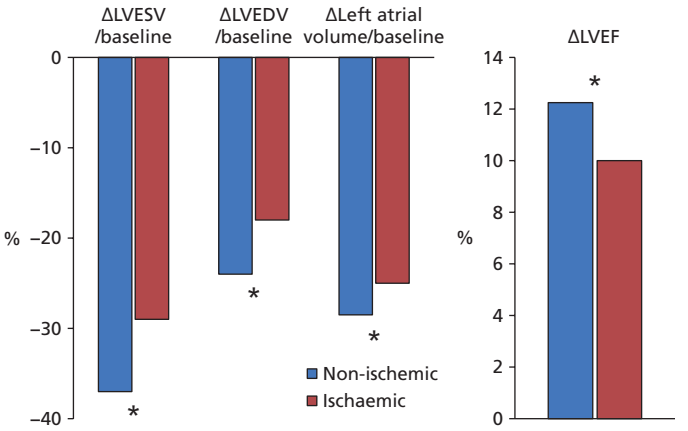


Figure 9.27 Effects of cardiac resynchronization therapy with defibrillation on echocardiographic measures in ischemic and non-ischemic cardiomyopathy patients in the MADIT-CRT trial. Asterisk indicate $P < .001$. The bars represent median values. ΔLVEF indicates the 1-year LVEF (%)—baseline LVEF (%). ΔVolume/baseline indicates (1 year volume − baseline volume)/baseline volume. LVEDV, left ventricular end-diastolic volume; LVEF, left ventricular ejection fraction; LVESV, left ventricular end-systolic volume. (Source: Barsheshet 2011.[48] Reproduced with permission of Oxford University Press.)

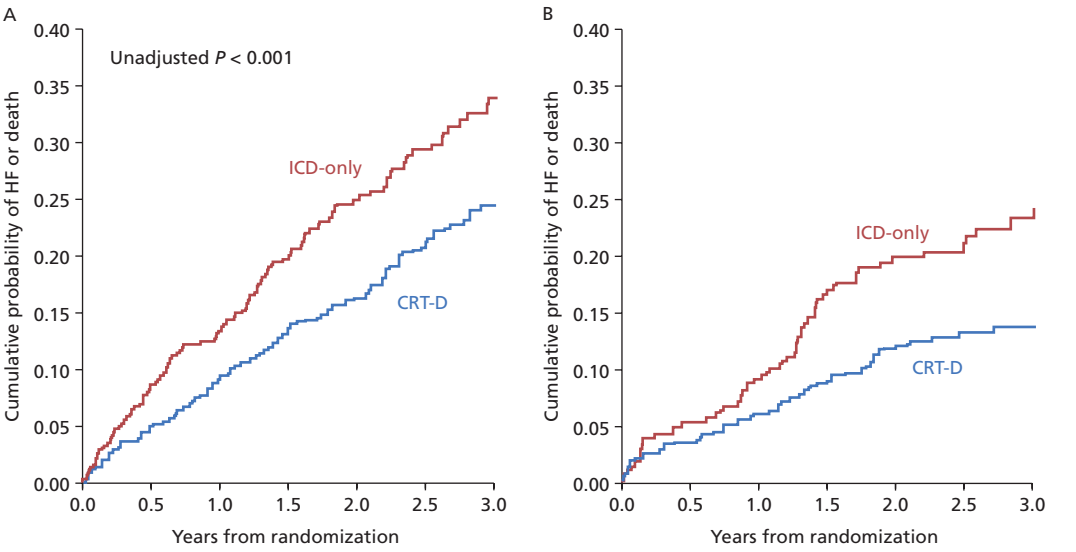


Figure 9.28 Kaplan–Meier estimates of probability of death or heart failure events in (A) all ischemic cardiomyopathy patients and (B) patients with non-ischemic cardiomyopathy. Unadjusted $P = 0.537$ for etiology-by-treatment interaction among all patients. CRT-D, cardiac resynchronization therapy with defibrillation; HF, heart failure; ICD, implantable cardioverter–defibrillator. (Source: Barsheshet 2011.[48] Reproduced with permission of Oxford University Press.)

interaction-term analysis did not show a statistically significant difference between ischemic and non-ischemic patients in the HF and death events with CRT-D therapy. It is difficult to be certain of the differential gain in terms of survival and HF events after CRT because ischemic heart disease has a worse natural course than non-ischemic disease.

Left ventricular structure and scar burden

The amount of scar tissue appears to be a predictor of response to CRT.[51,52] It is conceivable that a large scar burden, in some instances up to 50% of the LV mass, diminishes LV contractive force, irrespective of the pacing timing. Imaging modalities, including echocardiography, nuclear imaging, and magnetic resonance imaging, can be used to quantify the scar burden and assess the scar locations prior to CRT. Most transmural scars are located in the anterior, septal, and inferior walls, and apex of the LV. The LV lateral wall, a preferred LV lead location, is often spared from a large scar. A study has shown that 651 scar segments were identified using nuclear imaging assessment in 213 patients who received CRT devices.[51] Of these, only 11% of LV leads were positioned in scar segments, as shown in Figure 9.29. Patients may respond poorly to CRT when a posterolateral scar is present. In addition, a moderately dilated left ventricle, as opposed to a severely dilated one, predicts favorable reverse LV structural remodeling and response to CRT.[53]

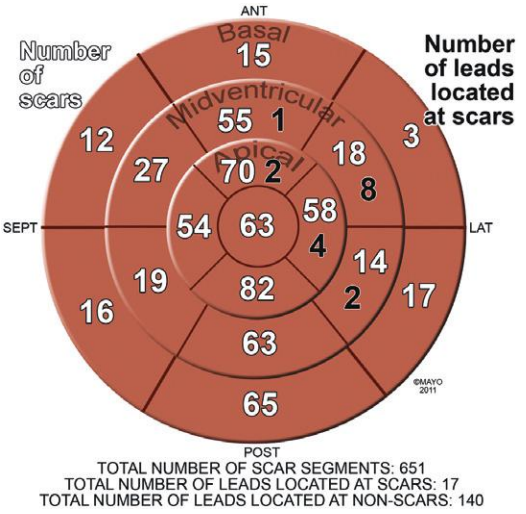


Figure 9.29 Distribution of scar sites and left ventricular (LV) leads located in a scar segment in the 17-segment polar map. In each location, the white number indicates the number of LV leads in a non-scar segment, and the black number indicates the number of LV leads located in a scar segment. (Source: Xu YZ *et al.* 2012.[51] Reproduced with permission of the Society of Nuclear Medicine.)

Optimal left ventricular lead position

The optimal LV pacing site varies between patients and is likely to be driven by multiple factors, such as venous anatomy, regional and global LV mechanical function, myocardial substrate, characterization of electrical delay, and other factors. The success of resynchronization depends on pacing from a site that causes a change in the sequence of ventricular activation that translates to an improvement in cardiac performance. Presumably, this site corresponds to the site of maximal mechanical delay. Such systolic improvement and mechanical resynchronization does not require electrical synchrony[54] and explains the lack of correlation between change in QRS duration and clinical response to CRT. Yet, the observed electrical dyssynchrony, as measured by the onset of QRS, to LV delay is strongly associated with CRT response.[55] Ideally, the pacing site or sites that produce the greatest hemodynamic effect would be selected.[56] This notion is supported by the fact that electrical and mechanical delays in the LV lateral wall frequently occur in patients with LBBB, often accompanied by HF.[57–59] Pacing free wall sites yields greater hemodynamic improvement than pacing anterior wall sites or any other LV region.[56,60,61]

Comprehensive echocardiography has been used to assess the delayed activation of the LV lateral wall. The presence of ventricular dyssynchrony, determined by tissue Doppler, may predict CRT outcome. However, a large, prospective randomized trial failed to demonstrate any meaningful utility for conventional and tissue Doppler-based echocardiographic methods of determining dyssynchrony (timing difference of peak contraction among all LV segments) in the prediction of CRT response.[62] Newer echocardiographic parameters may overcome the limitations of dyssynchrony measurement. Speckle tracking permits analysis of

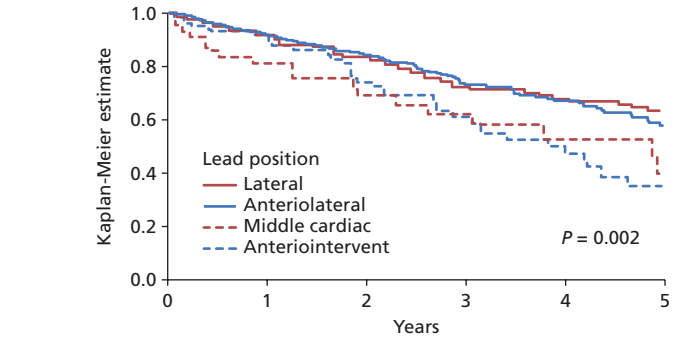
motion by matching natural acoustic reflections from frame to frame to permit angle-independent assessment of tissue deformation and motion. Speckle tracking imaging with measurement of radial dyssynchrony and scar mass, combined with localization of the latest contracting segment, seems promising as a potential tool for improving response to CRT, although more studies are needed to confirm the utility of this imaging technology.[63,64]

There is no consensus on the long-term outcomes of different lead locations and assessment of the tools to determine where a lead is best placed.[65–67] Improvement in NYHA class and LV systolic function may be seen for all lead position segments. Still greater hemodynamic and NYHA functional class benefits are seen in lateral lead positions than in the anterior lead position.[23] The greater response to CRT derived from a lateral lead location may explain the greater survival outcome than that in patients in the same single center study with a non-lateral lead location (Figure 9.30). However, sub-analysis of lead position on clinical outcome from clinical trials has not observed a survival difference with regard to the circumferential LV lead position.[68,69] Yet, pacing at the LV basal and mid area has shown a greater response to CRT than pacing at the LV apex.

Attempts to move the LV lead to a more optimal location may improve CRT response. Figure 9.31 shows a 55-year-old female who received a CRT-D for severe non-ischemic cardiomyopathy, NYHA class III, LVEF of 20%, and QRS duration of 170 ms with LBBB. The LV lead was initially placed in the anterolateral vein, more distally to the LV apex (Figure 9.31A). She had minimal improvement in LVEF to 25%. During LV lead revision, the lead was moved towards the LV base in the same anterolateral vein (Figure 9.31B). Thereafter, the patient gradually achieved normalization of LVEF to 52% and LV chamber size was reduced from 71 mm to 49 mm. Her HF symptoms were resolved. Figure 9.31C–E shows her 12-lead ECG prior to CRT (LBBB, QRS 170 ms), after CRT (QRS 132 ms), and after LV lead revision (QRS 110 ms), respectively. Note that lead I became more negative and lead III more positive, corresponding to the anatomical change of LV lead position.

When deciding on lead revision, one should take precaution to balance the gain and risks of the procedure in the individual patient. If the preferred location is not acceptable, owing to an anatomical barrier, high pacing threshold, or extracardiac pacing, venoplasty or a move to an alternative lateral location should be considered. Surgical placement of epicardial LV pacing leads or endocardial LV stimulation,[70] are options when the coronary venous approach or lateral lead position fails.

New techniques facilitating LV lead placement are on the horizon. LV lead placement guided by echocardiographic strain imaging may identify the



Lateral (PL+L)	349	293	217	149	103	52
Anteriolateral	237	192	145	89	69	40
Middle cardiac	45	30	21	16	9	6
Anteriointervent	79	63	42	29	18	9

Figure 9.30 Kaplan–Meier estimates of survival among left ventricular lead positions. A greater survival outcome is seen when the leads are placed in the lateral and anterolateral coronary veins.

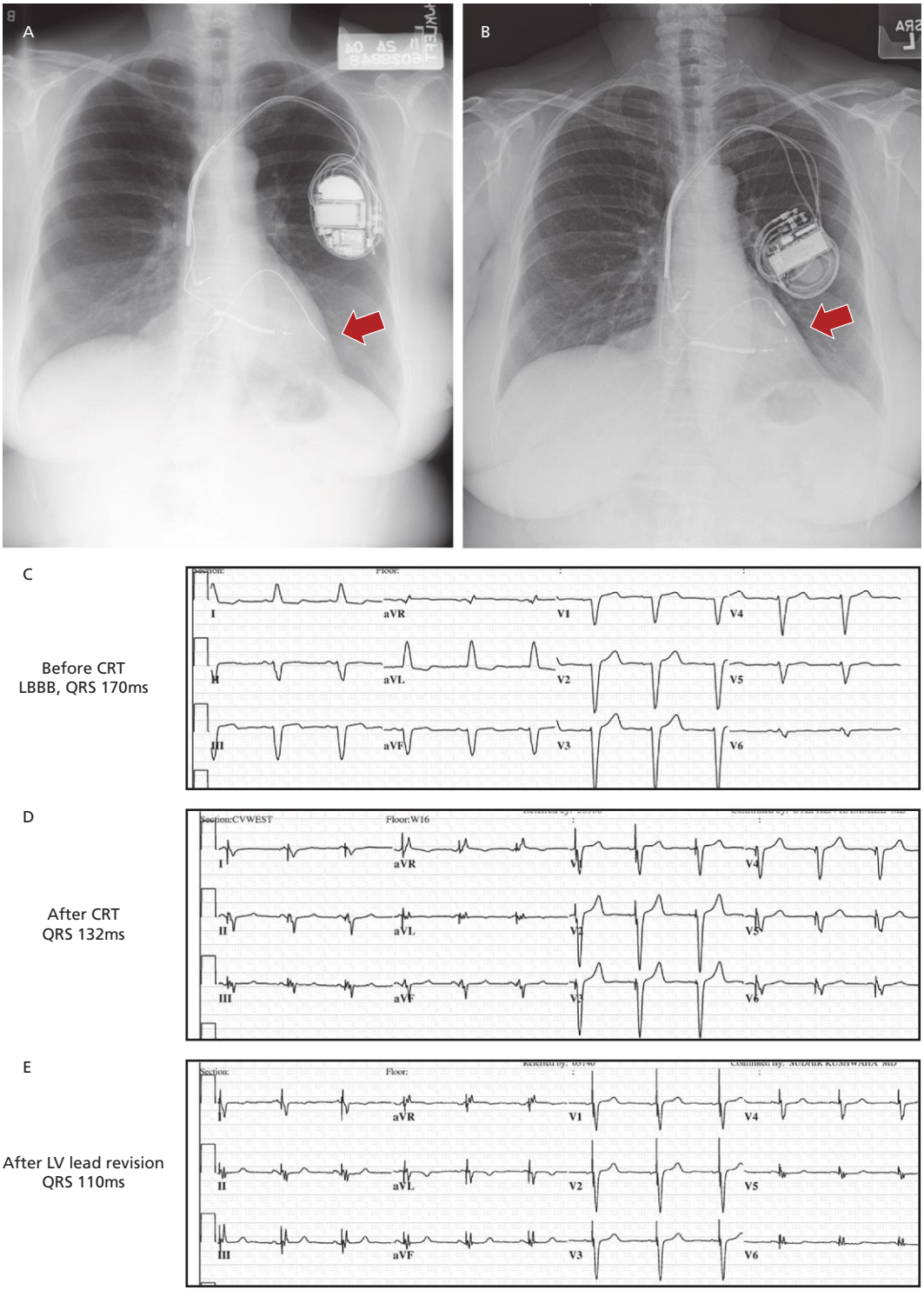


Figure 9.31 A patient received cardiac resynchronization therapy with defibrillation (CRT-D) for severe non-ischemic cardiomyopathy. (A) The left ventricular (LV) lead was initially placed in the anterolateral vein, more distally to the LV apex. (B) The LV lead was revised and moved towards the LV base in the same anterolateral vein. 12-lead ECG (C) before CRT (LBBB, QRS 170 ms), (D) after CRT (QRS 132 ms), and (E) after LV lead revision (QRS 110 ms). Note that lead I became more negative and lead III more positive with the change to the anatomical position of the LV lead.

optimal location for the LV lead. The CardioGuide system could efficiently generate 3D images of coronary vessels, being a capable tool for targeted LV lead placement.

Maximizing biventricular pacing

The percentage of biventricular pacing is an easily overlooked factor. The ideal target is 100% CRT, which is usually not difficult to attain in sinus rhythm. However, in AF, the adequacy of biventricular pacing depends on the competition between ventricular rate and pacing rate. Intermittent intrinsic ventricular conduction beats are often seen, diminishing the efficacy of CRT. There is no definitive percentage used as a biventricular pacing cut-off to separate non-responders from responders to CRT. The ALTITUDE study analyzed over 30 000 patients who were followed by the LATITUDE remote monitoring system. CRT-D survival by biventricular pacing quartiles showed a significant difference in survival. Patients who were paced 100% (Q4) had a 27% reduction in mortality compared to all other groups [hazard ratio (HR), .73; $P < .0001$), while patients who were paced less than 95% (Q1) had a 35% increase in mortality (HR, 1.35; $P < .0001$). Thus, a small difference in missing biventricular pacing, such as 99% versus 97%, may show a substantial difference in survival benefit (Figure 9.32).[71] Aggressive ventricular rate control is required to achieve the goal of CRT.

Often, permanent AVN ablation is advised to ensure 100% biventricular pacing and improve CRT outcome.[71] Meta-analysis has shown an association of AF with an increased risk of non-response to CRT when compared with responders (34.5% vs. 26.7%). Intriguingly, AVN ablation lowers the risk of clinical non-response (RR, 0.40; 95% CI, 0.28–0.58; $P < .001$) and risk of death[72] (Figure 9.33).

Frequent premature ventricular contractions (PVCs) may impact on true biventricular pacing, despite the fact that modern devices can trigger biventricular pacing after sensing an intrinsic QRS. In a multicenter study, CRT non-responders with more than 10 000 PVCs in 24 h underwent PVC ablation. PVCs were successfully eliminated in 88% of the cohort at 12-month follow-up. LVEF was significantly improved by 6.7%, with a concomitant reduction of LV volume and NYHA functional class after ablation.[73] The greater improvement in LVEF correlated with the greater frequency of PVCs (Figure 9.34).

AV and VV optimization

Optimization of programmed parameters is also considered important to maximize the therapeutic response. Both AV and VV timing intervals have demonstrated acute hemodynamic benefits. However, multicenter studies that show long-term clinical benefit have been lacking. Echocardiography-guided methods have been

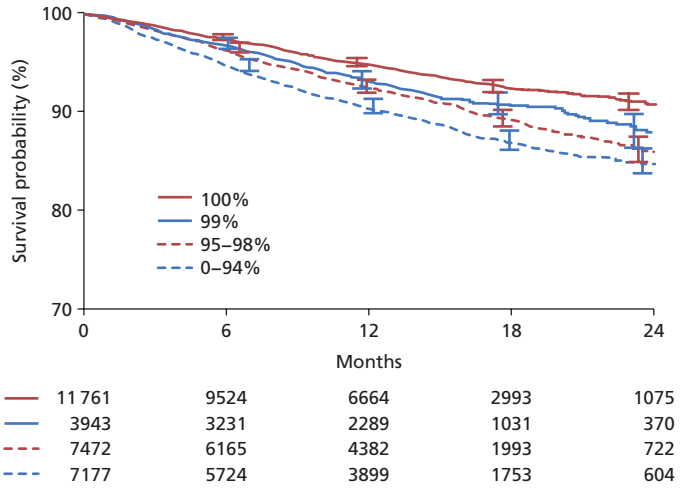


Figure 9.32 Cardiac resynchronization therapy (CRT-D) survival by biventricular pacing quartiles (time from first LATITUDE interrogation). (Source: Hauser RG, Hayes DL. Increasing hazard of Sprint Fidelis implantable cardioverter-defibrillator lead failure. *Heart Rhythm* 2009; 6(5): 605–10. Reproduced with permission of Elsevier.)

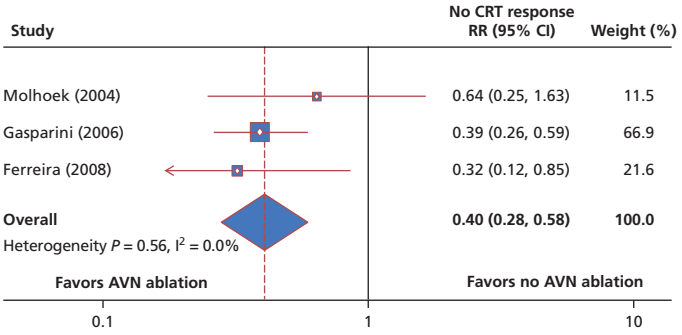


Figure 9.33 Meta-analysis of studies comparing the relative risk (RR) of clinical non-response to cardiac resynchronization therapy (CRT) among patients with atrial fibrillation who did undergo versus those who did not undergo concomitant atrioventricular nodal (AVN) ablation. $P = .001$ for the pooled RR. (Source: Wilton SB *et al*. 2011.[72] Reproduced with permission of Elsevier.)

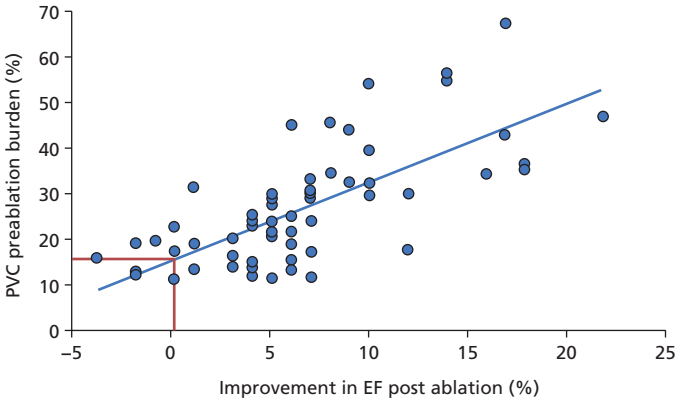


Figure 9.34 Correlation of premature ventricular contraction (PVC) frequency at baseline with improvement of left ventricular ejection fraction (EF) after PVC ablation. (Source: Lakkireddy D *et al*. 2012.[73] Reproduced with permission of Elsevier.)

used most commonly but have poor reproducibility. Hence, the role and efficacy of AV and VV optimization in improving clinical outcomes in CRT remain unclear. Currently, AV and VV optimization is used on an individualized basis (see Chapter 3).

The key features of the approach to non-responders are summarized in Table 9.10.

Algorithm to approach non-responders

In all patients, various heterogeneous factors may influence the outcome of CRT. Patient clinical characteristics, the anatomical limit for LV lead placement, and the need for individualized complex

Table 9.10 Key features of the management of non-responders

- Multiple factors may limit cardiac resynchronization therapy (CRT) response
- Patient factors that favor CRT outcome include non-ischemic cardiomyopathy, left bundle branch block, and a QRS duration of longer than 150 ms
- Optimal left ventricular (LV) lead position is the LV basal or mid lateral wall
- Biventricular pacing should be maximized to 100% and atrioventricular node (AVN) ablation considered in patients with atrial fibrillation (AF) and a ventricular rate higher than the pacing rate
- AV and VV optimization should be individualized

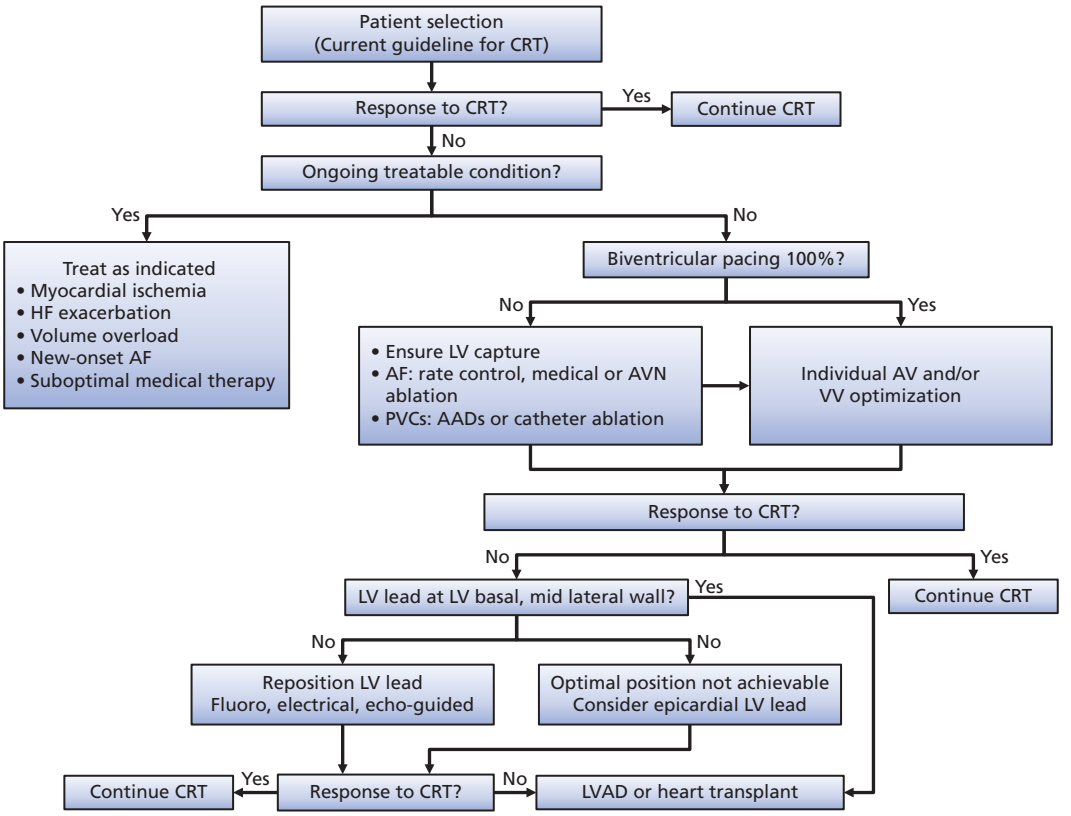


Figure 9.35 Algorithm used to approach cardiac resynchronization therapy (CRT) non-responders. AAD, antiarrythmic drug; AF, atrial fibrillation; AV, atrioventricular; HF, heart failure; LBBB, left bundle branch block; LV, left ventricular; PVC, premature ventricular contraction; VV, interventricular.

and physiological resynchronization programming are all taken into consideration. Often, more than one factor may account for a poor response to CRT. Moreover, concomitant co-morbidities, such as end-stage renal disease (cardiorenal syndrome), anemia, non-revascularizable coronary artery disease, and diabetes, can also dampen response to CRT.[74]

Figure 9.35 shows an algorithm for approaching non-responders to CRT. The first step is to treat correctable factors or conditions, such as volume overload, myocardial ischemia, new onset of AF, and suboptimal medical therapy. The second step is to confirm whether the patient is receiving 100% biventricular pacing. The loss of LV capture or anodal stimulation of the RV should be corrected. AF is the most common cause of low biventricular pacing rate. Definitive AVN ablation with complete AV block is recommended to attain 100% CRT. Frequent PVCs can be treated with either antiarrhythmic agents or catheter ablation. The third step is to consider individualized AV and/or VV optimization guided by echocardiography. The fourth step is to consider repositioning the LV lead if it is not located in the basal or mid LV lateral wall. The previous procedure note should be reviewed before considering LV lead revision. Repositioning of the LV lead can be guided under fluoroscopy. The local electrical activity identified by measuring the electrical conduction delay at the LV lead can be a useful reference. Placing the lead in the region of viable myocardium that is capable of thickening, measured by radial strain, has been shown to increase the CRT response rate.[75] In some cases, the optimal LV lead position may not be achievable due to anatomical or other constraints.

An epicardial LV lead would be an alternative option.

Despite all efforts, a fraction of patients will remain non-responsive to CRT and might be candidates for consideration of a ventricular assisted device or heart transplant.

Summary

CRT has been proven to be an effective non-pharmacological treatment alternative for patients with drug-refractory severe HF. Informed by recent clinical trials, updated CRT guidelines recommend expanding the resynchronization device therapy to patients with mild or moderate HF. A variable proportion of eligible patients fail to benefit from this treatment. Part of the complexity in the management of HF is related to the fact that evolution of HF is unpredictable in the single patient. Efforts to improve patient selection and to sophisticatedly manage the device and patient's condition after receiving CRT are required to achieve optimal CRT outcomes.

References

1 Kannel WB, Plehn JF, Cupples LA. Cardiac failure and sudden death in the Framingham Study. *Am Heart J* 1988; 115(4): 869–875.

2 Gheorghiade M, Pang PS. Acute heart failure syndromes. *J Am Coll Cardiol* 2009; 53(7): 557–573.

3 Tournoux FB, Manzke R, Chan RC, *et al*. Integrating functional and anatomical information to facilitate cardiac resynchronization therapy. *Pacing Clin Electrophysiol* 2007; 30(8): 1021–1022.

4 Linde C, Abraham WT, Gold MR, St. John Sutton M, Ghio S, Daubert C. Randomized trial of cardiac resynchronization in mildly symptomatic heart failure patients and in asymptomatic patients with left ventricular dysfunction and previous heart failure symptoms. *J Am Coll Cardiol* 2008; 52(23): 1834–1843.

5 Tang AS, Wells GA, Talajic M, *et al*. Cardiac-resynchronization therapy for mild-to-moderate heart failure. *N Engl J Med* 2010; 363(25): 2385–2295.

6 Moss AJ, Hall WJ, Cannom DS, *et al*. Cardiac-resynchronization therapy for the prevention of heart-failure events. *N Engl J Med* 2009; 361(14): 1329–1338.

7 Yu CM, Chau E, Sanderson JE, *et al*. Tissue Doppler echocardiographic evidence of reverse remodeling and improved synchronicity by simultaneously delaying regional contraction after biventricular pacing therapy in heart failure. *Circulation* 2002; 105(4): 438–445.

8 Chakir K, Depry C, Dimaano VL, *et al*. Galphas-biased β2-adrenergic receptor signaling from restoring synchronous contraction in the failing heart. *Sci Transl Med* 2011; 3(100): 100ra88.

9 Aiba T, Hesketh GG, Barth AS, *et al*. Electrophysiological consequences of dyssynchronous heart failure and its restoration by resynchronization therapy. *Circulation* 2009; 119(9): 1220–1230.

10 Wang S-B, Foster DB, Rucker J, O'Rourke B, Kass DA, Van Eyk JE. Redox regulation of mitochondrial ATP synthase/novelty and significance. *Circ Res* 2011; 109(7): 750–757.

11 Members WC, Epstein AE, DiMarco JP, *et al*. ACC/AHA/HRS 2008 guidelines for device-based therapy of cardiac rhythm abnormalities. *Circulation* 2008; 117(21): e350–e408.

12 Tracy CM, Epstein AE, Darbar D, *et al*. 2012 ACCF/AHA/HRS focused update of the 2008 guidelines for device-based therapy of cardiac rhythm abnormalities: A report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines. *J Am Coll Cardiol* 2012; 60(14): 1297–1313.

13 Abraham WT, Fisher WG, Smith AL, *et al*. Cardiac resynchronization in chronic heart failure. *N Engl J Med* 2002; 346(24): 1845–1853.

14 Bristow MR, Saxon LA, Boehmer J, *et al*. Cardiac-resynchronization therapy with or without an implantable defibrillator in advanced chronic heart failure. *N Engl J Med* 2004; 350(21): 2140–2150.

15 Cleland JG, Daubert J-C, Erdmann E, *et al*. The effect of cardiac resynchronization on morbidity and mortality in heart failure. *N Engl J Med* 2005; 352(15): 1539–1549.

16 Wilkoff BL, Cook JR, Epstein AE, *et al*. Dual-chamber pacing or ventricular backup pacing in patients with an implantable defibrillator: the Dual Chamber and VVI Implantable Defibrillator (DAVID) Trial. *JAMA* 2002; 288(24): 3115–3123.

17 Doshi RN, Daoud EG, Fellows C, *et al*. Left ventricular-based cardiac stimulation post AV nodal ablation evaluation (the PAVE study). *J Cardiovasc Electrophysiol* 2005; 16(11): 1160–1165.

18 Tournoux FB, Manzke R, Chan RC, *et al*. Integrating functional and anatomical information to facilitate cardiac resynchronization therapy. *Pacing Clin Electrophysiol* 2007; 30(8): 1021–1022.

19 Bax JJ, Marwick TH, Molhoek SG, *et al*. Left ventricular dyssynchrony predicts benefit of cardiac resynchronization therapy in patients with end-stage heart failure before pacemaker implantation. *Am J Cardiol* 2003; 92(10): 1238–1240.

20 Stevenson WG, Hernandez AF, Carson PE, *et al*.; Heart Failure Society of America Guideline Committee. Indications for cardiac resynchronization therapy: 2011 update from the Heart Failure Society of America Guideline Committee. *J Card Fail* 2012; 18(2): 94–106.

21 Butter C, Auricchio A, Stellbrink C, *et al*. Effect of resynchronization therapy stimulation site on the systolic function of heart failure patients. *Circulation* 2001; 104(25): 3026–3029.

22 Gold MR, Auricchio A, Hummel JD, *et al*. Comparison of stimulation sites within left ventricular veins on the acute hemodynamic effects of cardiac resynchronization therapy. *Heart Rhythm* 2005; 2(4): 376–381.

23 Dong YX, Powell BD, Asirvatham SJ, *et al*. Left ventricular lead position for cardiac resynchronization: a comprehensive cinegraphic, echocardiographic, clinical, and survival analysis. *Europace* 2012; 14(8): 1139–1147.

24 Gras D, Böcker D, Lunati M, *et al*. Implantation of cardiac resynchronization therapy systems in the CARE-HF trial: Procedural success rate and safety. *Europace*. 2007; 9: 516–522.

25 Barold SS, Stroobandt RX, Sinnaeve AF. *Cardiac Pacemakers Step-by-Step: An Illustrated Guide*. Chichester: John Wiley & Sons, 2003.

26 Maish MS. The diaphragm. *Surg Clin North Am* 2010; 90(5): 955–968.

27 van Rees JB, de Bie MK, Thijssen J, Borleffs CJW, Schalij MJ, van Erven L. Implantation-related complications of implantable cardioverter-defibrillators and cardiac resynchronization therapy devices: A systematic review of randomized clinical trials. *J Am Coll Cardiol* 2011; 58: 995–1000.

28 Cheng A, Wang Y, Curtis JP, Varosy PD. Acute lead dislodgements and in-hospital mortality in patients enrolled in the National Cardiovascular Data Registry Implantable Cardioverter Defibrillator Registry. *J Am Coll Cardiol* 2010; 56(20): 1651–1656.

29 Cazeau S, Leclercq C, Lavergne T, *et al*. Effects of multisite biventricular pacing in patients with heart failure and intraventricular conduction delay. *N Engl J Med* 2001; 344: 873–880.

30 Auricchio A, Prinzen FW. Non-responders to cardiac resynchronization therapy: The magnitude of the problem and the issues. *Circ J* 2011; 75: 521–527.

31 Young JB, Abraham WT, Smith AL, *et al*. Combined cardiac resynchronization and implantable cardioversion defibrillation in advanced chronic heart failure: The miracle icd trial. *JAMA* 2003; 289: 2685–2694.

32 Lozano I, Bocchiardo M, Achtelik M, *et al*.; VENTAK CHF/**CONTAK CD** Investigators Study Group. *Pacing Clin Electrophysiol* 2000; 23(11 Pt 2): 1711–1712.

33 Adabag S, Roukoz H, Anand IS, Moss AJ. Cardiac resynchronization therapy in patients with minimal heart failure: A systematic review and meta-analysis. *J Am Coll Cardiol* 2011; 58: 935–941.

34 Stellbrink C, Auricchio A, Butter C, *et al*.; PATH-CHF II Study Group. Pacing Therapies in Congestive Heart Failure II study. *Am J Cardiol* 2000; 86(9A): 138K–143K.

35 Sipahi I, Carrigan TP, Rowland DY, *et al*. Impact of qrs duration on clinical event reduction with cardiac resynchronization therapy: Meta-analysis of randomized controlled trials. *Arch Int Med* 2011;171: 1454–1462.

36 Saxon LA, Ellenbogen KA. Resynchronization therapy for the treatment of heart failure. *Circulation* 2003; 108: 1044–1048.

37 Beshai JF, Grimm RA, Nagueh SF, *et al*. Cardiac-resynchronization therapy in heart failure with narrow qrs complexes. *N Engl J Med* 2007; 357: 2461–2471.

38 Auricchio A, Fantoni C, Regoli F, *et al*. Characterization of left ventricular activation in patients with heart failure and left bundle-branch block. *Circulation* 2004; 109: 1133–1139.

39 Wokhlu A, Rea RF, Asirvatham SJ, *et al*. Upgrade and de novo cardiac resynchronization therapy: Impact of paced or intrinsic QRS morphology on outcomes and survival. *Heart Rhythm* 2009; 6(10): 1439–1447.

40 Nery PB, Ha AC, Keren A, Birnie DH. Cardiac resynchronization therapy in patients with left ventricular systolic dysfunction and right bundle branch block: A systematic review. *Heart Rhythm* 2011;8:1083–1087.

41 Fantoni C, Kawabata M, Massaro R, *et al*. Right and left ventricular activation sequence in patients with heart failure and right bundle branch block: a detailed analysis using three-dimensional non-fluoroscopic electroanatomic mapping system. *J Cardiovasc Electrophysiol* 2005; 16(2): 112–119; discussion 20–21.

42 Auricchio A, Stellbrink C, Butter C, *et al*. Clinical efficacy of cardiac resynchronization therapy using left ventricular pacing in heart failure patients stratified by severity of ventricular conduction delay. *J Am Coll Cardiol* 2003; 42(12): 2109–2116.

43 Bax JJ, Marwick TH, Molhoek SG, *et al*. Left ventricular dyssynchrony predicts benefit of cardiac resynchronization therapy in patients with end-stage heart failure before pacemaker implantation. *Am J Cardiol* 2003; 92: 1238–1240.

44 Fornwalt BK, Sprague WW, BeDell P, *et al*. Agreement is poor among current criteria used to define response to cardiac resynchronization therapy. *Circulation* 2010; 121(18): 1985–1991.

45 McLeod CJ, Shen WK, Rea RF, *et al*. Differential outcome of cardiac resynchronization therapy in ischemic cardiomyopathy and idiopathic dilated cardiomyopathy. *Heart Rhythm* 2011;8(3): 377–382.

46 Molhoek SG, Bax JJ, van Erven L, *et al*. Comparison of benefits from cardiac resynchronization therapy in

patients with ischemic cardiomyopathy versus idiopathic dilated cardiomyopathy. *Am J Cardiol* 2004; 93: 860–863.

47 Díaz-Infante E, Mont L, Leal J, *et al*. Predictors of lack of response to resynchronization therapy. *Am J Cardiol* 2005; 95: 1436–1440.

48 Barsheshet A, Goldenberg I, Moss AJ, *et al*. Response to preventive cardiac resynchronization therapy in patients with ischaemic and nonischaemic cardiomyopathy in MADIT-CRT. *Eur Heart J* 2011; 32(13): 1622–1630.

49 Likoff MJ, Chandler SL, Kay HR. Clinical determinants of mortality in chronic congestive heart failure secondary to idiopathic dilated or to ischemic cardiomyopathy. *Am J Cardiol* 1987; 59: 634–638.

50 Franciosa JA, Wilen M, Ziesche S, Cohn JN. Survival in men with severe chronic left ventricular failure due to either coronary heart disease or idiopathic dilated cardiomyopathy. *Am J Cardiol* 1983; 51: 831–836.

51 Xu YZ, Cha YM, Feng D, *et al*. Impact of myocardial scarring on outcomes of cardiac resynchronization therapy: extent or location? *J Nucl Med* 2012; 53(1): 47–54.

52 Bleeker GB, Kaandorp TA, Lamb HJ, *et al*. Effect of posterolateral scar tissue on clinical and echocardiographic improvement after cardiac resynchronization therapy. *Circulation* 2006; 113(7): 969–976.

53 Gasparini M, Regoli F, Ceriotti C, *et al*. Remission of left ventricular systolic dysfunction and of heart failure symptoms after cardiac resynchronization therapy: temporal pattern and clinical predictors. *Am Heart J* 2008; 155(3): 507–514.

54 Leclercq C, Faris O, Tunin R, *et al*. Systolic improvement and mechanical resynchronization does not require electrical synchrony in the dilated failing heart with left bundle-branch block. *Circulation* 2002; 106(14): 1760–1763.

55 Gold MR, Birgersdotter-Green U, Singh JP, *et al*. The relationship between ventricular electrical delay and left ventricular remodelling with cardiac resynchronization therapy. *Eur Heart J* 2011; 32(20): 2516–2524.

56 Butter C, Auricchio A, Stellbrink C, *et al*. Effect of resynchronization therapy stimulation site on the systolic function of heart failure patients. *Circulation* 2001; 104(25): 3026–3029.

57 Gold MR, Auricchio A, Hummel JD, *et al*. Comparison of stimulation sites within left ventricular veins on the acute hemodynamic effects of cardiac resynchronization therapy. *Heart Rhythm* 2005; 2(4): 376–381.

58 Ypenburg C, van Bommel RJ, Delgado V, *et al*. Optimal left ventricular lead position predicts reverse remodeling and survival after cardiac resynchronization therapy. *J Am Coll Cardiol* 2008; 52(17): 1402–1409.

59 Becker M, Kramann R, Franke A, *et al*. Impact of left ventricular lead position in cardiac resynchronization therapy on left ventricular remodelling. A circumferential strain analysis based on 2D echocardiography. *Eur Heart J* 2007; 28(10): 1211–1220.

60 Auricchio A, Stellbrink C, Sack S, *et al*. The Pacing Therapies for Congestive Heart Failure (PATH-CHF) study: rationale, design, and endpoints of a prospective randomized multicenter study. *Am J Cardiol* 1999; 83(5B): 130D–135D.

61 Auricchio A, Klein H, Tockman B, *et al*. Transvenous biventricular pacing for heart failure: can the obstacles be overcome? *Am J Cardiol* 1999; 83(5B): 136D–142D.

62 Chung ES, Leon AR, Tavazzi L, *et al*. Results of the Predictors of Response to CRT (PROSPECT) trial. *Circulation* 2008; 117(20): 2608–2616.

63 Becker M, Hoffmann R, Kuhl HP, *et al*. Analysis of myocardial deformation based on ultrasonic pixel tracking to determine transmurality in chronic myocardial infarction. *Eur Heart J* 2006; 27(21): 2560–2566.

64 Delgado V, van Bommel RJ, Bertini M, *et al*. Relative merits of left ventricular dyssynchrony, left ventricular lead position, and myocardial scar to predict long-term survival of ischemic heart failure patients undergoing cardiac resynchronization therapy. *Circulation* 2011; 123(1): 70–78.

65 Gasparini M, Regoli F, Galimberti P, Ceriotti C, Cappelleri A. Cardiac resynchronization therapy in heart failure patients with atrial fibrillation. *Europace* 2009; 11(Suppl 5): v82–86.

66 Kleemann T, Becker T, Strauss M, Dyck N, Schneider S, Weisse U, *et al*. Impact of left ventricular lead position on the incidence of ventricular arrhythmia and clinical outcome in patients with cardiac resynchronization therapy. *J Interv Card Electrophysiol.* 2010 Aug; 28(2): 109–116.

67 Foley PW, Chalil S, Ratib K, *et al*. Fluoroscopic left ventricular lead position and the long-term clinical outcome of cardiac resynchronization therapy. *Pacing Clin Electrophysiol* 2011; 34(7): 785–797.

68 Saxon LA, Olshansky B, Volosin K, *et al*. Influence of left ventricular lead location on outcomes in the COMPANION study. *J Cardiovasc Electrophysiol* 2009; 20(7): 764–768.

69 Singh JP, Klein HU, Huang DT, *et al*. Left ventricular lead position and clinical outcome in the Multicenter Automatic Defibrillator Implantation Trial-Cardiac Resynchronization Therapy (MADIT-CRT) trial. *Circulation* 2011; 123(11): 1159–1166.

70 DeRose Jr JJ, Ashton Jr RC, Belsley S, *et al*. Robotically assisted left ventricular epicardial lead implantation for biventricular pacing. *J Am Coll Cardiol* 2003; 41(8): 1414–1419.

71 Dong K, Shen WK, Powell BD, *et al*. Atrioventricular nodal ablation predicts survival benefit in patients with

atrial fibrillation receiving cardiac resynchronization therapy. *Heart Rhythm* 2010; 7: 1240–1245.

72 Wilton SB, Leung AA, Ghali WA, Faris P, Exner DV. Outcomes of cardiac resynchronization therapy in patients with versus those without atrial fibrillation: a systematic review and meta-analysis. *Heart Rhythm* 2011; 8(7): 1088–1094.

73 Lakkireddy D, Di Biase L, Ryschon K, *et al*. Radiofrequency ablation of premature ventricular ectopy improves the efficacy of cardiac resynchronization therapy in nonresponders. *J Am Coll Cardiol* 2012; 60(16): 1531–1539.

74 Mullens W, Grimm RA, Verga T, *et al*. Insights from a cardiac resynchronization optimization clinic as part of a heart failure disease management program. *J Am Coll Cardiol* 2009; 53(9): 765–773.

75 Khan FZ, Virdee MS, Palmer CR, *et al*. Targeted Left Ventricular Lead Placement to Guide Cardiac Resynchronization Therapy: The TARGET study: A randomized, controlled trial. *J Am Coll Cardiol* 2012; 59(17): 1509–1518.

76 Toma M, McAlister FA, Ezekowitz J, *et al*. Proportion of patients followed in a specialized heart failure clinic needing an implantable cardioverter defibrillator as determined by applying different trial eligibility criteria. *Am J Cardiol* 2006; 97(6): 882–885.

77 Cha Y, Rea RF, Wang M, *et al*. Response to cardiac resynchronization therapy predicts survival in heart failure: a single-center experience. *J Cardiovasc Electrophysiol* 2007; 18(10): 1015–1019.

78 Lozano I, Bocchiardo M, Achtelik M, *et al*.; VENTAK CHF/CONTAK CD Investigators Study Group. Impact of biventricular pacing on mortality in a randomized crossover study of patients with heart failure and ventricular arrhythmias. *Pacing Clin Electrophysiol* 2000; 23(11 Pt 2): 1711–1712.

79 Abraham WT, Young JB, León AR, *et al*.; Multicenter InSync ICD II Study Group. Effects of cardiac resynchronization on disease progression in patients with left ventricular systolic dysfunction, an indication for an implantable cardioverter-defibrillator, and mildly symptomatic chronic heart failure. *Circulation* 2004; 110(18): 2864–2868.

10 CHAPTER 10

ICD follow-up and troubleshooting

Fadi Mansour and Paul Khairy
University of Montreal, Montreal, QC, Canada

Introduction

The implantable cardioverter–defibrillator (ICD) represents a milestone in the evolution of arrhythmia management. It achieved the seemingly improbable (i.e. automated) termination of life-threatening arrhythmias by means of a sophisticated imbedded computer. Indications have expanded across a broad spectrum of patients with varied disorders associated with a high risk of sudden death. Technological advances have resulted in increasingly complex devices with intricate algorithms that dictate the recognition of arrhythmias and delivery of therapy. While ICDs are also equipped with multifaceted pacing features, this chapter will focus on the follow-up and troubleshooting specific to ICD functions. In so doing, ICD follow-up recommendations will be reviewed, programming options beyond "out of the box" settings discussed, company-specific issues addressed, therapies elaborated, special issues considered, and troubleshooting tips offered. Whenever possible, evidence-based guidelines will be emphasized.

ICD follow-up

Current guidelines recommend an initial follow-up visit 2–12 weeks after ICD implantation and every 3–6 months thereafter, barring particular circumstances.[1] Although remote monitoring may greatly reduce the need for inpatient visits, the first and at least one annual visit should be in person. Routine follow-up typically consists of ensuring that the patient is clinically stable, that device performance is intact, that clinical data are retrieved and reviewed, and that brady- and tachy-cardia programming is verified and optimized. Demonstration of audible and vibratory alerts should be performed at least once.

Considering that ICD patients constitute a relatively sick population, at each visit a directed history should inquire about syncope, shocks, and heart failure symptoms, if appropriate. A brief examination should focus on the ICD wound and signs of heart failure. Pertinent medications should be reviewed, such as amiodarone and oral anticoagulants. Amiodarone, for example, slows the ventricular tachycardia (VT) cycle length, which should be factored into device programming. Physicians should also be aware of the potential for antiarrhythmic agents to alter the defibrillation threshold (DFT). Knowledge of the anticoagulation status may prove helpful in the event that atrial fibrillation (AF) is detected.

Driving recommendations should be based on local regulations and guidelines, with priority given to the former. Published US guidelines [American Heart Association (AHA)/Heart Rhythm Society (HRS)] were last updated in 2007,[2] Canadian guidelines [Canadian Cardiovascular Society (CCS)] in 2003,[3] and European guidelines [European Heart Rhythm Association (EHRA)] in

Cardiac Pacing and ICDs, Sixth Edition. Edited by Kenneth A. Ellenbogen and Karoly Kaszala.
© 2014 John Wiley & Sons, Ltd. Published 2014 by John Wiley & Sons, Ltd.

2009.[4] Following ICD implantation, AHA/HRS guidelines recommend refraining from driving for at least 1 week, whereas CCS and EHRA guidelines propose a 4-week driving prohibition. The EHRA guidelines additionally recommend abstaining from driving for 1 week after an ICD generator change and 4 weeks after lead revision. Following appropriate ICD therapy [i.e.anti-tachycardia pacing (ATP) or shocks]), AHA/HRS guidelines recommend not driving for 6 months. In contrast, EHRA guidelines uphold a 3-month restriction and CCS guidelines specify 6 months if the ventricular tachyarrhythmic event led to impaired conscious and 3 months if it was hemodynamically well tolerated. Permanent driving restrictions are recommended for commercial and professional drivers.

Detecting clinical events

Detection of VT may warrant review of the patient's clinical status, medical therapy, and prior catheter ablation procedures, if any. Observational studies suggest that episodes of AF as brief as 6 min bear prognostic relevance with regard to stroke risk.[5] Risk appears to be proportional to the $CHADS_2$ score and duration, with higher risk for episodes of greater than 6 h per day.[5,6] It remains to be determined whether anticoagulation initiated on the basis of a particular cut-off duration will translate into a reduced stroke risk. In addition to considerations regarding stroke, observational data have also linked the detection of rapid AF ($\geq$1 h with average rates of $\geq$110 bpm) to inappropriate shocks.[7] It may be reasonable to expect that control of ventricular response rates during AF will reduce inappropriate shocks.

The flow of information and roles and responsibilities of caregivers faced with the detection of clinical events at ICD visits may vary according to local institutional practices and logistics of the pacemaker/ICD clinic. At a minimum, reliable information must be communicated to decision-makers in an efficient and timely fashion.

Device performance

The interrogation routine performed for pacemakers is largely applicable to ICDs. There are, however, a few important distinctions. Battery voltage is reported with a charge time, which in certain models (e.g. Boston Scientific devices) can also be used to estimate device longevity and elective replacement indicators (ERIs). If ICD capacitors are not reformed, this may also produce longer charge times. However, this issue is less relevant to modern ICDs in which automated restoration of the insulating dielectric between capacitor plates maintains charge times as short as possible. Each particular model and battery type has a specific formula to estimate longevity. End of life of the lithium–silver–vanadium battery, which is commonly used in ICDs, is less predictable than for standard pacemaker batteries, prompting most companies to report a voltage rather than an estimated time duration. More recent technological advances, with lithium–manganese dioxide (Boston Scientific) and silver pentoxide–vanadium (St. Jude Medical) batteries, now allow for the estimated duration to be provided in months/years. Generally, the longevity of ICD batteries is substantially reduced by bradycardia pacing, since the battery chemistry is primarily optimized for defibrillation functions. Newer battery designs now allow significant extension in device longevity even with pacing.

Lead integrity

The weakest link in an ICD is the high voltage lead, such that the integrity of the conductor and shocking coils must be monitored closely. Intermittent noise often precedes observed changes in standard lead parameters (i.e. impedance, sensing, pacing threshold).[8] Electrograms (EGMs) of noise reversion events and non-sustained VT should, therefore, be reviewed. The make–break potential can lead to inappropriate shocks (Figure 10.1).[9] Alerts for out-of-range lead impedance values have been available for many years, but sensitivity to timely detection of lead fracture was low. In order to enhance sensitivity, lead integrity alert (LIA™) was developed by Medtronic in 2008. This feature can be downloaded to older devices and is nominally included in Secura™ and subsequent models. It is triggered by an abrupt change in lead impedance or evidence of sensing non-physiological signals (i.e. very short V–V intervals that are not compatible with an arrhythmia). Oversensing is triggered when 30 or more short V–V intervals (cycle length $<$130 ms) and two non-sustained VT

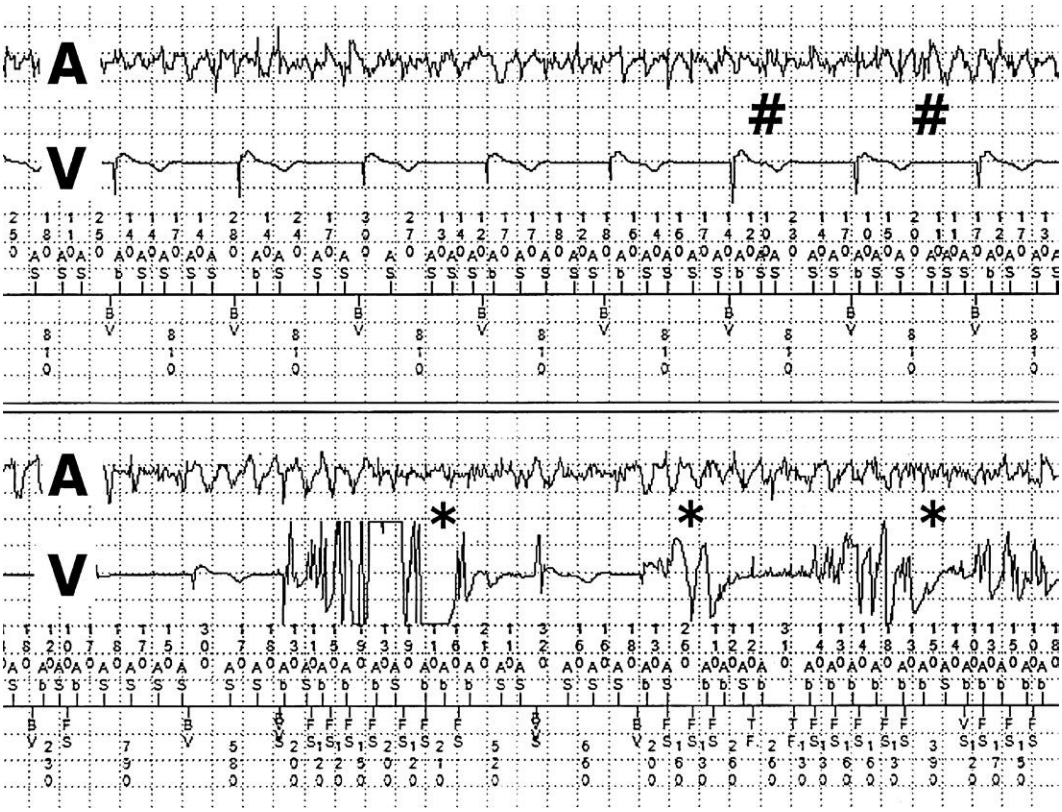


Figure 10.1 Make–break connections. Recording from a biventricular ICD with a Sprint Fidelis™ ICD lead. The patient presented with multiple ICD shocks. The tracing shows atrial fibrillation in the atrial channel and biventricular pacing in the middle panel. There are sudden non-physiological intervals (RR intervals: 120–130 ms) with make or break-type electrogram abnormalities and saturation of the amplifier channel (*). This is consistent with lead integrity failure. Note the difference between a fibrillatory wave recording in the atrial channel as compared to the noise on the ventricular channel. While some short A–A intervals may be seen even during atrial (or VV in ventricular) fibrillation (#), the characteristics of the signals are markedly different. A, atrial tip–ring; V, ventricular tip–ring.

episodes (five or more beats; cycle length <220 ms) are detected in 60 days. Short V–V intervals are not exclusively due to lead fracture, since other causes include T wave oversensing, lead dislodgement, electromagnetic interference (EMI), and double counting of QRS complexes. If LIA™ is triggered, audible alerts spaced 4 h apart are activated (as opposed to a daily alert), the number of intervals to detect (NID) VT is set at 30 of 40, and a Carelink™ alert is transmitted if this function is programmed. LIA™ combined with a timely intervention (e.g. within 24–72 h) has been associated with a significant reduction in appropriate shocks beyond standard remote monitoring alone.[10]

The SecureSense™ algorithm (St. Jude Medical) compares the near-field and far-field right ventricular (RV) signals during high-rate episodes, and ICD therapy is withheld if the signals are discordant. Intermittent noise also triggers ICD alert for the patient and for the remote monitoring system.

Sensing

In contrast to the fixed sensing of a traditional pacemaker, ICD sensing is dynamic. It auto-adjusts to the R wave amplitude and decays to reach the maximum programmed sensitivity, while avoiding T wave sensing. Alternatively, the signal gain may

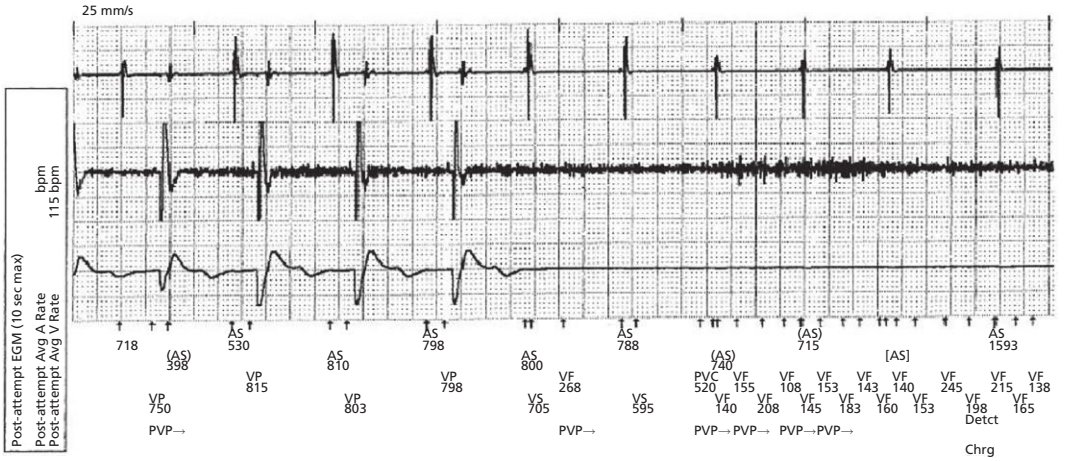


Figure 10.2 Sensing of diaphragmatic myopotentials. From top to bottom, atrial electrogram, ventricular near-field, and ventricular far-field (shock) channels. A regular atrial (sinus) rhythm is present throughout. High–frequency diaphragmatic myopotentials are sensed as ventricular fibrillation (VF), leading to VF detection and charging of the defibrillator.

be adjusted in a beat-to-beat fashion to adjust sensing of variable signal amplitudes (Boston Scientific). Long-standing experience suggests that an R wave amplitude greater than 5 mV is usually adequate to ensure appropriate detection of ventricular fibrillation (VF). While occasional ventricular oversensing is rarely problematic in pacemaker patients, it may lead to inappropriate shocks in ICD recipients.[11] Insights into the potential mechanism of oversensing may be gleaned from analyzing EGMs on interrogation and reviewing event logs (i.e. non-sustained VT and VT). Causes include T wave oversensing, double counting of R waves, sensing of diaphragmatic myopotentials (Figure 10.2), and oversensing P waves when leads are close to the tricuspid annulus. Non-physiological oversensing may be caused by lead fracture, header connection issues (make–break potential), or EMI. The latter is often present on both atrial and ventricular leads (Figure 10.3). Since integrated leads have larger "antennas," with sensing from tip to coil, historically they were associated with a higher incidence of oversensing,[12] but oversensing is less common in modern devices with better filtering.[13] More recent Medtronic devices (since Secura™) allow true bipolar leads to be programmed to sense intergrated bipolar or true bipolar configuration. This allows additional versatility in programming options to manage small R waves.

In the event that noise is recorded, the patient should be questioned about recent hospitalizations, since the hospital environment is the leading cause of EMI. Provocative maneuvers (e.g. arm lifting, deep breathing, pocket stimulation, and isometric exercises) should be performed in an attempt to reproduce detected noise, especially in the setting of a suggestive history. Interrogation may be followed by chest radiography to verify lead positioning and rule out a lead fracture or loose connection (e.g. pin not fully engaged in the generator header).

Solutions to oversensing depend on the cause. Reprogramming the ICD to a less sensitive setting can be an option in cases of near-field oversensing (R wave and T wave). This must be balanced against a potentially higher risk of undersensing true VT or VF. Another method of adjusting sensitivity is to modify the decay delay and threshold start. These parameters are programmable in St. Jude (Figure 10.4) and Biotronik devices. As illustrated in Figure 10.4, increasing the sensing threshold percentage and/or delaying the plateau interval may help to eliminate R wave double counting or T wave oversensing. Any time that sensing parameters are modified, the physician must judge

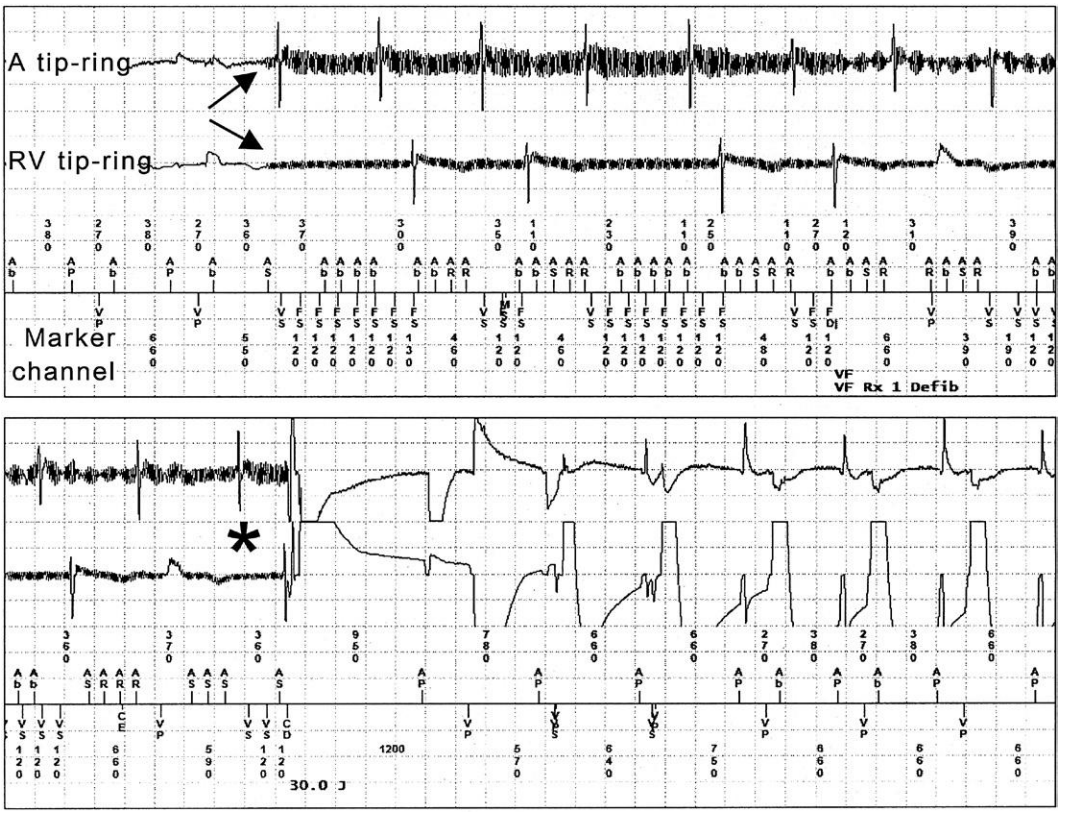


Figure 10.3 Electromagnetic interference (EMI) and ICD shock due to poorly grounded electrical equipment. The patient was working in an outside shed; he touched a wet surface and felt a tingle and soon afterwards he received a shock. Device interrogation showed EMI with oversensing in both the atrial and the ventricular channels (Ab and FS events, respectively) and subsequent delivery of an ICD shock (*). The electrical signals were sudden onset, continuous, and high frequency. Typical 60-Hz signals are commonly seen when patients interact with poorly grounded electrical currents. Sudden termination of EMI is common following an ICD shock as patients usually stop the provoking activity immediately. A tip–ring, near-field atrial channel; RV tip–ring, near-field RV bipolar signal; AP, atrial-paced event; AS, atrial-sensed event; Ab, atrial event in the blanking period; VS, ventricular-sensed event; VP, ventricular-paced event; FS, ventricular-sensed event in VF rate zone; FD, VF detected, CE, charge ended; CD, charge delivered; MS, mode switch episode. (Courtesy of Karoly Kaszala, MD.)

whether or not a defibrillation test is warranted to verify VF detection. In cases where oversensing cannot be overcome by programming (e.g. small R wave, large T wave), re-intervention should be considered.

Since the Protecta™ generation of devices, Medtronic has approached the problem of oversensing from a different perspective. Algorithms were developed not to eliminate but to identify oversensing, thereby averting inappropriate shocks. These algorithms are nominally "on." The T wave oversensing algorithm uses a differential sense EGM to magnify the ratio of R to T wave amplitude, enabling RT pattern recognition (Figure 10.5).[14] Sensitivity for VF is maintained at 100% with this algorithm, with 96% specificity for detecting T wave oversensing.[14] The noise algorithm is meant to avoid shocks secondary to lead fractures. It functions on the premise that noise secondary to a conductor fracture will be detected by the near-field (tip-to-ring) EGM, but not the far-field (coil-to-can) EGM. The algorithm cross-checks the EGMs and withholds therapy if fast events are detected only by the near-field EGM. Patients with

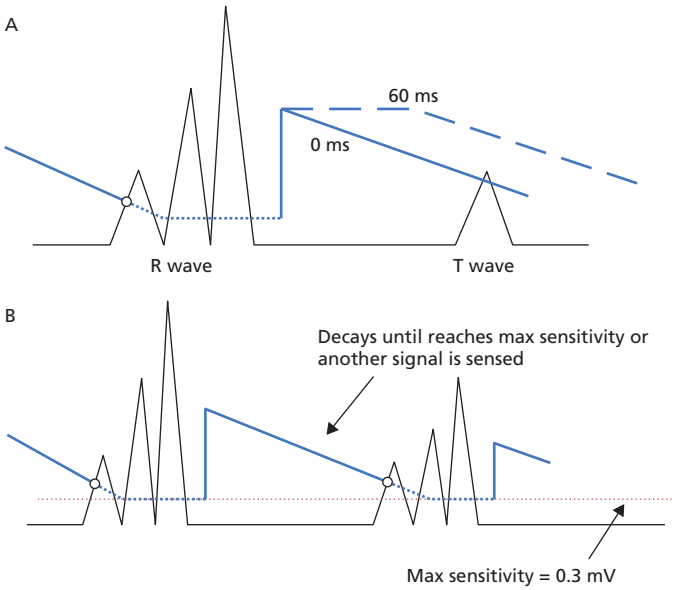


Figure 10.4 Decay delay and threshold start. Digitally rectified signals as used in detection algorithms. (A) Sensing begins at the open circle, initiating a sensed refractory period. The sensed refractory period is marked by the dashed line that crosses the R wave. In this example, 62.5% of the peak of the maximum amplitude signal recorded during this period is defined as the next "threshold start" value, indicated by the vertical line. As the sensed refractory period elapses, two examples of decay are provided, the first with no delay (solid blue line) and the second with a delay of 60 ms (dashed line). (B) Decay continues until maximum sensitivity is reached (dotted line at 0.3 mV) or another signal is sensed. (Source: St. Jude Medical, Inc. Reproduced with permission of St. Jude Medical, Inc.)

EMI that affects both near- and far-field EGMs will not be protected against inappropriate shocks. A similar noise algorithm (SecureSense™) is now available for St. Jude Assura and Ellipse™ ICDs.

Defibrillation thresholds

Defibrillation thresholds can vary in time as a result of changes in the myocardial substrate and/or pharmacological therapy (e.g. amiodarone, sodium channel blockers). At present, there is no clear evidence to suggest that DFT testing should be performed routinely after implant. Decisions are, therefore, individualized and at the discretion of the treating physician. DFT testing beyond the initial implant may also be considered in patients with a high baseline DFT in whom amiodarone is initiated, or in the setting of unsuccessful appropriate shocks. However, it is important to appreciate the probabilistic nature of defibrillation such that one unsuccessful shock is not necessarily indicative of an unacceptably high DFT.

Remote monitoring

All the major device companies now offer the possibility of remote monitoring using a home transmitter, which interrogates the device either by a telemetry wand or automated wireless technology. Data are transmitted using a landline or cellular phone line (by most providers) to a secure server accessible on the web. A transmission schedule is typically programmed in the pacemaker/ICD clinic and unscheduled transmissions may be sent by the patient or in the event of triggered programmed alerts. Short message service text messaging and e-mail notifications are also available.

In the ICD population, remote monitoring has been demonstrated to reduce the number of patient visits without compromising safety. Some data suggest that remote monitoring may lower hospitalization rates and shorten the length of cardiovascular hospitalizations.[15–17] In addition, remote monitoring saves time and money for

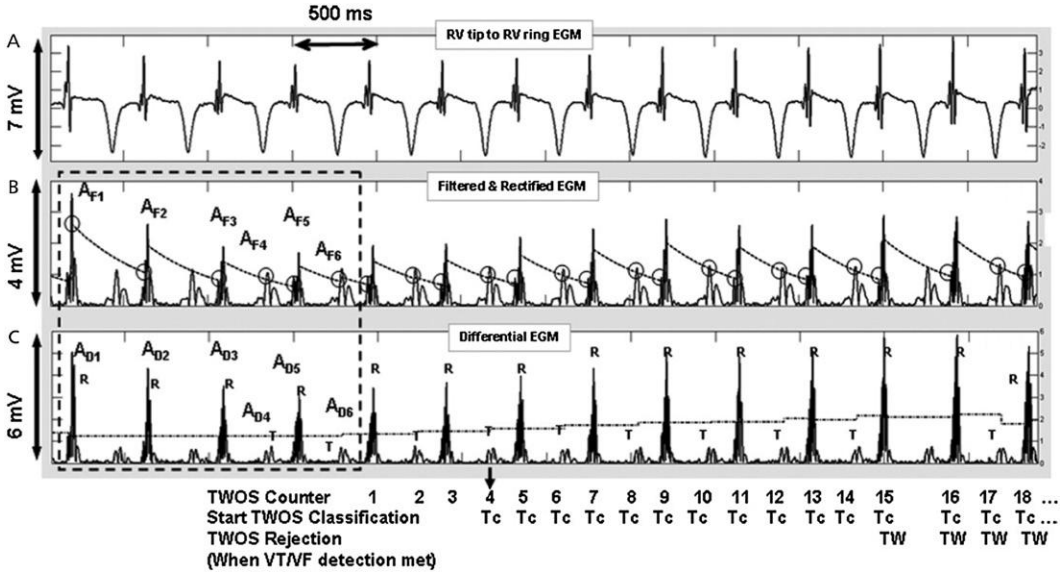


Figure 10.5 T wave oversensing (TWOS) rejection algorithm. (A) Device stored right ventricular (RV) tip-to-RV ring electrogram (EGM) during spontaneous T wave oversensing (TWOS). (B) Filtered and rectified EGM (solid line) and auto-threshold (dashed line) with a sensitivity setting of 0.3 mV. The initial value of sensitivity is at 75% of sensed peak R or T wave (up to 10× the programmed sensitivity setting). Circles indicate the sense markers when sensing EGM exceeds the auto-threshold. (C) Differential EGM (solid line) based on filtered EGM. Specifically, Differential EGM(i) − Filtered EGM(i) − Filtered EGM($i - 1$) at a sampling frequency of 1024 Hz. A_{Fi} and A_{Di} ($i = 1$–6) indicate the peak amplitudes for filtered and differential filtered signals, respectively. Comparing signal amplitude (differential versus filtered), T wave amplitude is reduced more than the R wave amplitude. In the six sensed event windows (C), $R_1 = \max(AD_1, AD_2)$, $R_2 = \max(AD_3, AD_4)$, $R_3 = \max(AD_5, AD_6)$, and differential EGM threshold = 37.5% × Ravg, where Ravg = $[(R_1 + R_2 + R_3 - \max(R_1, R_2, R_3))/2]$. The dashed line in C represents the threshold used to identify candidate R waves and T waves. In 6 sensed event window, the 3R3T or 4R2T pattern and other TWOS criteria will trigger the increment of TWOS counter. This event window moves beat by beat. TWOS is identified when four or more of the last 20 sensed events meet TWOS criteria (see "Tc" annotation). When ventricular tachycardia (VT)/ventricular fibrillation (VF) detection and TWOS detection criteria are both met, the "TW" marker is displayed, indicating VF or VT detection withholding due to TWOS rejection. The algorithm will not withhold VT/VF detection when the corrected RR interval as determined by the TWOS algorithm is less than max(SVT Limit, FDI; VT detection "off" or Monitor) or less than max(SVT Limit, TDI; VT detection "on"). SVT, supraventricular tachycardia; FDI, fibrillation detection interval; TDI, tachycardia detection interval. (Source: Cao J *et al*. 2012.[14] Reproduced with permission of Elsevier.)

patients and family members of accompanied patients, which is relevant to an increasing number of ICD recipients.[16] The value of remote monitoring may be appreciated in the routine follow-up of a stable device or when a component requires closer surveillance (e.g. device approaching ERI, unstable lead parameters, device or lead advisory). Most devices remotely execute the same tests performed in clinic, with the modern ICDs conducting threshold tests for all three leads, followed by automated adjustments to output parameters to maintain secure pacing margins.

Remote monitoring also shines in its speed of communicating events, especially in more complex devices and/or sicker patients. The most frequently transmitted events are new-onset or rapid AF. While remote monitoring can lead to timely intervention (i.e. anticoagulation and rate control), its clinical benefit in this setting has yet to be demonstrated (IMPACT and EFFECT trials). Activating alerts for these events, therefore, remains at the clinician's discretion. Device-related adverse events such as lead fractures could also be detected more rapidly, carrying the potential to reduce

inappropriate shocks (ECOST trial). While awaiting evidence-based guidance, activation of the following unscheduled reports should be considered: excessive charge times, disabled VF/VT therapies, and delivered or unsuccessful VT/VF therapies.

Organizational and legal aspects, including reimbursement issues, remain topics of heated discussion. Since no data currently support 24-h surveillance of transmitted information, a key message provided by most institutions is that remote monitoring does not replace emergency consultations. Data verification often parallels the clinic schedule. Nevertheless, some institutions have opted to provide a 24 h a day on-call service by clinic staff for unscheduled alerts. Other pacemaker/ICD clinics choose to share responsibilities and access for transmitted data with their respective heart failure service that assumes the brunt of clinical management decisions.

Advisories

Advisories can involve generators or leads. The most common generator advisory is for rapid battery depletion (e.g. Medtronic's Maximo™ and Entrust™; Boston Scientific's Cognis™ and Teligen™). Two major high-voltage lead advisories were issued by the Food and Drug Administration (FDA): Medtronic's Sprint Fidelis™ 6949 in 2007 and St. Jude's silicone-coated Riata/Riata ST™ leads in 2011. Fidelis leads have a higher rate of conductor fracture and, to a lesser extent, coil fracture, such that simply adding a low voltage pace/sense lead is not recommended by Medtronic. Riata™ leads are subject to inside–out abrasion of conductors through the silicone layer, with highest risk in 8-Fr followed by 7-Fr leads. Since conductors have their own coating [ethylene tetrafluoroethylene (ETFE)], lead parameters can remain unchanged. The risk of external abrasion (outside–in) has also been described, but is of lesser magnitude, likely because outside–in abrasion commonly takes place in the device pocket due to device–lead interaction; fluoroscopic diagnosis is limited. Definite lead-related deaths have been due to short-circuiting of high voltage components.[18] At the present time, Riata™ and Durata™ leads covered by Optim™ are not part of the advisory but are closely being followed. Data from over 27 000 patients from the VA National Cardiac Device Surveillance Center quantified the following yearly electrical failure rates: Riata™ 0.78%, Sprint Fidelis™ 2.08%, Sprint Quattro™ 0.15%, and Endotak™ (Boston Scientific) 0.16%.[18] These prevalence rates increase with time and are derived from variable follow-up durations.

Pacemaker/ICD clinics are generally responsible for identifying and informing patients concerned by an advisory. It is the responsibility of the manufacturer to keep physicians up to date. While the manufacturer may offer recommendations, the resulting action ultimately remains the decision of the physician. For the vast majority, activating programming alerts and routine 1–3-month follow-up visits or, ideally, remote monitoring constitute a reasonable course of action. Importantly, in 2012 the FDA recommended routine chest X-rays in patients with Riata™ leads to detect externalization of conductors. Whether or not one should act upon an abnormal finding remains a contentious issue. How to handle a functioning lead under advisory at the time of generator change is likewise a matter of debate. A risk–benefit assessment should be undertaken that considers co-morbidities, pacemaker dependency, numbers of leads, and vascular access. Routine extraction cannot be recommended due to its inherent risks.

ICD programming

Bradycardia programming

Since the Dual Chamber and VVI Implantable Defibrillator (DAVID) trial,[19] physicians have become increasingly concerned about unnecessary RV pacing for fear of potential harmful effects on heart failure and mortality, especially in patients with poor ventricular function. Most major device companies now have algorithms that allow AAI pacing and switching to DDD mode in the event of conduction block. Medtronic released Managed Ventricular Pacing (MVP), Sorin Safe R, Boston Scientific Rhythm IQ, and Biotronik ADI mode. Ventricular pacing can effectively be reduced by such algorithms (down to 1% in patients with sick sinus syndrome), albeit occasionally at the cost of tolerating long atrioventricular (AV)

delays that disrupt left-sided AV timing (AV desynchronization).[20]

Increasing evidence is challenging the practice of routinely programming atrial pacing at 60–70 bpm as a means of increasing cardiac output. In patients with a PR of 240 ms or shorter, programming Medtronic devices with MVP at 70 bpm was not superior to VV1 50-bpm back-up pacing.[19] In patients with more pronounced AV block (i.e. ≥230 ms at randomization, mean 260 ms), programming devices to MVP at 60 bpm was associated with an increased rate of the combined end-point of death or heart failure events when compared to back-up pacing.[21] In this subgroup study, the proportion of ventricular pacing was comparable in the two groups. It was, therefore, hypothesized that atrial pacing may have aggravated AV dyssynchrony since paced AV intervals were longer than in sinus rhythm.

Thus, in ICD recipients, minimizing ventricular pacing and avoiding unnecessary atrial support appear to be reasonable objectives, especially in patients with marked first-degree AV block. Optimal programming remains to be defined in patients with first-degree AV block who are not candidates for cardiac resynchronization therapy (CRT).[21]

Tachycardia programming

Current practice is rightfully shifting away from "shock box" programming (i.e. single VF zone with shocks) and companies are modifying nominal settings to minimize inappropriate and potentially avoidable shocks.[22] These changes will be discussed here and pertain to cut-off rates, detection time, discriminators, and the use of ATP. Traditionally, VT and VF zones differed in that discriminators and ATP could be programmed only in VT zones. Once VF zone rate and duration criteria were met, the only therapy available was shocks. Devices now provide options for tachycardia discrimination in the VF zone (Medtronic) and allow ATP therapy before defibrillation (now widely available). We favor multizone programming in patients with primary and secondary prevention ICDs. However, the recently published MADIT-RIT trial suggests that a single programmed high cut-off rate zone (≥200 bpm, with an ATP + shocks) appears to be a viable option in primary prevention patients.[23]

Cut-off rates

ICD recipients with primary compared to secondary prevention indications experience faster ventricular tachyarrhythmias, with rates averaging 200 versus 153 bpm, respectively.[24] In contrast, clinical supraventricular tachycardia (SVT) usually ranges between 160 and 180 bpm. The first tachycardia zone (VT or VF) is typically programmed around 182–188 bpm in patients with primary prevention indications, to avoid inappropriate detection of SVT or shocks during slower non-sustained asymptomatic VT.[25] Cut-off rates should be programmed even higher (e.g. 200–220 bpm) in younger patients. Safety does not seem to be compromised with programmed rate cut-offs of up to 200 bpm.[23,26] For patients with secondary prevention indications, a safety margin of 30–60 ms between the slowest spontaneous or induced VT and the cut-off rate has been recommended. If the clinical VT rate is unknown, the VT zone may be programmed in the 150–160-bpm range.[27] Despite this precaution, VT slower than the programmed cut-off rate occurs in approximately 5% of patients per year, with an incidence as high as 25% if antiarrhythmic drug therapy is prescribed.[27,28] A monitoring zone to detect slower VT may be helpful and a larger safety margin should be considered in the presence of antiarrhythmic drug therapy.

Monitoring zone

Detecting slow VT is an important issue given its high prevalence[28] and occasional association with heart failure.[24] Monitoring zones can serve this purpose. In the presence of high cut-off rates, the monitoring zone may be of value to assess the need for multizone programming.[26] When a slow VT is detected, the clinician must decide whether lowering the cut-off rate to treat the slow VT is reasonable when balanced against a higher risk of inappropriate shocks and possibly shocks for asymptomatic and potentially self-terminating VT.[23] In addition to detecting slow VT, monitoring zones in single chamber devices may identify asymptomatic AF or flutter that warrants anticoagulation for stroke prevention. While one may question the impact of monitoring zones on battery longevity, company technicians report negligible effects.[22]

In current Boston Scientific, Medtronic, and Biotronik devices, monitoring zones are free from interaction with active zones. Cases of inappropriate shocks have been reported as a result of interactions between monitoring and active zones in Sorin, St. Jude, and older Medtronic devices.[11] In the St. Jude devices that preceded the Atlas II series, this risk was substantial. VT therapy timeout [formerly called maximum time to fibrillation (MTF)] was designed to minimize the risk of undersensed VF episodes. This algorithm could be activated if an episode fell in the VT zone, including the VT monitor zone. If occasional faster (VF) events were detected in this zone, even though traditional VF sensing had not been satisfied, VF therapy could be initiated. The VF counter had the potential to continuously increment over a prolonged period of time, leading to a shock once the programmed number of intervals was met (e.g. as may occur with ventricular premature beats during sinus tachycardia) (Figure 10.6). Following the Atlas II series and St. Jude algorithm updates, the risk of interaction with monitoring zones was significantly reduced, but not entirely eliminated. VT therapy timeout can no longer be activated in the monitoring zone. However, binning VF once the zone is opened (e.g. rapid AF) can lead to a shock. VF binning is reset once six intervals are identified in a tachycardia zone. Thus, occasional VF binned events without a minimum of six intercurrent tachycardia intervals could eventually trigger therapy. With the Ellipse™ model, binning within a monitoring zone was modified to only include VF events that would have otherwise triggered therapy in the absence of a monitoring zone. In this latest iteration, the monitoring zone can, therefore, be theoretically considered a true monitoring zone.

Detection time/intervals

Once a tachycardia has reached the cut-off rate, it must satisfy the programmed duration to be classified as sustained. Device manufacturers rely on different algorithms and, even within the same device, algorithms that govern VT and VF zones may differ. Biotronik, Sorin, and Medtronic VF algorithms rely on a probabilistic counter (x of y), where, very roughly, a fast event increments the counter and a slow event decrements it. This probabilistic counter tolerates occasional undersensing, whereas a consecutive counter, as in Medtronic's VT algorithm, resets (counter starts again from zero) in the presence of a single slow event (Figure 10.7). St. Jude uses an entirely different binning system. An interval is binned based on its current value and the average of the last four intervals. A fast event pertaining to a tachycardia zone is binned in a unidirectional incremental counter, as long as the zone is open.[29] The counter can only be reset when sinus rhythm is redetected (nominally five slow events).[30]

Classifying an arrhythmia as sustained is a somewhat arbitrary balance between over-treating otherwise self-terminating arrhythmias and delaying therapy for potentially unstable arrhythmias. The trend has been toward programming longer detection times to avoid treating non-sustained VT and intermittent noise. Medtronic trials (PainFree I and II, Prepare, Advance III)[25,31] reported that increasing detection intervals in the VF zone from 12 of 16 to 18 of 24, and even 30 of 40, effectively reduced shocks without sacrificing security. Comparative data are increasingly available for St. Jude and Guidant/Boston Scientific devices, which are nominally programmed to aggressive settings.[23,30] Following development of the Unify™/Fortify™ devices, St. Jude Medical reviewed its nominal settings (Decision Tx™), extending the number of intervals from 12 to 16 in the VT zone. In the PROVIDE trial, programming the required number of beats in the VT zone (181–214 bpm) to 25 and the VF zone (214–250 bpm) to 18 reduced the rate of inappropriate shocks.[32] For Boston Scientific devices, MADIT-RIT demonstrated the value and safety of more lenient programming schemes in reducing appropriate (i.e. self-terminating, non-sustained VT) and inappropriate therapy (i.e. treatment of SVT). Strategies with longer detection times (60 s at 170–200 bpm, 12 s at 200– bpm, 2.5 s at >250 bpm) or higher cut-off rates (200 bpm) were superior to conventional programming (2.5 s in the VT zone and 1 s in the VF zone).[23]

SVT discriminators

Primary prevention

Although mean SVT rates are usually less than 180 bpm in older medicated patients, brief runs at

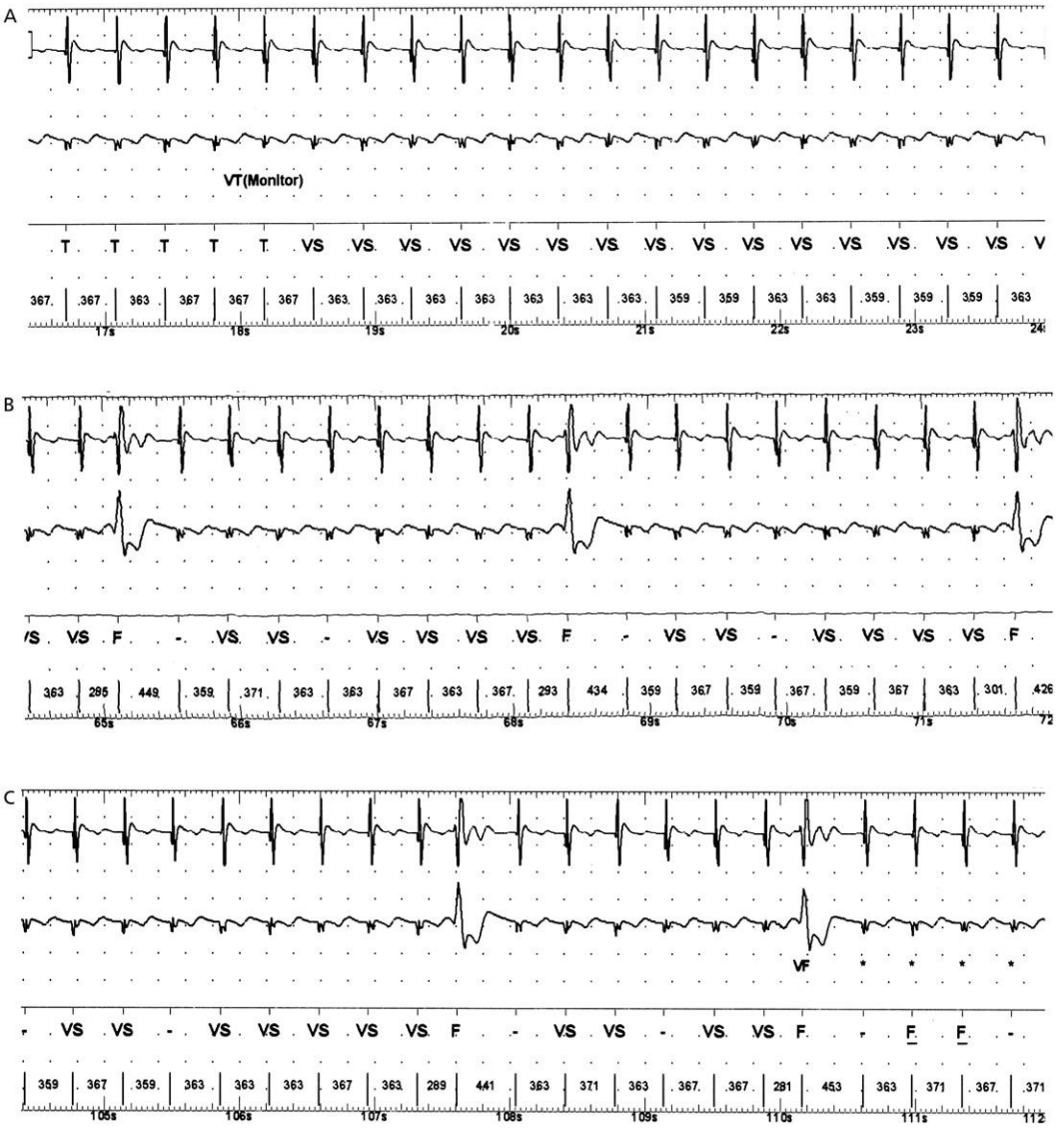


Figure 10.6 Inappropriate shock due to isolated premature ventricular beats in a monitoring zone. (A) In a 32-year-old woman with hypertrophic cardiomyopathy, sinus tachycardia gradually accelerated, triggering an episode recorded as ventricular tachycardia (VT) in the monitoring zone. Of note, the maximum time to fibrillation (MTF) counter was not "on." (B) Occasional premature ventricular beats are binned in the ventricular fibrillation zone (F), adding to a cumulative counter. (C) Upon the 12th such premature ventricular beat, ventricular fibrillation (VF) is detected, leading to an inappropriate shock for sinus tachycardia. (Source: Mansour F, Khairy PJ 2008.[11] Reproduced with permission of John Wiley & Sons Ltd.)

A

I

BEAT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
INTERVAL	VF	VF	VF	Sinus	VF	VF	VF	Sinus	Sinus	Sinus	Sinus	Sinus	Sinus	VF	Sinus
COUNTER	1	2	3	3	4	5	6	6	6	6	6	6			

VF counter: 6/12

II

BEAT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
INTERVAL	VF	VF	VF	Sinus	VF	VF	VF	Sinus	Sinus	Sinus	Sinus	Sinus	Sinus	VF	Sinus
COUNTER	x	1	2	2	3	4	5	5	5	5	5	5	5		

VF counter: 5/12

III

BEAT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
INTERVAL	VF	VF	VF	Sinus	VF	VF	VF	Sinus	Sinus	Sinus	Sinus	Sinus	Sinus	VF	Sinus
COUNTER	x	x	1	1	2	3	4	4	4	4	4	4	4	5	

VF counter: 5/12

IV

BEAT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
INTERVAL	VF	VF	VF	Sinus	VF	VF	VF	Sinus	Sinus	Sinus	Sinus	Sinus	Sinus	VF	Sinus
COUNTER	x	x	x	0	1	2	3	3	3	3	3	3	3	4	4

VF counter: 4/12

B

BEAT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
INTERVAL	VT	VF	VF	VF	VF	VT	VT	VF	Sinus	VT	VT	VT	VF	VF	VF	VF	VF	VF
VF COUNT	0	1	2	3	4	4	4	5	5	5	5	5	6	6	6	6	6	7
VT COUNT	1	1	1	1	1	2	3	3	0	1	2	3	3	3	3	3	3	3
COMBINED COUNT	1	2	3	4	5	6	7	8	5	6	7	8	9	9	9	9	9	10

Figure 10.7 (A) The sliding window principle and (B) arrhythmia detection by the combined counter in Medtronic devices, illustrating how tachycardia counters operate in a Medtronic device. (A) A window in the ventricular fibrillation zone progressively slides beat by beat from I to IV. Each interval represents how the device adjudicates each sensed event [sinus beat, ventricular fibrillation (VF) beat]. Shown are the numbered beats, intervals binned, and the VF zone counter. The counter advances with each VF-sensed event until programmed detection is reached (e.g. 8 of 12) in a sliding window, which would trigger VF detection. (B) Example of the effects of specific intervals on VF, ventricular tachycardia (VT), and combined counters. There is a separate VT and VF zone programmed. A VF event increments both the VT and VF counters, whereas VT events only advance the VT counter. Once VF events reach and maintain a count of 6 in the sliding window, both VT and VF events would increment the combined counter. VF therapy would be delivered once the minimum combined counter interval is reached In this example, VF detection was set to 9 of 12 intervals, corresponding to a combined counter threshold of 10 intervals. (Source: Mansour F, Khairy PJ 2008.[11] Reproduced with permission of John Wiley & Sons Ltd.)

higher rates (e.g. bursts of fast AF) could lead to VT or VF detection. Discriminator algorithms and longer detection durations may reduce such occurrences. Tailoring use according to prior history of SVT is, unfortunately, not always reliable, as the presence and rate of prior SVTs poorly predict SVT characteristics on follow-up.[22] Routine use of discriminators when programming high cut-off rates was previously considered controversial. It is now *increasingly* standard of care since published trials show a reduction in inappropriate shocks to 3.4% when discriminating rhythm cut-offs are programmed up to 200 bpm.[25] While it can be argued that shocking an SVT faster than 180 bpm may be desirable, the shock vector is not ideal for this purpose and repetitive unsuccessful shocks can be pro-arrhythmic.

The main arguments against systematically enabling discriminators are their reliability and associated risks of underdetecting VT. With single chamber discriminators, underdetection occurs in 0–5% of VT episodes and for dual chamber devices, VT underdetection has been reported in 0–1% of events.[33,34] Although an underdetected VT should eventually accelerate and ultimately be treated in the VF zone, hemodynamic instability from detection delay could lead to unsuccessful shocks. Underdetection of true VF because of discriminators has not been reported. In patients with primary prevention ICDs, underdetection of VT appears to be less of an issue than inappropriate shocks for SVT.

The bulk of current data suggest that programming discriminators up to a rate of 200–222 bpm appears reasonable. In St. Jude studies, SVT discriminators were programmed up to 214–222 bpm.[32,35] In Boston Scientific's MADIT-RIT trial, discriminators were programmed up to 250 bpm in one arm of the study.[23] In Medtronic's most recent ICD model (Protecta™), the SVT limit is nominally programmed to 230 bpm. This setting is based on the fact that an SVT limit of 200 bpm was associated with a 12–17% rate of inappropriate shocks in reviewed internal data. It requires prospective corroboration to ensure safety.[36] If one chooses not to enable discriminators, we recommend programming them to a "passive" mode to maximize available information for future tailoring. Since SVT cannot conduct rapidly in patients with permanent complete AV block, discriminators should be deactivated to avoid underdetection of VT. Table 10.1 describes the most common discriminators.

Secondary prevention or antiarrhythmic drugs

Discriminators appear most useful in patients with secondary prevention ICDs or under antiarrhythmic drug therapy, since lower programmed cut-off rates expose them to a higher risk of inappropriate therapy for SVT.[22] Most inappropriate shocks are for sinus tachycardia in patients without structural heart disease, and for atrial tachycardia/AF in patients with structural heart disease. In the absence of clear data regarding an upper limit of safety, we consider 200–222 bpm a reasonable cut-off in ICDs that have a programmable upper limit for discriminators within the VT zone (i.e. Medtronic, St. Jude).[22] For Boston Scientific, Sorin, and Biotronik devices, discriminators apply to the entire VT zone.

Timers to override discriminators

Sustained rate duration (SRD; Boston Scientific), high rate timeout (HRT; Medtronic), SVT timeout (St. Jude Medical), and sustained VT (Biotronik) are timers used to override discriminators. Once the programmed timer elapses, therapy is delivered even if it had been appropriately withheld. These overriding timers were designed as a safety feature in the event that VT is misclassified as SVT, but the weight of published data suggests they are an important source of inappropriate shocks.[37] This is not surprising since SVTs usually persist longer than default settings (e.g. 3 min with Guidant/Boston Scientific devices; 30 s in older St. Jude devices). The literature suggests that this safety feature is of little value, with no reported adverse events when it is not available (i.e. Sorin devices)[38] or programmed "off."[25] Indeed, in Medtronic, Biotronik, and the last generation of St. Jude Medical ICDs (i.e. Accel/Fortify), this feature is nominally set "off." For single chamber ICDs, the paucity of data precludes specific recommendations. While in our practice we generally program it "off," a more conservative approach may be to consider activating the overriding timer while extending its duration.

Table 10.1 Common discriminators

Discriminator	*Purpose*	*Limitations*
Stability	Withholds detection in the setting of an irregular ventricular rate Useful for atrial fibrillation (AF)	Polymorphic ventricular tachycardia (VT) Inappropriate classification of a stable supraventricular tachycardia [SVT; e.g. flutter, atrial tachycardia, atrioventricular nodal re-entrant tachycardia (AVNRT)] as VT Rapid pseudoregular AF
Onset	Withholds detection of gradual onset tachycardia Useful for sinus tachycardia	Gradual onset VT (e.g. undetected slower VT gradually accelerating in the treatment zone, exercise-induced VT) Inappropriate classification of a sudden onset SVT (e.g. flutter, atrial tachycardia, AVNRT) Cannot reassess onset since classified once at the onset of the episode
Morphology	Withholds detection of SVT on the basis of electrograms (EGMs) that are similar to sinus rhythm	Aberrancy (could rely on EGM with rapid atrial pacing to avoid/minimize this) EGM clipping (correct the amplitude range or change morphology vectors) Post shock distortion VT with a template that resembles sinus rhythm
Chamber of onset	Withholds detection of tachyarrhythmia with an atrial onset, classifying it as an SVT	Premature ventricular beats Premature atrial beats Undersensing because of low amplitude signals or blanking periods
AV associations	V > A indicates VT During VT, there is a loss of AV association when compared to flutter	Far-field R waves on the atrial channel cloud the AV relationship Undersensing of atrial events may result in a diagnosis of VT

Table 10.2 provides a general overview of programming recommendations for primary and secondary prevention ICDs.

Company-specific issues

Medtronic

For single chamber devices, discriminators include sudden onset, stability, and morphology. The merits and relative benefits of the different combinations have not been compared. Morphology is the most studied discriminator, with 98.6% sensitivity for VT detection and 78.2% accuracy in classifying SVT.[38] The sensitivity for slower VT is reported to be slightly lower.[39] It does not appear to be affected by underlying bundle branch block. The "can" to right ventricular coil (HVB) channel provides the EGM with the most accurate discrimination (nominal setting), as it is less susceptible to exercise- and body position-related changes than the "can" to superior vena cava coil (HVX) channel. Automatic updates of the morphology template appear reliable. Suboptimal correlations, noted in 4%, were due to EGM clipping.[38] Therefore, it is recommended that it is verified that recorded EGMs exceed 3 mV and are not clipped.

Although morphology was not previously offered as a discriminator in dual chamber devices, it is available and nominally "on" in the new ICD model (Protecta™). If an SVT escapes detection by PR logic (e.g. sudden onset atrial tachycardia, pseudoregular AF), morphology will be assessed and detection withheld if appropriate. The morphology discriminator is also applied to the VF

Table 10.2 Suggested company-specific ICD programming in primary and secondary prevention (Source: Adapted from Mansour F, Khairy P 2011.[22] Reproduced with permission of John Wiley & Sons Ltd.)*

		Primary prevention	*Secondary prevention*
Detection	*General comments*	Consider slower cut-off rates if receiving antiarrhythmic drugs	
Rate cut-off	*Monitoring zone*	Avoid routine use in St. Jude Medical devices prior to Ellipse™	
		150–160 bpm	130–140 bpm
	VT zone	182–188 bpm to 220 bpm (250 bpm if FVT via VF with Medtronic devices)	10–20 bpm slower than clinical arrhythmia (30–60 ms) or 150–162 bpm if unknown
	VF zone	220 bpm Alternate: single zone VF 200 bpm	220 bpm
Detection times		Medtronic: 30 of 40 St. Jude Medical: VT 25; VF 18 Boston Scientific single zone VF 2.5 s Boston Scientific multiple zones: 12 s up to 250 bpm; up to 60 s in slower zones (<200 bpm)	
Discriminators	*General comments*	Program "on"; when available use cut-off of 260–300 ms Program "off" if complete AV block	
	Medtronic	VR: wavelet DR: PR logic (activate 1:1 SVT on follow-up after verifying atrial lead) and Wavelet (Protecta: pending clinical data), do not use Stability and Onset routinely	
	St. Jude	VR: 2 of 3: morphology, onset, stability DR: Morphology "on"; Stability passive or "on" (with AVA if stability is used) with Association programmed to ANY; Onset: passive Devices with Decision Tx/Shockguard: activate all discriminators with association "if all" (pending PROVIDE study results)	
	Boston Scientific	VR and DR: Rhythm ID	
	Sorin	VR: Onset and Stability DR: PARAD+	
	Biotronik	VR: Onset and Stability DR: SMART	
	Discrimator time-out	Program off; more conservative programmers could extend short nominal values to 5 min	
Therapy	*VT zone*	At least two bursts of 8–10 pulses; 88% of BCL; 10 ms readaptive BIV: ATP pacing in ischemic cardiomyopathy Maximal shocks (pending further data)	4–6 ATP; 8–10 pulses; 91–88% of BCL; 10 ms SCAN;
	VF zone	ATP during (or before) charging Maximal shocks	

*The table is intended to summarize general guiding principles based on available data and does not represent a prospectively validated programming scheme. Physician preferences may vary and individualized programming must be adapted to patient- and device-specific particularities.

See text for a discussion of device-specific discrimination algorithms (i.e. PR logic, Wavelet, Rhythm ID, PARAD+, SMART).

VT, ventricular tachycardia; VF, ventricular fibrillation; VR, single chamber ICD; DR, dual chamber ICD; AVA, atrioventricular association; BCL, basic cycle length.

zone within the boundaries of the programmed SVT limit and may be used if PR logic is deactivated (e.g. unreliable atrial lead). PR logic analyzes relationships between atrial and ventricular events and classifies tachyarrhythmias according to predefined patterns. Intermittent far-field R waves (FFRW) render pattern analyses unreliable. Atrial sensitivity should, therefore, be programmed to avoid FFRW or, conversely, to ensure that FFRW signals are constant and correctly identified. Medtronic uses a very short cross-chamber post-ventricular atrial blanking period (PVAB; 30 ms) and atrial events detected in the PVAB are used by arrhythmia detection features. More recently, a programmable PVAB was introduced, first with EnTrust™ ICDs. "Partial+" briefly increases atrial sensing threshold after the start of ventricular events, while "Absolute PVAB" behaves as a traditional blanking device, ignoring atrial events for the programmed blanking period. Programmable PVAB may be important in the management of far-field R wave oversensing.

Figure 10.8 summarizes "Adaptive PR Logic" (Entrust™ and most recent models), which is the latest iteration of PR logic that no longer relies on establishing a VT–sinus tachycardia boundary.

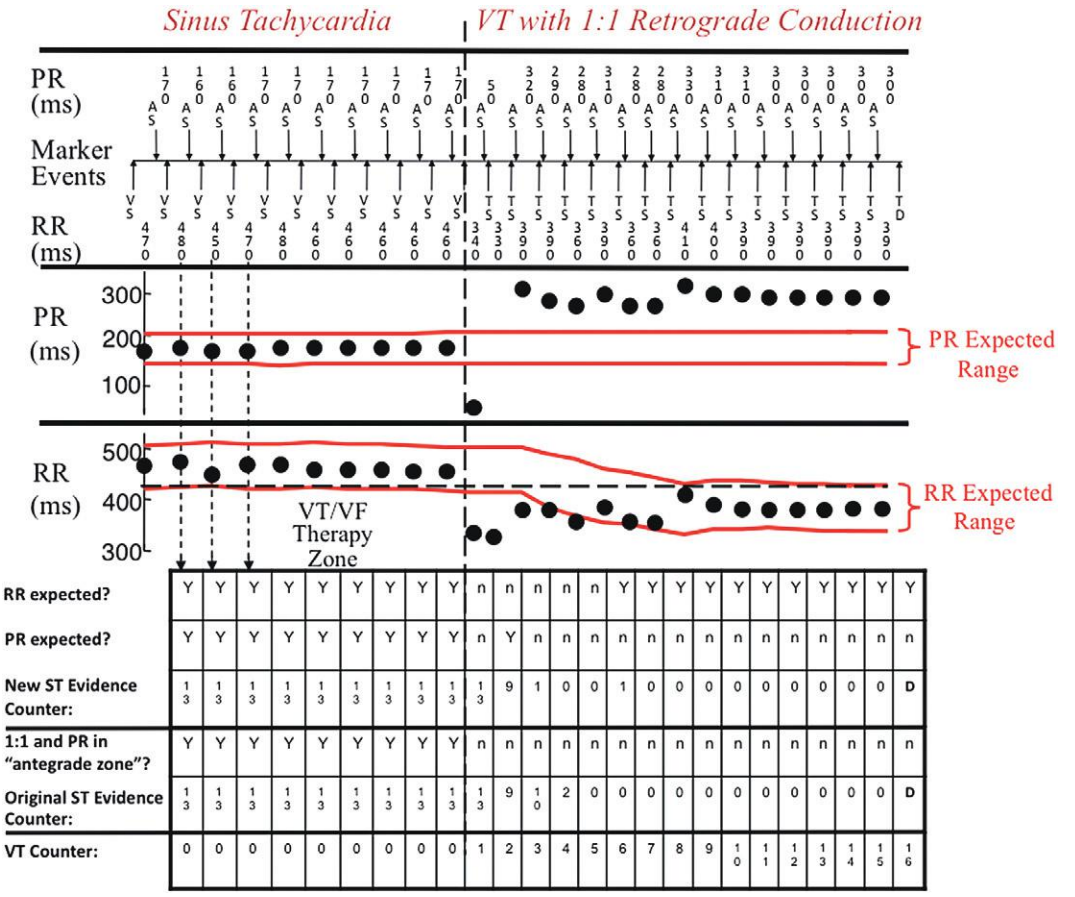


Figure 10.8 Medtronic Adaptive PR Logic™ as applied to sinus rhythm and ventricular tachycardia with 1:1 retrograde conduction. Shown are PR intervals, marker events, RR intervals, and plots of PR and RR intervals for rhythms classified as sinus tachycardia (left) and ventricular tachycardia with 1:1 retrograde conduction (right). The Adaptive PR Logic™ algorithm, shown below the interval plots, considers expected and observed values to classify the rhythm as sinus versus ventricular tachycardia. (Source: Adapted from Mansour F, Khairy P 2011.[22] Reproduced with permission of John Wiley & Sons Ltd.)

Sinus tachycardia is characterized by smooth changes in PR and RR intervals, in contrast to more abrupt changes with VT. The adaptive algorithm monitors and continuously updates PR and RR intervals, defining expected ranges of variation. Single chamber discriminators (except morphology in devices prior to Protecta™) may be programmed in addition to PR logic in dual chamber devices. Since they have priority over PR logic, if sudden onset or stability inhibits detection (e.g. VT during exercise or with slight variations in cycle length), the VT counter will not be satisfied and PR logic will never be applied, rendering the VT potentially undetected. Single chamber stability is the only active discriminator during redetection after tachycardia therapy. While there are no data to support the activation of single chamber discriminators along with PR logic, such an approach is of theoretical value in patients with multiple inappropriate shocks for AF.

In Medtronic Protecta™ devices, Smartshock™ technology was introduced to reduce inappropriate shocks. This includes increasing the SVT limit to 230 bpm and addition of right ventricular lead noise discrimination, T wave oversensing discrimination, confirmation +, and PR logic + wavelet algorithms in dual chamber devices. Features such as lead integrity alert, default inactivation of high rate timeout, and no timeout for ATP have been retained. Clinical efficacy and potential interactions of the new features, all of which are nominally activated, is currently under study.[36]

Sorin Group

Performance of single chamber discriminators (i.e. stability and onset alone or in combination) have not been formally assessed. In Sorin ICDs, discriminators remain active for arrhythmia redetection after therapy delivery. Discriminators are also active during redetection in Guidant/Boston Scientific devices (except onset and morphology following a shock) and are programmable in Biotronik devices. In contrast, St. Jude discriminators and Medtronic PR logic are not active during redetection.

Discriminators in dual chamber Sorin ICDs are activated as a group known as "PARAD." Features of the tachyarrhythmia are analyzed and inputted into a branching algorithm, summarized in Figure 10.9.[22] Until the introduction of St. Jude's recent Ellipse™ ICD model, this was the only algorithm that used the chamber of acceleration to differentiate atrial from ventricular arrhythmias. A PARAD+ algorithm was introduced to increase specificity for detecting fast AF. It incorporates a feature termed VT long cycle (VTLC; also available in single chamber devices), which monitors for longer ventricular intervals when the rhythm is classified as stable. Unlike in VT, occasional longer RR intervals are common in rapid AF.

Guidant/Boston Scientific

Guidant developed two algorithms for discriminators. The classical onset/stability algorithm is based on sudden onset, rate stability, and atrial rate (AF threshold), while the most recent algorithm, Rhythm ID, principally relies on morphology defined as VTC (vector timing correlation) (Figure 10.10).[22] With the availability of the Teligen™ and Cognis™ models, it is possible to select between onset/stability and Rhythm ID. If an atrial lead is unreliable, Rhythm ID may nevertheless be programmed and will act as a single chamber algorithm, relying only on VTC without an AF rate threshold, stability, or V > A criterion. Flutter and especially atrial tachycardia pose specific challenges to onset/stability criteria, as they are usually stable and of sudden onset. In contrast, the morphology-based Rhythm ID algorithm was associated with specificities of 80% and 90% for atrial tachycardia and flutter, respectively.[33] Success of the morphology algorithm is based on an accurate template. The automatic update feature has been validated and should, therefore, be activated. It functions appropriately even in highly paced patients. In patients with CRT, automated updates deactivate biventricular pacing and increase the AV delay, which may be particularly useful in the event of QRS remodeling.

Newer Boston ICD models (Incepta™) added "RhythmMatch" to Rhythm ID, which now allows for a customizable match rate instead of the fixed 94% value. The percentage correlation is provided beat by beat in recorded EGMs.

St. Jude Medical

St. Jude Medical uses the same discriminators for single and dual chamber devices: morphology,

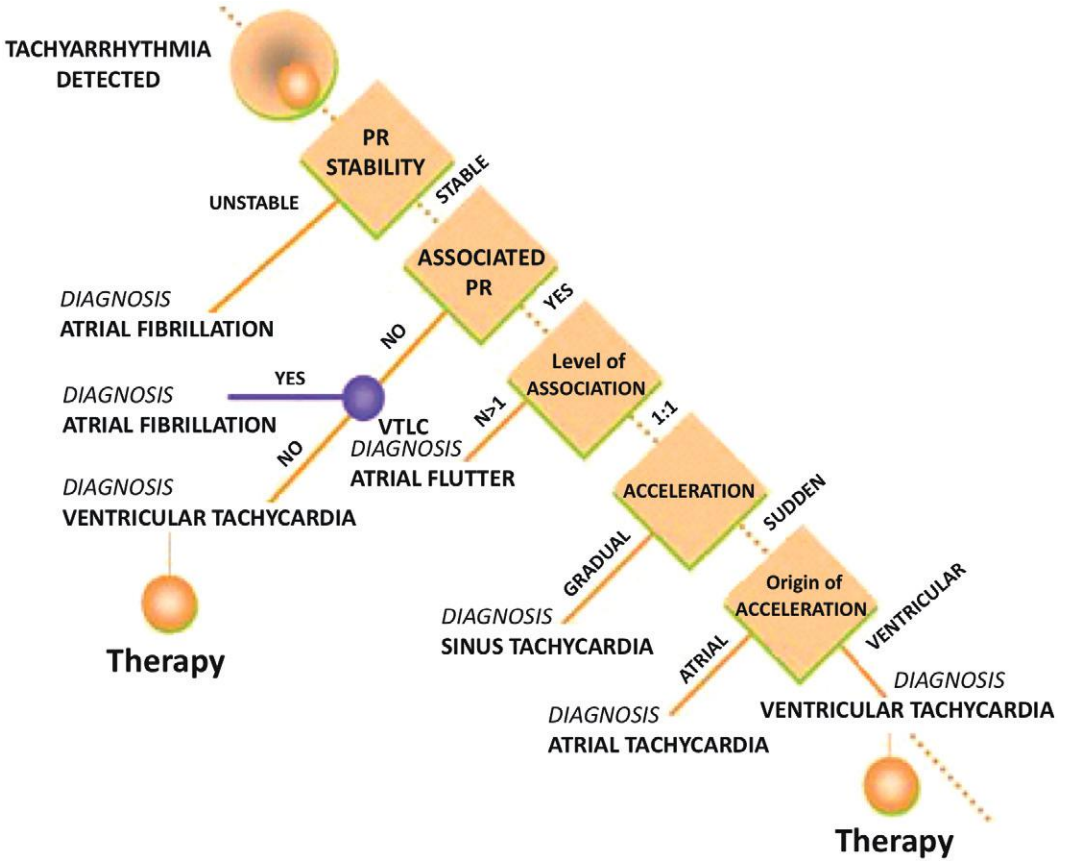


Figure 10.9 Sorin PARAD™ algorithm. The Sorin PARAD™ algorithm considers RR stability, associated PR interval, level of association, pattern of acceleration, and origin of acceleration to classify the rhythm as atrial fibrillation, atrial flutter, sinus tachycardia, atrial tachycardia, or ventricular tachycardia. VTLC denotes ventricular tachycardia long cycle length. It refers to a searching feature for a long cycle during stable tachycardia to detect rapid atrial fibrillation. Therapy is inhibited for 24 cycles following detection of a VTLC. (Source: Adapted from Mansour F, Khairy P 2011.[22] Reproduced with permission of John Wiley & Sons Ltd.)

stability, and sudden onset. Discriminators can be linked by the "any" parameter (deliver therapy if one discriminator indicates VT) or by the "all" parameter (deliver therapy if all discriminators indicate VT). In single chamber devices, studies show morphology to be the best performing single discriminator. However, requiring two of three discriminators to classify the rhythm as VT maximizes accuracy (sensitivity 96%; specificity 90.9%).[33]

A rate branch algorithm that considers ventricular and atrial rates is available for dual chamber devices. Most VTs meet the V > A criterion. Remaining tachycardias are further analyzed by programmed discriminators. When V = A, sudden onset and morphology may discriminate between sinus tachycardia, 1:1 SVT, and 1:1 VT. For this purpose, morphology is the most accurate discriminator, with sudden onset of little added value.[33] In fact, "sudden onset" was responsible for most inappropriately detected atrial tachycardias and exercise-induced VT. Programming stability and morphology with "any" logic was less specific (by 8–29%) than morphology alone.[33] If stability is used, AV association (nominally "off") should also be programmed. For example, with atrial flutter, stability may identify the rhythm as VT, but AV association should permit correct classification, as the AV relationship is more stable in atrial flutter

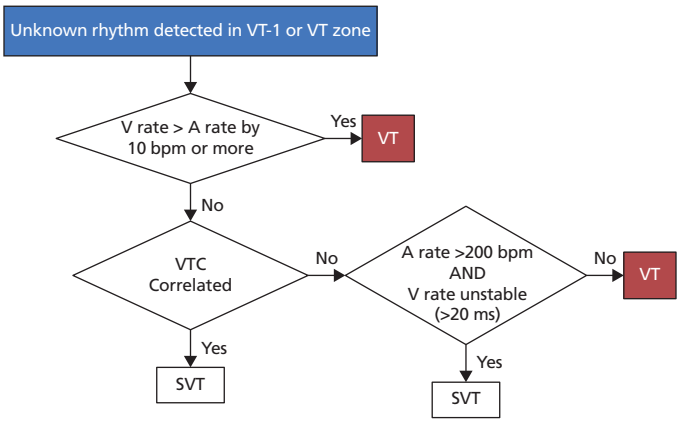


Figure 10.10 Initial detection with the Boston Rhythm ID™ algorithm. The Boston Scientific Rhythm ID™ algorithm considers the relationship between the ventricular (V) and atrial (A) rate, vector timing and correlation (VTC), and stability of the ventricular rate to classify a rhythm detected in the ventricular tachycardia (VT) or VT-1 zone as supraventricular tachycardia (SVT) or VT. (Source: Adapted from Mansour F, Khairy P 2011.[22] Reproduced with permission of John Wiley & Sons Ltd.)

than VT. "All" logic provides the best specificity for SVT but carries a greater risk of underdetecting VT,[33] though some studies suggest that the increase in risk is modest, especially since the availability of the Fortify™/Unify™ devices.[40]

Another particularity of St. Jude Medical devices is the VT therapy timeout, intended to limit the time permitted for VT therapies before delivering VF therapies. As opposed to other company brands, the timer does not start to elapse once ATP is initiated but, rather, once the rhythm is classified as VT and one interval average is binned shorter than a programmable cut-off (timeout zone). Since the availability of the Fortify™/Unify™ devices, St. Jude Medical has also made important changes to its nominal values for tachycardia programming via its Decision Tx™ algorithm and Shockguard™ technology. Default cut-off rates are higher and the number of intervals required for detection in the VT zone is increased. Discriminators are linked by "if all" (for greater SVT detection accuracy) and SVT timeout is disabled. AV association is nominally "on" to differentiate atrial flutter from VT. ATP is now programmed in all zones.

Updated Shockguard™ is available in the St. Jude's Assura™ family and Ellipse™ ICD models. The addition includes Far Field MD™ Morphology Discrimination (can-to-RV coil), to improve upon the use of near-field (tip-to-ring) morphology analysis. It may be also used in CRT devices. Automatic template updates, if programmed on, are collected with periodic suppression of biventricular pacing (similar to Boston Scientific algorithms). A RV lead noise discrimination algorithm (i.e. SecureSense™) is also available and functions similarly to Medtronic's algorithm (Figure 10.11). In dual chamber devices, when V = A, nominal programming favors "chamber onset" over "sudden onset," although the latter remains programmable. Prior to these advances, "chamber onset" was only available in Sorin devices (PARAD algorithm). Computational modeling suggests that Decision Tx™, Shockguard™, and their updated versions result in a significant reduction in inappropriate therapy and shocks. The efficacy and safety of these new nominal algorithms remain to be corroborated by clinical studies. The PROVIDE study, which incorporates Decision Tx™ but not the updated Shockguard™ (Chamber of onset, SecureSense, FarField MD) algorithms, supports strategic programming to reduce shocks in St. Jude devices.[32]

Biotronik

Single chamber Biotronik devices use sudden onset and stability as discriminators. Dual chamber devices rely on an algorithm named "SMART,"

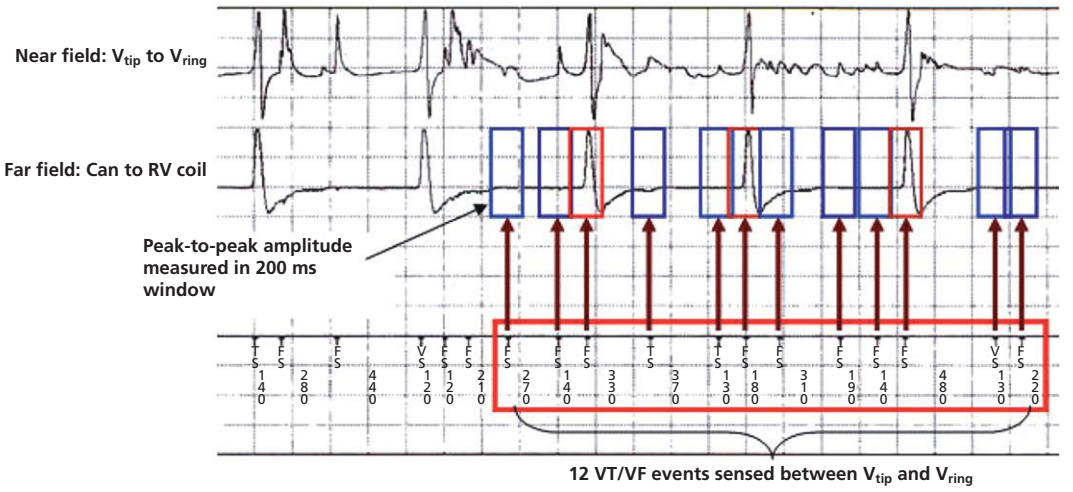


Figure 10.11 Protecta™ right ventricular lead noise discrimination. Lead noise oversensing is typically isolated to the near-field sensing signal. The noise discrimination algorithm consists of analyzing the far-field (FF) electrogram (EGM) to determine if the event sensed on the near-field EGM is noise or a true ventricular event. When the ventricular tachycardia (VT) count = 2 or ventricular fibrillation (VF) count = 3, the algorithm begins by processing the FF EGM to determine the peak-to-peak amplitude in a ±100 ms window (for a total of 200 ms) centered on either side of the corresponding ventricular-sensed event (see blue and red squares). A set of 12 FF peak-to-peak amplitudes is evaluated. The algorithm then determines whether the 12 VT/VF events meet both of the following criteria: (1) the average of the two smallest values is <1 mV, and (2) the average of the two smallest peak-to-peak amplitudes is less than one-sixth the maximum amplitude. The algorithm uses a counter that increments by one, with the next set of 12 peak-to-peak amplitudes evaluated using a rolling window. If at least three of the last 12 sets are classified as noise, detection is withheld. (Source: Medtronic, Inc. Reproduced with permission of Medtronic, Inc.)

which, like St. Jude algorithms, uses a rate branch scheme (Figure 10.12). Sudden onset is particularly useful to detect sinus tachycardia, stability for AF detection, multiplicity (i.e. ratio of atrial to ventricular signals) for atrial flutter, and V dissociation for VT. No morphology discriminator is available such that detection of atrial tachycardia is limited (e.g. cannot differentiate SVT with 1:1 conduction from VT with stable retrograde conduction).

Biotronik developed a new ICD (Lumax™ VRT Dx) for a VDD lead. The objective is to take advantage of the simplicity of implanting a single lead system while benefitting from atrial EGMs for diagnostic purposes (e.g. AF, SVT). The atrial signal is pre-amplified and blanking periods are modified to avoid oversensing. This device uses the SMART algorithm in the presence of a valid atrial signal (i.e. at least one atrial signal between two ventricular signals) and, in the absence of such a signal, relies on onset/stability criteria. One study reported that the Lumax™ VRT ICD had 100% sensitivity for VT detection, with non-inferior specificity for SVT when compared to dual chamber devices (although a non-significant trend favored the dual chamber ICD).[41]

Therapies

Antitachycardia pacing

Fast VT

Pace termination of monomorphic re-entrant VT is supported by solid evidence in primary and secondary prevention patients with ischemic or non-ischemic cardiomyopathy: it is quick, painless, and effective.[35,42] The mechanism of termination is that accelerated pacing waveforms (ATP) collide with the waveform of the tachycardia in such a way that tachycardia front exit from the scar (or

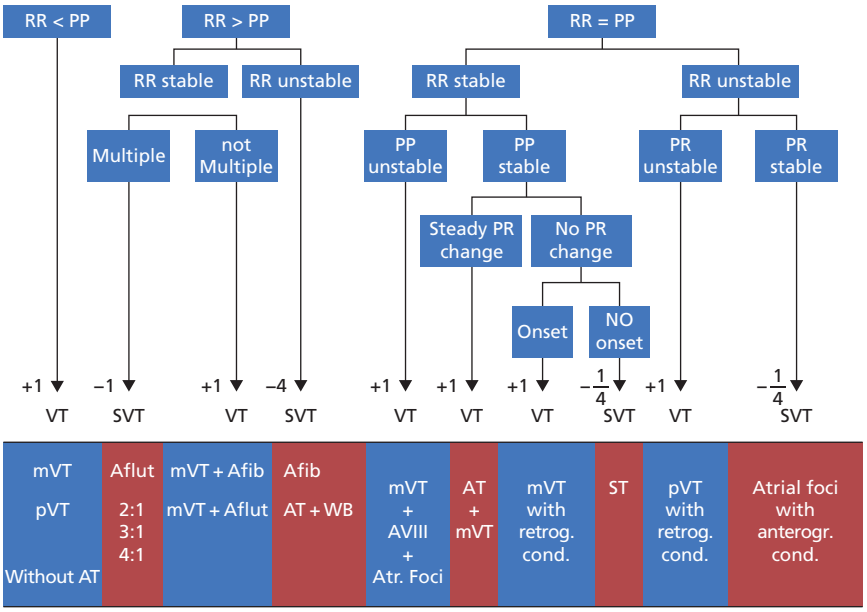


Figure 10.12 Biotronik SMART algorithm. Like St. Jude Medical, Biotronik relies on a rate branch algorithm for discrimination. If the RR interval is shorter than the PP interval, the rhythm is considered ventricular tachycardia (VT). Other arrhythmias are classified using stability (RR and PP intervals), atrioventricular association (multiplicity, stability/change of the PR relationship), and onset criteria. Morphology is not yet available. On a beat-by-beat fashion, the ventricular tachycardia detection counter is incremented (VT, +1) or decremented (SVT, negative numbers in the figure) based on how the particular beat is categorized, until therapy is indicated or the tachycardia subsides. SVT, supraventricular tachycardia; mVT, monomorphic VT; pVT, polymorphic VT; Aflut, atrial flutter; Afib, atrial fibrillation; AT, atrial tachycardia; AVIII, third degree AV block; WB, Wenckebach; Atr. Foci, atrial foci; retrog., retrograde; cond., conduction; ST, sinus tachycardia; anterogr., anterograde. (Source: Adapted from Mansour F, Khairy P 2011.[22] Reproduced with permission of John Wiley & Sons Ltd.)

protected isthmus of the tachycardia) is blocked. Using one to two ATP sequences [eight-pulse burst pacing train at 88% of the fast VT (FVT) cycle length with a 10-ms decremental scan] for VTs between 188 and 250 bpm is associated with a 72–89% success rate.[31,36] The incidence of syncope resulting from delayed therapy or VT acceleration does not appear to be significantly higher than shock-only programming. When compared to physician-tailored programming, a standardized single ATP sequence in the FVT zone was associated with a significantly lower rate of shock.[25,27] The success rate is higher if more sequences are used. Current data support the use of at least two ATP sequences, as the second terminates 35% of VTs, with up to eight sequences in selected patients.[23,35,42,43] Even in induced VT faster than 250 bpm, a 30% success rate was noted with up to six ATP sequences.[44] Rate acceleration occurred more frequently, but all shocks were ultimately successful. Interestingly, failure of an ATP sequence did not predict subsequent failure of the same ATP sequence during a subsequent VT episode. Automated deactivation of failed ATP (i.e. Medtronic Smart Mode nominally "off"; not available with other manufacturers) is, therefore, not necessarily desirable. Biotronik has a programmable option [i.e. ATP optimization (nominally "off")]. A successful ATP setting is memorized by the ICD and delivered as the first therapy for future events.

When comparing ATP schemes, burst has a significantly higher success rate than ramps, with a trend toward less VT acceleration (Figure 10.13).[45] No significant advantage was found on extending the number of pulses from eight to 15 (88% of the FVT cycle length).[46] However, in a subgroup of patients without heart failure and an ejection fraction of greater than 40%, 15 was superior to eight pulses.[46]

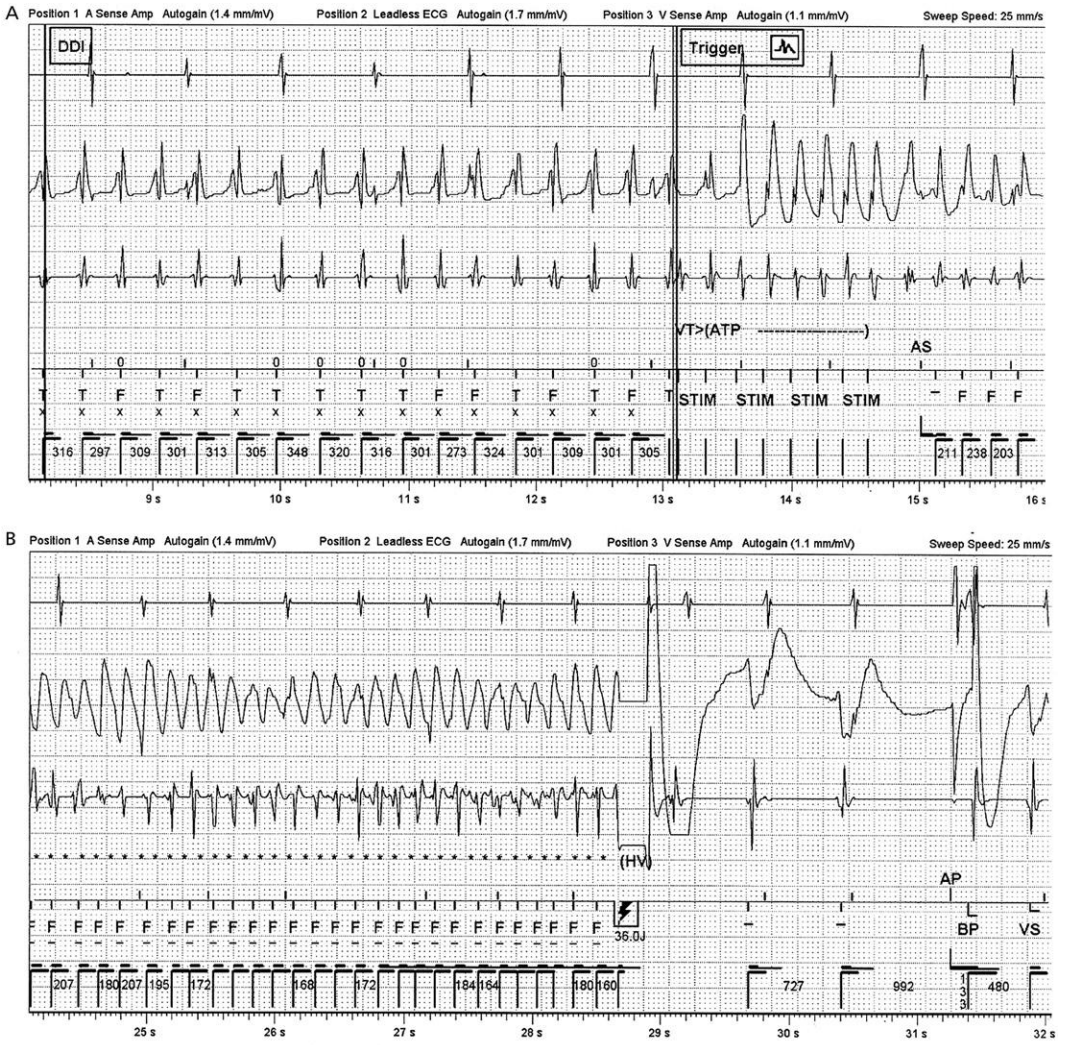


Figure 10.13 Degeneration of ventricular tachycardia by decremental stimuli (i.e. "ramp"). (A,B) From top to bottom, intracardiac atrial electrogram (EGM) recordings, far-field EGMs (ICD can-to-right ventricular coil), intracardiac ventricular EGMs, and telemetered marker channels. (A) Monomorphic ventricular tachycardia (VT) is detected in the VT zone, programmed at 171 bpm. Antitachycardia pacing by means of a "ramp" protocol (onset at 80% of the tachycardia cycle length; 10-ms decrement per stimulus; eight stimuli) results in tachycardia acceleration. (B) The rapid polymorphic VT is detected in the ventricular fibrillation zone, set to 200 bpm. The arrhythmia is terminated by a 36-J shock. (Source: Khairy P, Mansour F 2011.[30] Reproduced with permission of Elsevier.)

In summary, the weight of evidence suggests that at least two burst sequences should be programmed for VTs between 188 and 250 bpm. In single zone programming, ATP during or before charging should be programmed. ATP during charging is available in Medtronic and newer St. Jude Medical devices (Fortify™ ICDs). Boston Scientific's Quick-convert delivers one ATP sequence in the VF zone before charging and is limited to rates slower than 250 bpm. Sorin and Biotronik (one attempt) devices can deliver ATP before charging in the VF zone, if the rhythm is stable. ATP should not be programmed in patients prone to polymorphic VT (e.g. long-QT, Brugada syndrome).

Slow VT

While programming ATP for slower VTs is common practice, evidence-based programming schemes (e.g. number of sequences and programmed beats, burst versus ramp, etc.) are scarce. On the whole, burst versus ramp schemes appear to be of comparable efficacy. Less aggressive bursts seem to yield superior results (e.g. 91% versus 81% of the basic cycle length). At least four sequences should be programmed to maximize success.[47] When the option is available in patients with ischemic cardiomyopathy and CRT devices, ATP delivered from both ventricles simultaneously is associated with a higher success rate than ATP from the right ventricle alone.[48] For many patients with slow VT, VT ablation is ultimately the most appropriate therapy.

Diagnostic value

In addition to its therapeutic potential, ATP may provide valuable diagnostic information.[22,49]

Response pattern

To assist in diagnosing 1:1 tachyarrhythmias (e.g. VT with retrograde conduction versus atrial tachycardia, sinus tachycardia, AV, or AV nodal re-entrant tachycardia), one may analyze the atrial response during ATP:

- If the atrial cycle length remains stable and independent of the ATP cycle length (i.e. dissociation), a diagnosis of atrial tachycardia or, possibly, AV nodal re-entrant tachycardia with retrograde block in the lower common pathway is favored (Figure 10.14). Exceptions include a double tachycardia (e.g. co-existing atrial tachycardia and VT), although in such cases the A–V relationship is not perfectly stable.
- If an atrial cycle length that varies during ATP (i.e. retrograde Wenckebach or block), the tachycardia is consistent with AV nodal re-entrant tachycardia or VT.
- If the atrial cycle length accelerates to the ATP (paced) cycle length and the arrhythmia is not aborted upon termination of ATP (i.e. entrainment occurs), the diagnosis may be further narrowed by considering the intervals following ATP:

  a *VAAV:* A VAAV response (i.e. two consecutive atrial events following the last paced ventricular beat) suggests atrial tachycardia, as depicted in Figure 10.15. A pseudo-VAAV response may occur in AV nodal re-entrant tachycardia with a very slow retrograde pathway when the VA interval is longer than the ATP interval. Linking each retrograde atrial event to the corresponding paced ventricular beat should help sort out this scenario.

  b *VVA:* VVA response (i.e. a ventricular event following the last paced ventricular beat) suggests a diagnosis of VT.

  c *VAV:* a VAV response is not helpful in distinguishing VT from AV nodal or AV re-entrant tachycardia.

Post pacing interval variability

In the setting of VT, the RV lead is closer to the re-entrant circuit than the atrial lead. The post-pacing interval (PPI) after a burst of ATP should, therefore, be shorter in VT than SVT and less subject to variability. In an analysis of arrhythmias not terminated by more than one ATP, a PPI that varied by less than 50 ms correctly identified all VTs, whereas 90% of SVTs had a PPI that varied by more than 50 ms during sequences with different numbers of stimuli.[49] In practice, episodes are often aborted before such multiple bursts can be delivered. Nevertheless, a relatively stable PPI observed after multiple ATP attempts favors a diagnosis of VT (Figure 10.14).

Shocks

No study has specifically compared incremental versus high-energy shocks. Advantages of low-energy shocks include shorter charge times, extended battery life, and possibly less myocardial damage.[22] Nevertheless, in the modern era, charge time is not a major issue, lower energy shocks may be more pro-arrhythmic, and higher energy shocks carry a greater probability of success.[50] Additional advantages of higher energy shocks may include a higher probability of terminating inappropriately treated SVTs (for which the shock vector is suboptimal), and a slightly longer charging time that allows for ATP and favors self-termination of non-sustained arrhythmias. Until further data are available, maximum shock outputs should be considered, especially if defibrillation threshold testing has not been performed.

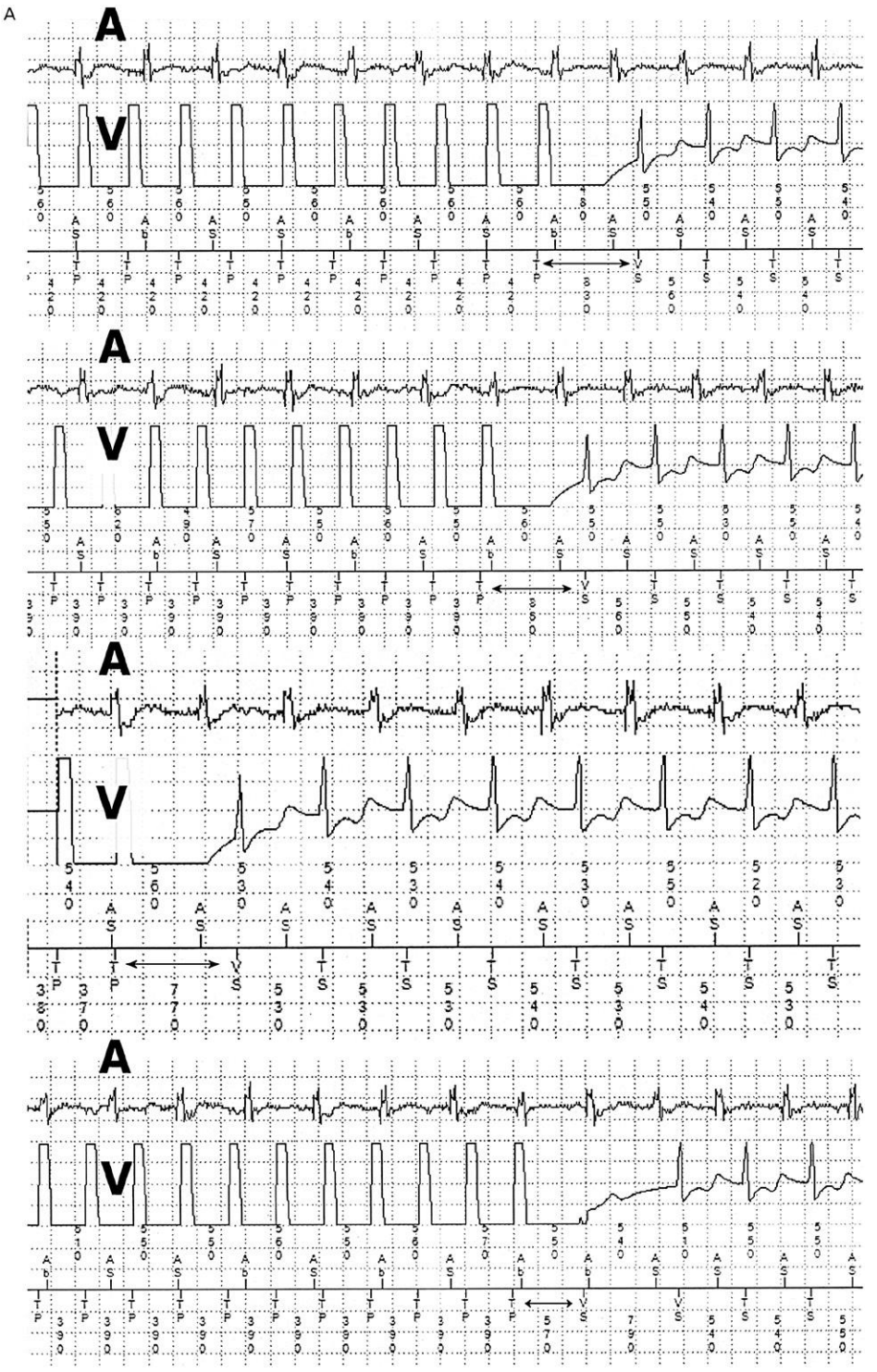


Figure 10.14 Responses to multiple episodes of ventricular overdrive pacing (antitachycardia pacing, ATP) during (A) atrial tachycardia and (B) ventricular tachycardia (VT). Post-pacing interval (double headed arrows↔) is highly variable during atrial tachycardia and stable during VT (*). In these examples the presence of an atrial channel is even more helpful in differentiating the tachycardia mechanism. (A) There is VA dissociation

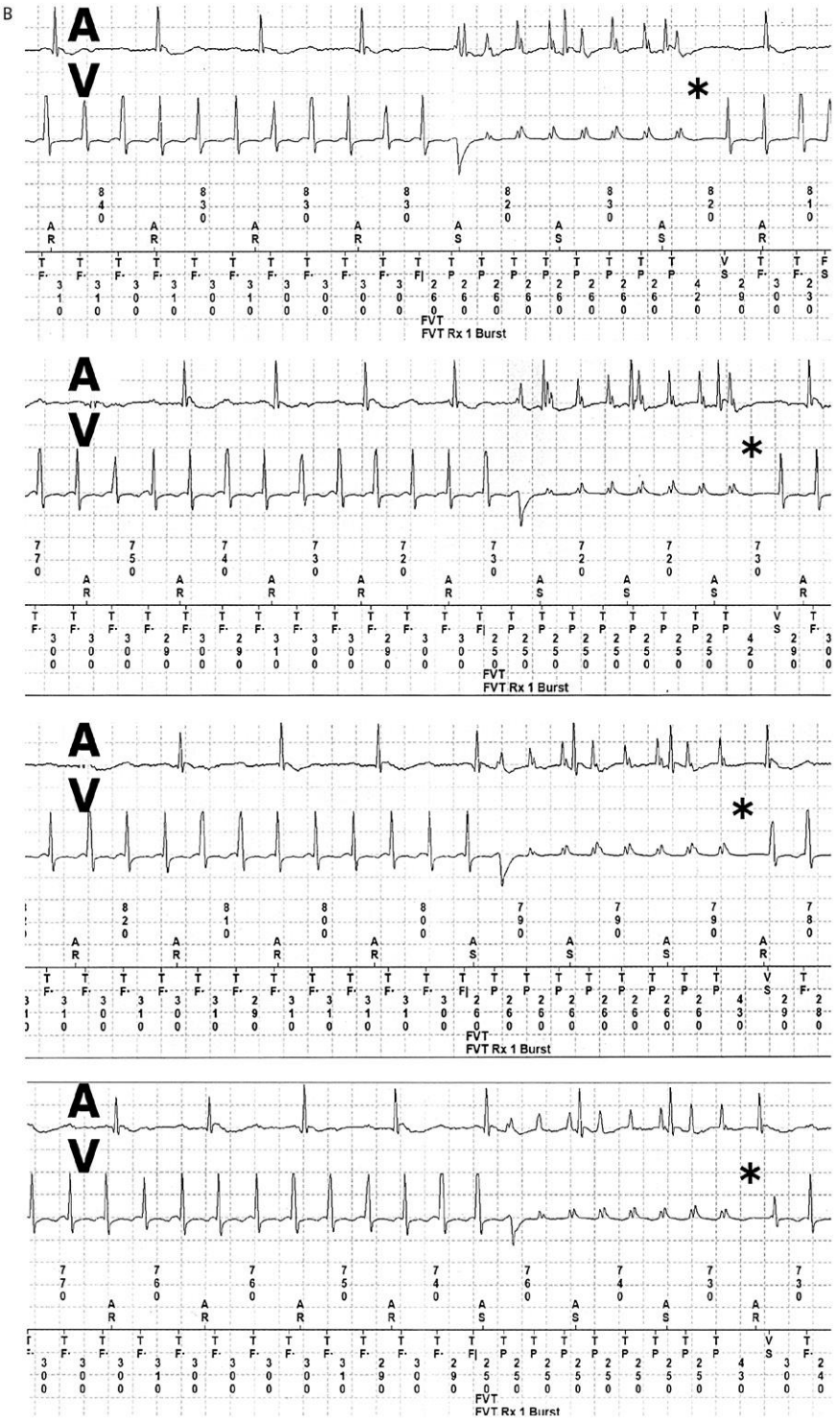


Figure 10.14 (*Continued*) during an atrial tachycardia. During ventricular pacing, the atrial activation is unaffected and atrial tachycardia continues undisturbed. (B) There is AV dissociation during VT. If these episodes were recorded in a single chamber device, only the post-pacing interval would help to differentiate between the tachycardia mechanisms. A, atrial tip to ring; V, ventricular tip to ring.

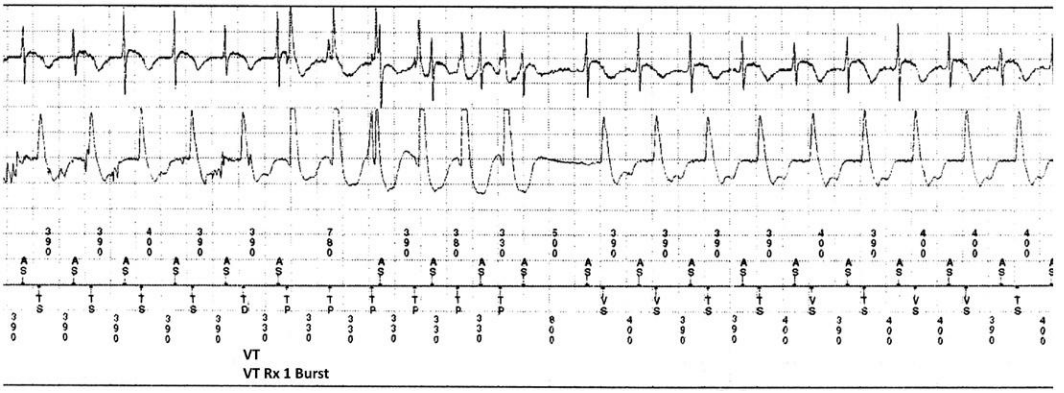


Figure 10.15 A "VAAV" response during antitachycardia pacing in a 1:1 tachycardia. Shown from top to bottom are intracardiac atrial electrograms (EGMs), ventricular EGMs, and telemetered marker channels. A 1:1 tachycardia is detected in the ventricular tachycardia (VT) zone, with a cycle length of 390–400 ms. Antitachycardia ventricular pacing is delivered with a six-beat drive train at 330 ms. The last three beats result in ventricular capture, with the final two beats accelerating the atrial rhythm to the paced cycle length. The last paced beat (V) is followed by an AAV response, consistent with an atrial tachyarrhythmia. (Source: Adapted from Mansour F, Khairy P 2011.[22] Reproduced with permission of John Wiley & Sons Ltd.)

Pharmacological or catheter-based therapy

A substantial proportion of inappropriate shocks for AF occurs in the VF zone, where no discriminators are present. In the VT zone, stability and morphology are unreliable for rapid AF, since RR intervals regularize and conduction aberrancy may develop. In the absence of morphology algorithms, discriminators poorly identify atrial tachycardia and re-entrant SVT.[22] Pharmacological therapy and/or catheter ablation may effectively manage these arrhythmias without increasing the risk of underdetecting VT. Catheter ablation may also be the preferred option for slow VT, for which programming lower zones may increase the risk of inappropriate shocks.

ICD in the dying patient

Managing the dying ICD patient is an increasingly common scenario.[51,52] Roughly 20% of ICD recipients receive shocks during their final weeks of life, causing distress to the patients and their families. Proactive discussions regarding comfort care strategies for terminal heart failure can prevent this scenario. Timing of such discussions and physician responsibilities remain matters of debate.[53] Currently, few physicians initiate these discussions and most patients do not consider ICD deactivation in their advance directives. Deactivating an ICD must be performed within the legal framework of one's institution and system. In general, a patient request for ICD deactivation falls under the same legal rights as "do not resuscitate" requests, and is also valid for non-dying patients.

In North America, deactivating the ICD upon request is not considered active euthanasia. It must be clearly explained to the patient that it is not a form of physician-assisted suicide, that it does not directly cause death, and that it is not synonymous with end of care. The patient must be well informed and capable of providing consent. If the court has declared the patient incompetent, a legally assigned surrogate assumes responsibility. Decisions are not binding and the patient is free at any time to change his/her mind. Routine psychiatric evaluation is not required, but should be requested if pathology such as depression is suspected. Involving the treating physician, family, or caregiver is always desirable.

The process must be well documented. A physician should not be obliged to deactivate an ICD if it conflicts with his/her personal values, but he/she then carries the responsibility of finding a suitable

colleague to carry out the intervention. If a patient is primarily concerned about comfort but desires continued therapy, shocks may be deactivated while maintaining ATP functions. If the ICD cannot be deactivated with a programmer in the final moments before death, a magnet may be taped over the ICD.

Electromagnetic interference

The main concerns regarding EMI with ICDs is ventricular oversensing leading to shocks and, less frequently, electrical reset to VVI/VOO pacing modes.[54] ICDs are well shielded from most sources of EMI. Bipolar sensing (versus integrated), electronic filtering, and noise reversion modes all contribute to minimizing EMI (Figure 10.16).[41] Limitations to eliminating EMI result from concerns about undersensing VF.

Avoiding and quantifying all possible EMI in daily life is not a simple task. Nevertheless, interactions of concern are rare. Airport metal detectors, laser therapy for cosmetic purposes, cellular phones, and all well-grounded appliances are unlikely to interfere with ICDs.[55,56] *In-vitro* studies have prompted the recommendation to avoid keeping a cellular phone over the ICD pocket. Interactions with theft detectors are variable, with highest EMI risk associated with magneto-acoustic and electromagnetic devices. We, therefore, suggest to patients not to linger around such detectors. Arc wielding and transcutaneous electrical nerve stimulation (TENS) are generally not recommended due to risks of ventricular oversensing. Recent publications seem to show that the potential for risk of EMI by induction cooktops might be less significant than previously thought.

Most EMI occurs within the hospital setting. Procedures commonly associated with EMI include magnetic resonance imaging (MRI), electrocautery, radiofrequency ablation, and dental interventions. Cases of MRI performed safely after deactivating ICD therapies have been published.[57] Nevertheless, before a truly MRI-conditionally safe ICD is released, safety cannot be assumed. ICDs remain a contraindication to MRI, with scanning performed in selected cases after weighing advantages and potential complications. Dental equipment (e.g. composite curing light, ultrasonic scaler, ultrasonic cleaning system) can create EMI, and should be kept at least 2 cm away from the ICD generator and 7–10 cm away from leads.[58]

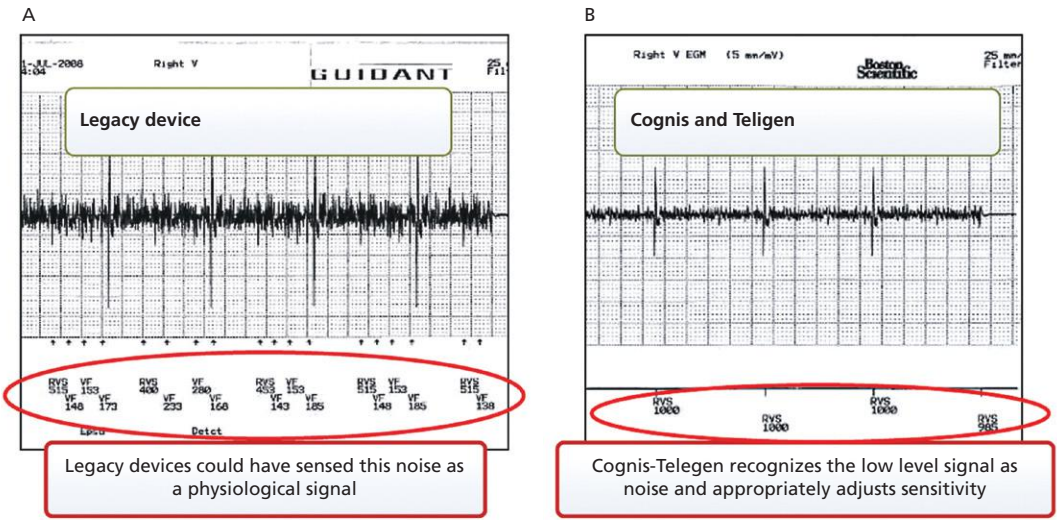


Figure 10.16 Noise rejection algorithm. (A,B) The ICDs are subjected to identical noise from electromagnetic interference (EMI) and both devices have 5-mV R waves. (A) In the older Legacy™ device, ventricular fibrillation (VF) counts are detected. (B) In contrast, a noise rejection algorithm is available (Cognis™ and Teligen™) such that low level signals are appropriately recognized as noise and sensitivity is adjusted accordingly.

Table 10.3 Perioperative management of ICDs

General preoperative management	Management in conjunction with the pacemaker clinic Device interrogation within prior 6 months to ensure proper function Clarify dependency status and magnet response (default is to inhibit detection, but programmable in some models)
General intraoperative management	Limit electrocautery to short bursts in the absence of ICD reprogramming or magnet inhibition of therapies Use oximetry to monitor patients during electrocautery artifacts If bipolar electrocautery cannot be used, place the return patch so as to keep the ICD system outside the current flow (thigh or ipsilateral limb) Monitor patient during surgery and as long as ICD is deactivated Use external patches during surgery if history of malignant arrhythmia
Infraumbilical surgery	Risk of interference minimal: either do nothing or place magnet on ICD
Supraumbilical surgery	Risk of electromagnetic interference: use magnet or inactivate detection In pacemaker-dependent ICD recipients: inactivate detection and pace in VOO/DOO mode (magnet has no effect on pacing except in Sorin ICDs) Do not program VOO/DOO if the patient is not fully dependent to avoid competing rhythms during surgery
Cardioversion/ defibrillation with external pads	Place pads in an anteroposterior position $\geq$8 cm away from the ICD generator Use a minimal efficacious biphasic shock to avoid overloading Zener diode or causing electrical reset/damage
Postoperative management	Identify the person responsible for reprogramming at the end of surgery If not reprogrammed, interrogate the ICD, ideally before removing telemetry for major, urgent, or cardiothoracic surgery or post cardioversion, or within a month for other situations

Preoperative management of ICDs in the setting of electrocautery has been addressed in the Heart Rhythm Society (HRS) 2011 consensus and is summarized in Table 10.3.[59] In order to avoid ventricular oversensing from electrocautery, an external magnet is generally preferred over device reprogramming, since it provides the surgical team with greater control in the advent of a ventricular arrhythmia and also eliminates human error in forgetting to reactivate ICD therapies. Importantly, it should be noted that a magnet does not necessarily inactivate therapies in all ICDs. The magnet response is programmable in St. Jude Medical ("normal" or "ignore") and Boston Scientific ("on" or "off") ICDs. It is rarely tampered with in the pacemaker clinic unless the device has been the subject of specific recalls (e.g. older Guidant Contact Renewal CRT-D).[60] Of note, a magnet has no effect on pacing in ICDs, except for in Sorin's devices. Electrosurgery during upper gastrointestinal endoscopy using monopolar electrocauterization should be managed with a magnet even though the risk of EMI is low. Although videocapsule endoscopy represents a low risk of EMI, its use is not recommended by the manufacturer in the presence of a device. While interaction is possible, no adverse event has been reported and because the risk of EMI is low, the HRS has refrained from formal recommendations regarding videocapsule endoscopy. Transurethral prostate resection carries minimal risk of EMI in modern devices. Lithotripsy also incurs minimal risk, especially if it is directed more than 18 cm away from the device system. Risks of EMI associated with cataract and laser surgery are negligible. Chapter 11 includes further discussion on patient management and EMI.

Troubleshooting

When a shock is delivered, one must determine whether the shock is appropriate (VT/VF) or

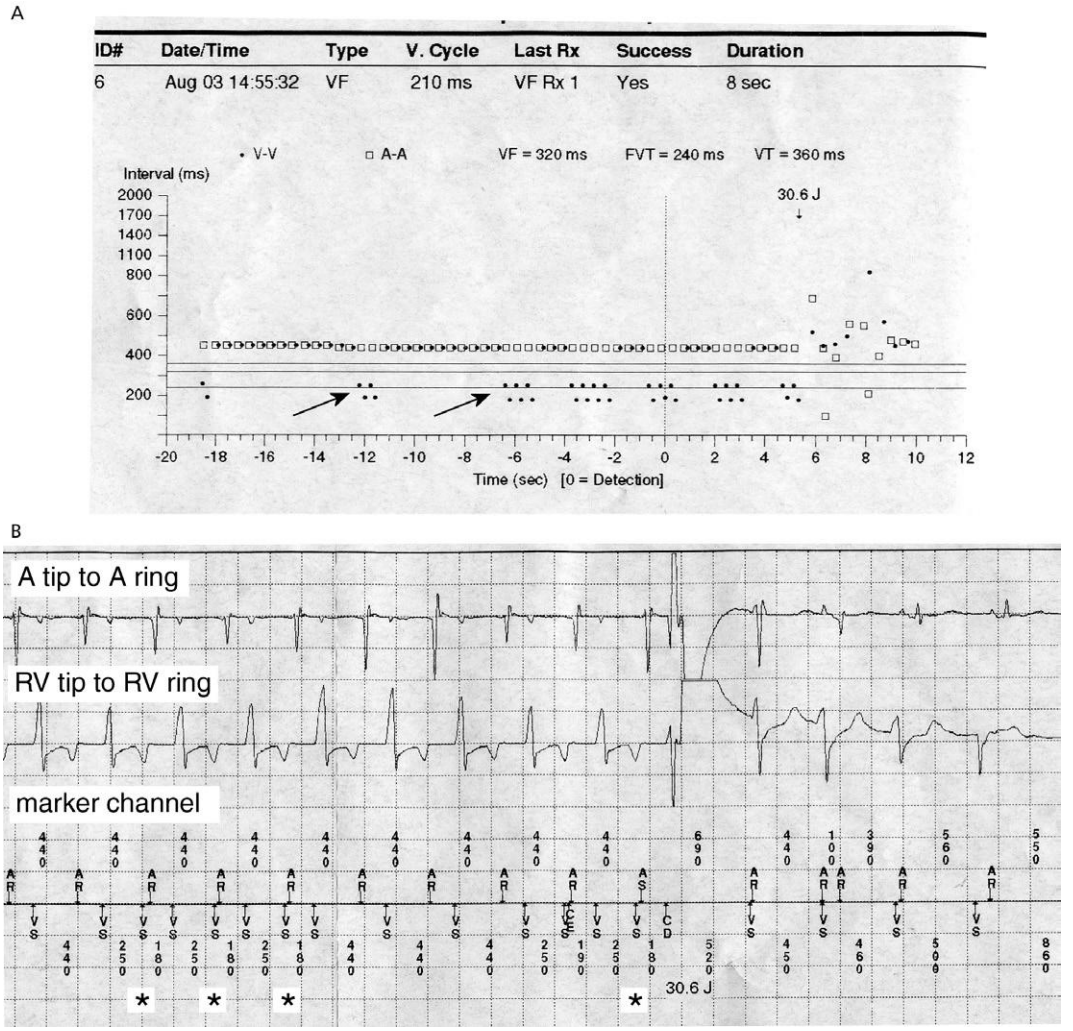


Figure 10.17 Inappropriate ICD shock due to T wave oversensing. (A)Plot diagram in a Medtronic dual chamber device. Note the typical railroad-track appearance of intermittent T wave oversensing events (arrows). (B) Electrograms retrieved from the device memory. T wave oversensing is recognized by ventricular sense events corresponding to the T wave (*) and double counting. Due to baseline sinus tachycardia, these intermittent oversensing episodes resulted in an ICD shock therapy.

inappropriate. Inappropriate shocks can be further classified as due to SVT, intracardiac oversensing (P, R, or T waves; Figure 10.17), or extracardiac oversensing (e.g. myopotentials, EMI, lead fracture). True ICD malfunction is exceedingly rare. Inappropriate shocks and absence of appropriate shocks are almost always a matter of programming and device algorithms.

Patient evaluation

After a single shock, it may be reasonable for an asymptomatic patient to non-urgently present to or notify a pacemaker/ICD clinic during working hours. However, in the presence of symptoms or multiple shocks, a visit to the emergency room is warranted for rapid management. The clinical history surrounding the shocks should be elicited.

Inappropriate shocks are suggested by the lack of heralding symptoms (e.g. SVT, oversensing), preceding exercise (e.g. sinus tachycardia, rapid AF), exposure to EMI (i.e. oversensing), or less commonly, arm movement or pocket stimulation (e.g. lead failure, loose set screw). Chest radiography can identify improperly positioned pin connectors in the ICD header, a fractured lead, a displaced ventricular lead (sensing atrial in addition to ventricular signals), or Twiddler's syndrome (Figure 10.18).

Single shock

When reviewing EGMs, analyzing the rhythm using the same logic employed by ICD discriminators may help to determine whether a shock is appropriate. In single chamber devices, an unstable rhythm is more likely to represent AF and gradual acceleration is more compatible with sinus tachycardia. The most challenging rhythm strips to classify are sudden onset regular tachycardias that can either be SVT (e.g. AV nodal re-entrant tachycardia, atrial tachycardia, atrial flutter) or VT. Arrhythmia termination by ATP supports a diagnosis of VT, although the differential diagnosis may include AV reciprocating tachycardia or termination of an SVT by retrograde penetration of the AV node (Figure 10.19). Morphology can be very useful when comparing the far-field channel from sinus rhythm with the one in arrhythmia. Morphology of beats that immediately follow shocks should not be relied on for comparison because of possible EGM distortion. This does not apply to arrhythmias terminated by ATP.

In dual chamber ICDs, addition of an atrial channel significantly increases physician accuracy for recognizing SVTs,[61] even if its value in reducing inappropriate shocks remains debated. The simplest and most reliable method to differentiate VT from SVT is by identifying more ventricular than atrial events (V > A; Figure 10.14). This single criterion correctly classifies the vast majority of VTs. Transient ventriculoatrial (VA) block helps to identify VTs with 1:1 retrograde conduction, which accounts for less than 10% of all VTs. Conversely, transient AV block (with V < A) favors a diagnosis of SVT. Additionally, it is useful to see how the arrhythmia was initiated; if initiated by a premature atrial contraction (PAC), SVT is likely, and VT is more likely initiated with a premature ventricular contraction (PVC) (Figure 10.20). Other situations may benefit from considering additional discriminators. In the presence of a double tachycardia, AV association may be useful in identifying atrial flutter, whereas a regular ventricular response during AF favors VT. When V = A, identifying slight variations in cycle length can further help to differentiate SVT from VT by determining the "driving chamber." A change in A–A interval that precedes a corresponding change in V–V interval supports a diagnosis of SVT, and *vice versa* for VT. If doubt persists, programming a far-field morphology channel can help analyze future episodes. Not all dual chamber ICDs have a far-field EGM recording as their default setting. In addition, for discriminators to function appropriately, reliable sensing is a prerequisite. Atrial undersensing can lead to an incorrect diagnosis of VT. FFRW sensing may result in underdetection of VT if constant (A > V) or to an inappropriate diagnosis of VT if inconsistent.

Multiple shocks

Multiple shocks may be appropriate in the setting of a VT storm or failed shocks for VT/VF. Non-sustained VT can lead to "appropriate" but unnecessary shocks. To avoid shocking non-sustained VT, shocks are nominally non-committed. This is accomplished through a confirmation algorithm that assesses whether VT/VF has persisted or terminated following capacitor charging prior to delivering a shock. If a few short intervals (typically shorter than the slowest VT zone) are present after charge completion, a shock is generally delivered. However, in the event of arrhythmia termination, the algorithm may be fooled by PVCs that result in inappropriate shocks. Depending on the manufacturer, a shock can also become committed if a first shock was diverted and the episode has not terminated (e.g. Boston Scientific ICDs).[62] Thus, a non-sustained tachyarrhythmia that recurs before an episode is declared terminated will provoke a committed shock or, in some ICD devices (from St. Jude Medical and Medtronic), will not be subject to SVT discriminators. Mastering each manufacturer's algorithms, which are refined over time, is essential to troubleshooting. Increasing detection and redetection times generally remains the best

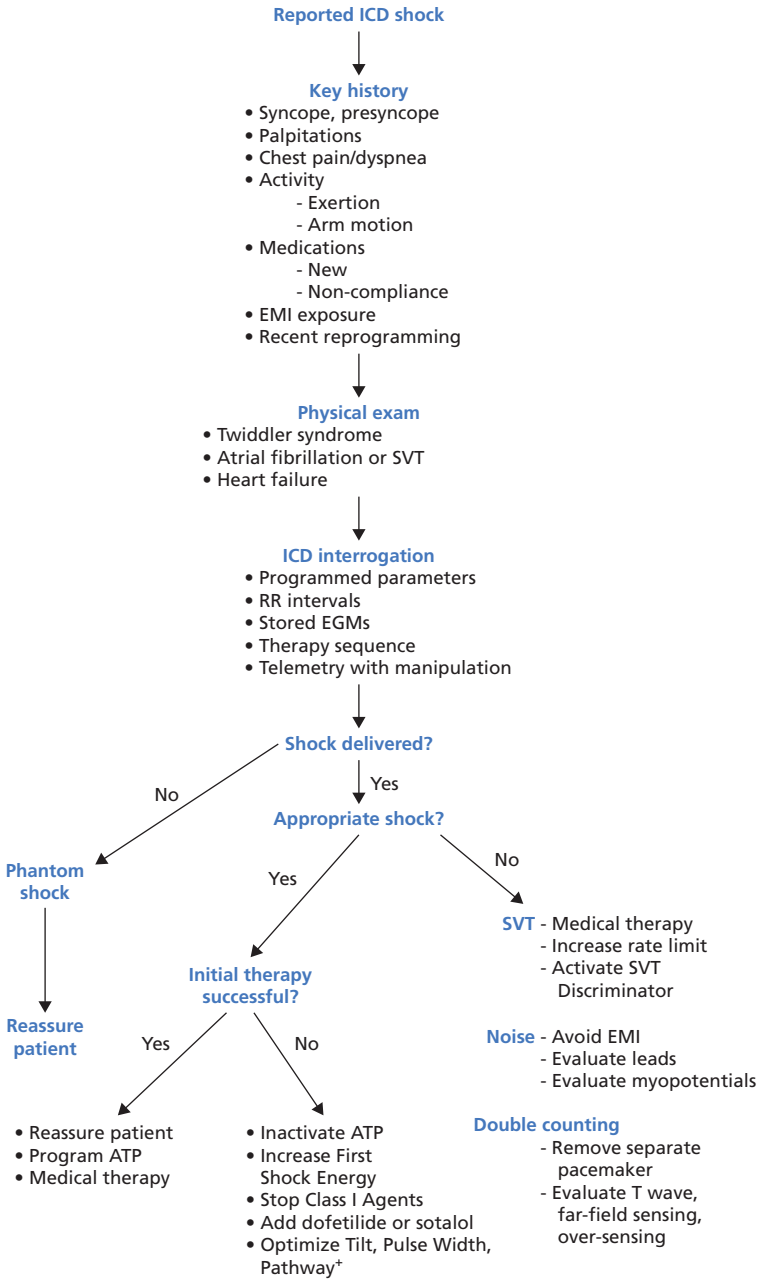


Figure 10.18 Flow diagram for evaluating ICD shocks. ATP, antitachycardia pacing; EGM, electrocardiogram; EMI, electromagnetic interference; SVT, supraventricular tachycardia.

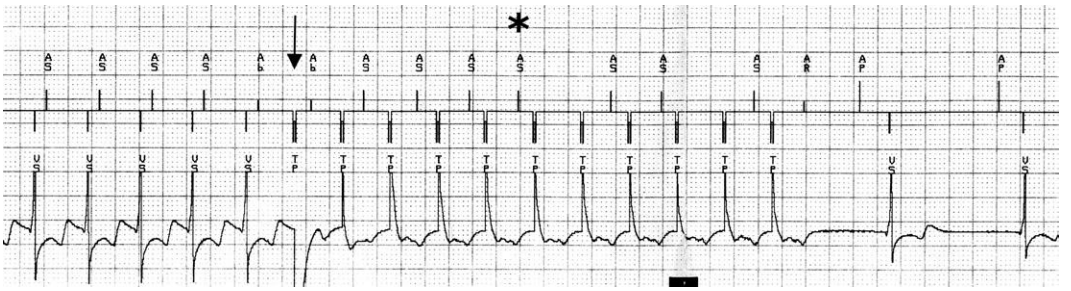


Figure 10.19 ATP terminating a tachycardia with a 1:1 AV relationship. The episode is recorded from a patient who presented in the clinic with a tachycardia below the VT detection rate. Manual ATP was performed (arrow). The tachycardia cycle length is 440 ms, ATP was initiated at 400 ms. Only the fifth ventricular pacing complex affects the atrial activation (*) and subsequently the tachycardia terminates with intermittent VA block. This response is most consistent with AV nodal re-entry tachycardia (confirmed in this case in a subsequent electrophysiological study). VT is unlikely with VA block with similar cycle length ventricular pacing. Atrial tachycardia cannot be entirely ruled out due to entrainment of the atrium before termination of the tachycardia.

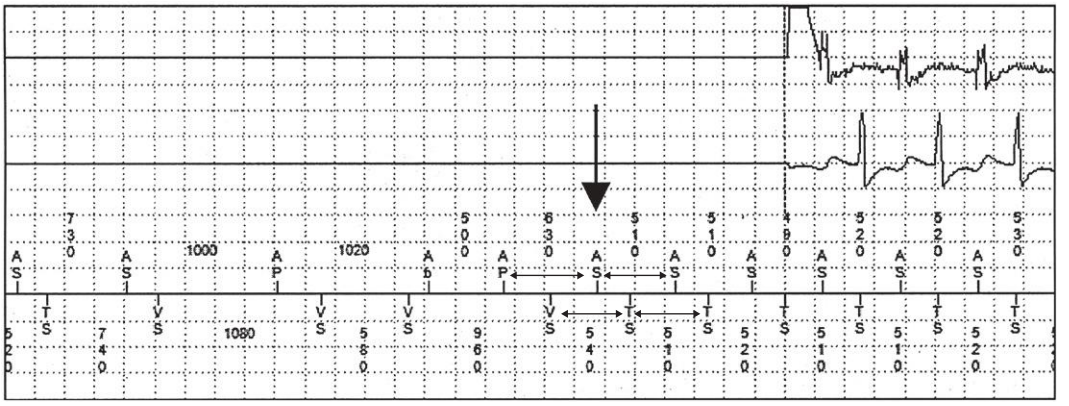


Figure 10.20 Tachycardia initiation in a Medtronic ICD. The first part of the tracing only shows the marker channel recordings. The long RP tachycardia initiates in the atrium (arrow) and continues in a 1:1 manner. Also, note that the change in the AA interval predicts the change in the VV interval (double-headed arrows), suggesting atrial tachycardia as a mechanism for the tachycardia. A, atrial tip-to-ring; V, ventricular tip-to-ring.

method of avoiding multiple shocks for non-sustained arrhythmias.

Multiple shocks are often inappropriate and most commonly due to SVT, oversensing, or EMI (Table 10.4). EGM characteristics of oversensing differ based on the cause (Figure 10.21).[63] Availability of a magnet to rapidly inhibit detection in the emergency room is particularly useful when ICD shocks are accompanied by normal sinus rhythm on telemetry.

Unsuccessful shock

In the presence of an unsuccessful shock, all potential scenarios must be considered. The ICD system should be verified, including the battery, lead integrity, and high-voltage (HV) coils. SVT must be ruled out. The vector is suboptimal for SVT such that it is not uncommon for shocks to fail in this setting. In interpreting a single isolated unsuccessful shock, one should bear in mind the probabilistic nature of defibrillation. However, in the presence

Table 10.4 Multiple ICD shocks

Cause	*Management options*
Phantom shock	Reassure patient Begin ACLS measures, sedation
Ventricular tachycardia (VT) storm	Treat ischemia or other precipitating factors such as heart failure Judicious use of a magnet or inactivation of ICD therapy Pharmacological therapy for VT (e.g. β-blockers, amiodarone); possible catheter ablation Intra-aortic balloon pump or hemodynamic support for hypotension Replace electrolytes (K^+, Mg^{2+}) All patients should receive β-blockers as tolerated Left stellate ganglionic blockade in selected patients Identify specific diseases that may need specific therapy (e.g. recurrent VT in Brugada syndrome may respond to isoproterenol and quinidine)
Supraventricular tachycardia (SVT)	• Treat SVT (pharmacological therapy or ablation) • Program higher cut-off rates and/or discriminators if feasible
Lead failure	• Turn off detection and admit patient for lead replacement
Loose connection	• Reoperate
T wave oversensing	• Reprogram if possible • Reposition lead • Force pacing if T wave oversensing not present during pacing and patient not a candidate for lead repositioning
Diaphragmatic myopotential	• Change sensitivity and retest for sensing during VF • Reposition lead
P wave oversensing	• May be difficult to program around since usually in integrated lead near tricuspid annulus or as a result of lead dislodgement • Reoperate
R wave oversensing	• Decrease sensitivity and retest for sensing during VF • Adjust blanking period if programmable • Reposition lead
Electromagnetic interference (EMI)	• Identify source of EMI • Avoid source of EMI

VF, ventricular fibrillation.

of multiple unsuccessful maximum output shocks, the substrate should be re-evaluated (e.g. ischemia/scar, progressive heart failure) and changes in drug therapy should be considered (e.g. amiodarone, sodium channels blockers). The DFT can then be (re)assessed in the electrophysiology laboratory. In the event of a high threshold, options include modifying the shock waveform (e.g. polarity, waveform duration, or tilt) and testing other shock vectors (including or excluding the superior vena cava coil or "can"). A suboptimal DFT can occur in the setting of an active "can" that has migrated inferiorly, thereby altering the shock vector. Additional options include lead repositioning, changing to a high output generator, adding HV coils (e.g. superior vena cava, coronary sinus, azygous vein, subcutaneous array), or the use of drugs (e.g. dofetilide, sotalol) to help decrease the DFT.

Failure to detect or treat sustained VT

In a functioning ICD system, the most common cause of absence of "appropriate" VT therapy is VT slower than the lower programmed rate cut-off. This may occur in patients with high programmed cut-off rates or, more commonly, when VT is slowed by antiarrhythmic drug therapy. In patients with symptoms suggestive of an arrhythmic event despite unremarkable device interrogation, a monitoring zone may detect slow VT. Another potential cause of failure to detect or treat sustained VT is tachycardia detection inactivation. Inadvertent failure to reprogram therapies may occur after a

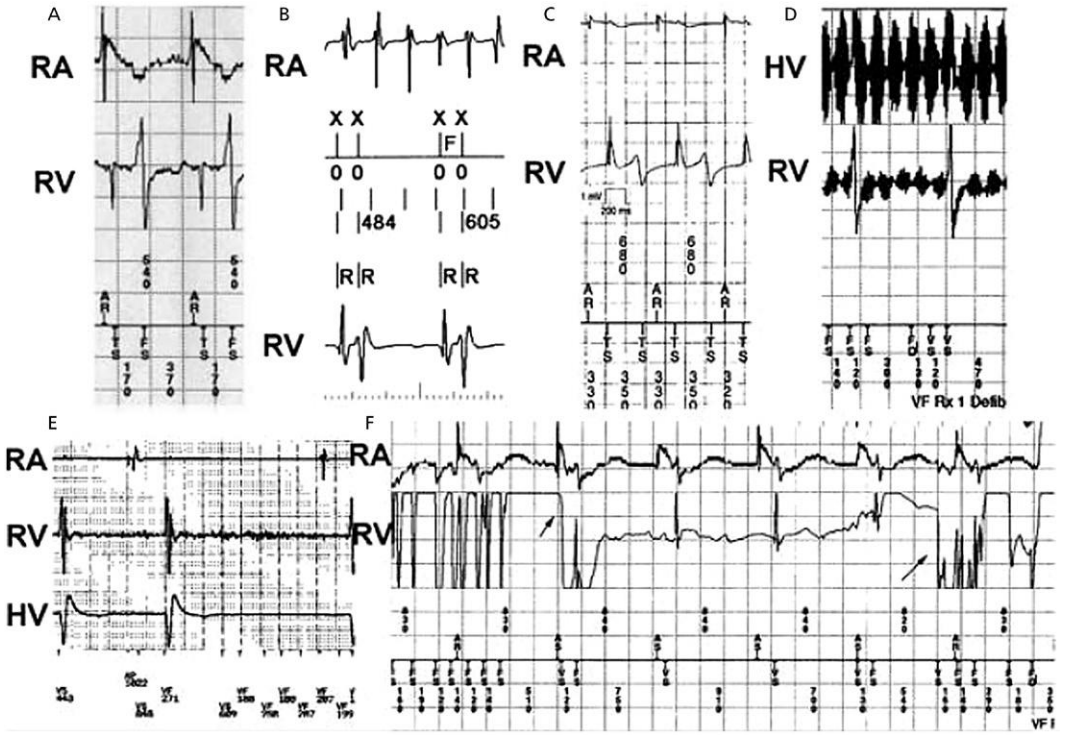


Figure 10.21 Types of oversensing resulting in appropriate detection of ventricular tachycardia and fibrillation. (A–C) Oversensing of physiological, intracardiac signals. (D–F) Oversensing of extracardiac signals. (A) P wave oversensing in sinus rhythm from integrated bipolar lead with distal coil near the tricuspid valve. (B) R wave double counting during conducted atrial fibrillation in a biventricular-sensing ICD. (C) T wave oversensing in a patient with a low-amplitude R wave (note mV calibration marker). (D) Electromagnetic interference from a power drill has higher amplitude on a widely spaced high-voltage electrogram than on a closely spaced true bipolar sensing electrogram. (E) Diaphragmatic myopotential oversensing in a patient with an integrated bipolar lead at the right ventricular apex. Note that the noise level is constant, but oversensing does not occur until automatic gain control increases the gain sufficiently, about 600 ms after the sensed R waves. (F) Lead fracture noise results in intermittent saturation of amplifier range denoted by arrow. RA, right atrium; RV, right ventricular sensing electrogram; HV, high-voltage electrogram. (Source: Swerdlow CD, Friedman PA 2005.[63] Reproduced with permission of John Wiley & Sons Ltd.)

surgical intervention. Some older ICD models may also be subject to electrical reset that consists of reversion to a back-up mode with inactive tachycardia therapy functions. Lead dysfunction (especially of the HV coil) can also result in the failure to deliver a shock. Moreover, sensing issues can compromise VT/VF detection. Undersensing can occur in the presence of small VF waves. With second pacing devices (e.g. epicardial pacemaker in a post-cardiac surgery patient), the ICD may interpret pacing stimuli as a normal rhythm leading to underdetection of VT/VF. SVT discriminators can also falsely inhibit VT detection.

Less frequently, pacing algorithms may result in VT underdetection.[64,65] This has been reported with rate smoothing, which reduces the maximum variation in cycle length by a programmable value.[66] Rate smoothing is available in Guidant/Boston Scientific, Medtronic, and Sorin devices, but not St. Jude Medical or Biotronik devices. By minimizing short–long–short intervals, rate smoothing was developed to reduce the ventricular arrhythmia burden. Underdetection of VT may occur due to the ventricular blanking period that follows atrial pacing provoked by the algorithm.[67] Although initially thought to be

predominantly mediated by aggressive programming of rate smoothing (e.g. 12%), the potential for underdetection was later shown to be unpredictable. Since more recent data show no benefit from rate smoothing in a heterogeneous population of ICD recipients, its routine use does not appear to be justified. It may be considered in patients with long-QT syndrome or demonstrated VT triggered by short–long–short sequences. If programmed, a value of 12% or greater is recommended.[22]

Finally, ventricular undersensing may rarely occur as a result of auto-adjusting sensitivity features and decay delay.[68] In St. Jude Medical's sensing algorithm, the peak amplitude of a ventricular signal serves to establish the "threshold start" value, which is used to define sensitivity at the onset of the following cardiac cycle. This value remains fixed for a programmable amount of time, termed the "decay delay," after which it declines linearly. Sensitivity decays at a rate of 1 mV every 312 ms until it reaches the maximum threshold value or senses the next signal. The higher the "threshold start" value and the longer the decay delay, the less sensitive the settings. Patients with polymorphic VT, such as torsades de pointes, can have highly variable "threshold start" values that may undulate in an erratic or patterned fashion. Undersensing may occur when higher amplitude signals, i.e. those that generate higher "threshold start" values, are followed by lower amplitude signals, particularly with longer decay delays (Figure 10.22).

Device pro-arrhythmia

ATP may accelerate or decelerate VT, or induce SVT or VT if inappropriately delivered. Shocks for VT or SVT, particularly low energy shocks, can

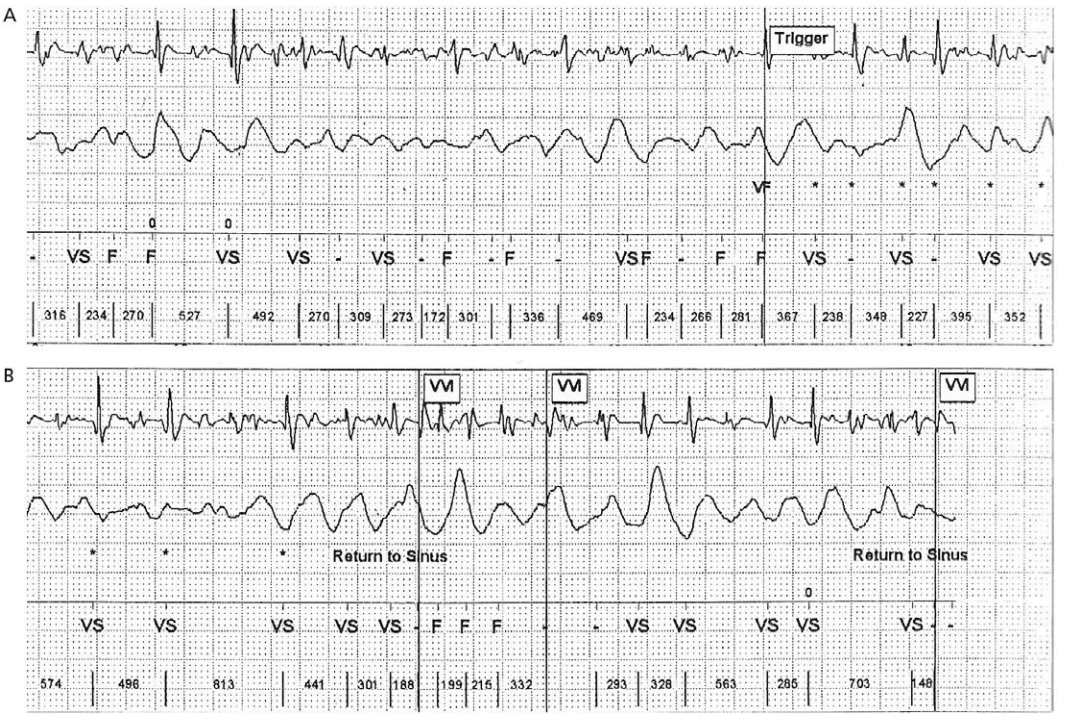


Figure 10.22 (A) Ventricular fibrillation (VF) triggered and (B) followed by return to sinus. (A,B) From top to bottom, intracardiac ventricular electrogram (EGM) recordings, far-field EGMs (ICD can-to-right ventricular coil), and telemetered marker channels. (A) Polymorphic ventricular tachycardia is noted with a variable amplitude and cycle length. The term "trigger" marks the recognition of VF. (B) Subsequently, due to ventricular undersensing, the ICD considers the arrhythmia to have reverted back to sinus rhythm. No shock is delivered. VS denotes a ventricular-sensed event. (Source: Michaud J *et al*. 2009.[68] Reproduced with permission of Elsevier.)

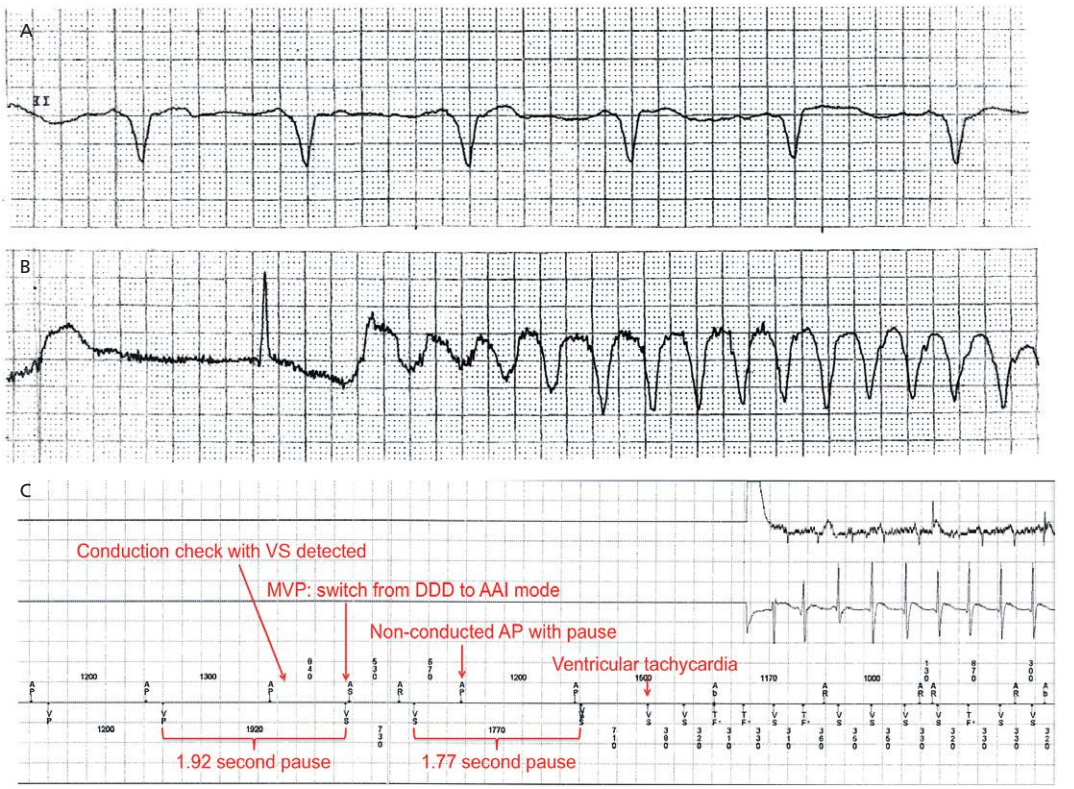


Figure 10.23 Electrical storm due to managed ventricular pacing. (A) Patient's underlying atrial and ventricular paced rhythm (lead II) at the lower programmed rate limit of 50 bpm. (B) A >1.9-s pause is terminated by a ventricular escape beat with a seemingly long-QT interval (albeit recorded on only one lead), followed by the onset of ventricular tachycardia at approximately 170 bpm. (C) Top to bottom, intracardiac atrial electrograms (EGMs), ventricular EGMs, and telemetered marker channels. The ICD initially functions in a DDD mode, with atrial (AP) and ventricular (VP) pacing. In accordance with the managed ventricular pacing (MVP) algorithm, verification for intrinsic atrioventricular conduction occurs after the third paced atrial beat. A 1.92-s pause is terminated by a ventricular escape beat (VS). Since a ventricular beat is detected between the two consecutive atrial events, the ICD reverts to an AAI pacing mode. The first atrial-paced beat is non-conducted, resulting in an additional 1.77-s ventricular pause, followed by the onset of ventricular tachycardia. (Source: Mansour F, Khairy P 2012.[69] Reproduced with permission of Elsevier.)

induce VF. When multiple consecutive events are recorded, an analysis of the first episode is critical, since subsequent ATP and shocks can cloud the initial event. Post-shock bradycardia (e.g. oversensing due to double counting of T waves, increased thresholds) has been described, but is infrequent. Algorithms aimed at minimizing pacing may occasionally result in lengthy pauses with ventricular pro-arrhythmic effects via short–long–short sequences. Without ICD back-up, potentially fatal episodes may occur (Figure 10.23).[69] Pro-arrhythmia associated with epicardial LV pacing has also been described, prompting deactivation of the LV lead.[70]

Conclusion

ICD programming options, governing algorithms, and potential therapies have evolved considerably over the past decade, with important repercussions regarding follow-up and troubleshooting. The single lead one zone "shock box" approach that

initially prevailed has been progressively replaced by tailored programming. Optimization of device settings and effective troubleshooting require an appreciation for the various components of the ICD, their potential limitations and interactions, and the sophisticated rules and algorithms that determine signal recognition and interpretation, and guide therapeutic responses. While, in general, ICDs do what they are told to do, this may be at odds with what the programmer has in mind. Risks and benefits of programming schemes should be subject to rigorous analyses. In order to fully understand ICD responses and troubleshoot accordingly, the electrophysiologist is challenged to keep pace with novel and emerging algorithms and options. While an in-depth understanding of ICD functions is critical, effective troubleshooting should extend beyond what the ICD may see and incorporate all relevant external information, such as changes to pharmacological therapy, sources of device interference, triggers for events, and underlying substrates. As Sydney J. Harris once said, "The real danger is not that computers will begin to think like men, but that men will begin to think like computers."

Acknowledgments

The authors wish to thank Claude Provencal (Medtronic, Inc.), Pierre Veilleux and Jennifer Rhude (St. Jude Medical, Inc.), Eric Lavallée (Boston Scientific Corporation), Pascale Ferland (Biotronik Canada, Inc.), and Rémi Nitzsché (Sorin Group, Inc.) for their expert technical assistance.

References

1 Wilkoff BL, Auricchio A, Brugada J, *et al*. HRS/EHRA expert consensus on the monitoring of cardiovascular implantable electronic devices (CIEDS): Description of techniques, indications, personnel, frequency and ethical considerations. *Heart Rhythm* 2008; 5: 907–925.

2 Epstein AE, Baessler CA, Curtis AB, *et al*. Addendum to "personal and public safety issues related to arrhythmias that may affect consciousness: Implications for regulation and physician recommendations: A medical/scientific statement from the American Heart Association and the North American Society of Pacing and Electrophysiology": Public safety issues in patients with implantable defibrillators: A scientific statement from the American Heart Association and the Heart Rhythm Society. *Circulation* 2007; 115: 1170–1176.

3 Gillis AM, Philippon F, Cassidy MR, *et al*. Guidelines for implantable cardioverter defibrillator follow-up in Canada: A consensus statement of the Canadian Working Group on Cardiac Pacing. *Can J Cardiol* 2003; 19: 21–37.

4 Vijgen J, Botto G, Camm J, Hoijer CJ, *et al*. Consensus statement of the European Heart Rhythm Association: Updated recommendations for driving by patients with implantable cardioverter defibrillators. *Europace* 2009; 11: 1097–1107.

5 Healey JS, Connolly SJ, Gold MR, *et al*. Subclinical atrial fibrillation and the risk of stroke. *N Engl J Med* 2012; 366: 120–129.

6 Glotzer TV, Daoud EG, Wyse DG, *et al*. The relationship between daily atrial tachyarrhythmia burden from implantable device diagnostics and stroke risk: The trends study. *Circ Arrhythm Electrophysiol* 2009; 2: 474–480.

7 Fischer A, Ousdigian KT, Johnson JW, Gillberg JM, Wilkoff BL. The impact of atrial fibrillation with rapid ventricular rates and device programming on shocks in 106,513 ICD and CRT-D patients. *Heart Rhythm* 2012; 9: 24–31.

8 Swerdlow CD, Gunderson BD, Ousdigian KT, *et al*. Downloadable algorithm to reduce inappropriate shocks caused by fractures of implantable cardioverter–defibrillator leads. *Circulation* 2008; 118: 2122–2129.

9 Schoenfeld MH. Contemporary pacemaker and defibrillator device therapy: Challenges confronting the general cardiologist. *Circulation* 2007; 115: 638–653.

10 Blanck Z, Axtell K, Brodhagen K, *et al*. Inappropriate shocks in patients with Fidelis(r) lead fractures: Impact of remote monitoring and the lead integrity algorithm. *J Cardiovasc Electrophysiol* 2011; 22: 1107–1114.

11 Mansour F, Khairy P. ICD monitoring zones: Intricacies, pitfalls, and programming tips. *J Cardiovasc Electrophysiol* 2008; 19: 568–574.

12 Weretka S, Michaelsen J, Becker R, *et al*. Ventricular oversensing: A study of 101 patients implanted with dual chamber defibrillators and two different lead systems. *Pacing Clin Electrophysiol* 2003; 26: 65–70.

13 Powell B, Cha Y-M, Asirvatham S, *et al*. Noise and oversensing-related inappropriate ICD shocks diagnosed with remote monitoring: The Altitude EGM Study. *Heart Rhythm* 2010; 7: S7.

14 Cao J, Gillberg JM, Swerdlow CD. A fully automatic, implantable cardioverter-defibrillator algorithm to prevent inappropriate detection of ventricular tachycardia or fibrillation due to T-wave oversensing in spontaneous rhythm. *Heart Rhythm* 2012; 9: 522–530.

15 Crossley GH, Boyle A, Vitense H, Chang Y, Mead RH. The CONNECT (Clinical Evaluation of Remote

Notification to Reduce Time to Clinical Decision) trial: The value of wireless remote monitoring with automatic clinician alerts. *J Am Coll Cardiol* 2011; 57: 1181–1189.

16 de Cock CC, Elders J, van Hemel NM, *et al*. Remote monitoring and follow-up of cardiovascular implantable electronic devices in the Netherlands : An expert consensus report of the Netherlands Society of Cardiology. *Neth Heart J* 2012; 20: 53–65.

17 Guedon-Moreau L, Chevalier P, Marquie C, *et al*. Contributions of remote monitoring to the follow-up of implantable cardioverter-defibrillator leads under advisory. *Eur Heart J* 2010; 31: 2246–2252.

18 Kaszala K, Ellenbogen KA. In search of the shocking truth. *Heart Rhythm* 2012; 9: 1236–1238.

19 Wilkoff BL, Cook JR, Epstein AE, *et al*. Dual-chamber pacing or ventricular backup pacing in patients with an implantable defibrillator: The Dual Chamber and VVI Implantable Defibrillator (DAVID) trial. *JAMA* 2002; 288: 3115–3123.

20 Mansour F, Talajic M, Thibault B, Khairy P. Pacemaker troubleshooting: When mvp is not the most valuable parameter. *Heart Rhythm* 2006; 3: 612–614.

21 Sweeney MO, Ellenbogen KA, Tang AS, *et al*. Atrial pacing or ventricular backup-only pacing in implantable cardioverter–defibrillator patients. *Heart Rhythm* 2010; 7: 1552–1560.

22 Mansour F, Khairy P. Programming ICDs in the modern era beyond out-of-the box settings. *Pacing Clin Electrophysiol* 2011; 34: 506–520.

23 Moss AJ, Schuger C, Beck CA, *et al*. Reduction in inappropriate therapy and mortality through ICD programming. *N Engl J Med* 2012; 367: 2275–2283.

24 Wilkoff BL, Hess M, Young J, Abraham WT. Differences in tachyarrhythmia detection and implantable cardioverter defibrillator therapy by primary or secondary prevention indication in cardiac resynchronization therapy patients. *J Cardiovasc Electrophysiol* 2004; 15: 1002–1009.

25 Wilkoff BL, Williamson BD, Stern RS, *et al*. Strategic programming of detection and therapy parameters in implantable cardioverter–defibrillators reduces shocks in primary prevention patients: Results from the prepare (primary prevention parameters evaluation) study. *J Am Coll Cardiol* 2008; 52: 541–550.

26 Clementy N, Pierre B, Lallemand B, *et al*. Long-term follow-up on high-rate cut-off programming for implantable cardioverter defibrillators in primary prevention patients with left ventricular systolic dysfunction. *Europace* 2012; 14: 968–974.

27 Wilkoff BL, Ousdigian KT, Sterns LD, Wang ZJ, Wilson RD, Morgan JM. A comparison of empiric to physician-tailored programming of implantable cardioverter-defibrillators: Results from the prospective randomized multicenter empiric trial. *J Am Coll Cardiol* 2006; 48: 330–339.

28 Bansch D, Castrucci M, Bocker D, Breithardt G, Block M. Ventricular tachycardias above the initially programmed tachycardia detection interval in patients with implantable cardioverter-defibrillators: Incidence, prediction and significance. *J Am Coll Cardiol* 2000; 36: 557–565.

29 Mansour F, Thibault B, Dubuc M, *et al*. Shocking truths about implantable cardioverter defibrillator monitoring zones. *Pacing Clin Electrophysiol* 2007; 30: 1146–1148.

30 Khairy P, Mansour F. Counting down before blasting off. *Heart Rhythm* 2011; 8: e2–4.

31 Wathen MS, DeGroot PJ, Sweeney MO, *et al*. Prospective randomized multicenter trial of empirical antitachycardia pacing versus shocks for spontaneous rapid ventricular tachycardia in patients with implantable cardioverter-defibrillators: Pacing fast ventricular tachycardia reduces shock therapies (painfree rx ii) trial results. *Circulation* 2004; 110: 2591–2596.

32 Saeed M, Razavi M, Neason CG, Petrutiu S. Rationale and design for programming implantable cardioverter-defibrillators in patients with primary prevention indication to prolong time to first shock (PROVIDE) study. *Europace* 2011; 13: 1648–1652.

33 Boriani G, Occhetta E, Pistis G, *et al*. Combined use of morphology discrimination, sudden onset, and stability as discriminating algorithms in single chamber cardioverter defibrillators. *Pacing Clin Electrophysiol* 2002; 25: 1357–1366.

34 Glikson M, Swerdlow CD, Gurevitz OT, *et al*. Optimal combination of discriminators for differentiating ventricular from supraventricular tachycardia by dual-chamber defibrillators. *J Cardiovasc Electrophysiol* 2005; 16: 732–739.

35 Saeed M, Neason CG, Razavi M, *et al*. Programming antitachycardia pacing for primary prevention in patients with implantable cardioverter defibrillators: Results from the PROVE trial. *J Cardiovasc Electrophysiol* 2010; 21: 1349–1354.

36 Auricchio A, Meijer A, Kurita T, *et al*. Safety, efficacy, and performance of new discrimination algorithms to reduce inappropriate and unnecessary shocks: The painfree SST clinical study design. *Europace* 2011; 13: 1484–1493.

37 Dorian P, Philippon F, Thibault B, *et al*. Randomized controlled study of detection enhancements versus rate-only detection to prevent inappropriate therapy in a dual-chamber implantable cardioverter–defibrillator. *Heart Rhythm* 2004; 1: 540–547.

38 Klein GJ, Gillberg JM, Tang A, *et al*. Improving SVT discrimination in single-chamber ICDs: A new electrogram morphology-based algorithm. *J Cardiovasc Electrophysiol* 2006; 17: 1310–1319.

39 Toquero J, Alzueta J, Mont L, *et al*. Morphology discrimination criterion wavelet improves rhythm discrimination in single-chamber implantable cardioverter–defibrillators: Spanish Register of Morphology Discrimination Criterion Wavelet (REMEDIO). *Europace* 2009; 11: 727–733.

40 Theuns DA, Rivero-Ayerza M, Boersma E, Jordaens L. Prevention of inappropriate therapy in implantable defibrillators: A meta-analysis of clinical trials comparing single-chamber and dual-chamber arrhythmia discrimination algorithms. *Int J Cardiol* 2008; 125: 352–357.

41 Sticherling C, Zabel M, Spencker S, *et al*. Comparison of a novel, single-lead atrial sensing system with a dual-chamber implantable cardioverter–defibrillator system in patients without antibradycardia pacing indications: Results of a randomized study. *Circ Arrhythm Electrophysiol* 2011; 4: 56–63.

42 Wathen MS, Sweeney MO, DeGroot PJ, *et al*. Shock reduction using antitachycardia pacing for spontaneous rapid ventricular tachycardia in patients with coronary artery disease. *Circulation* 2001; 104: 796–801.

43 Martins RP, Blangy H, Muresan L, *et al*. Safety and efficacy of programming a high number of antitachycardia pacing attempts for fast ventricular tachycardia: A prospective study. *Europace* 2012; 14: 1457–1464.

44 Sivagangabalan G, Eshoo S, Eipper VE, Thiagalingam A, Kovoor P. Discriminatory therapy for very fast ventricular tachycardia in patients with implantable cardioverter defibrillators. *Pacing Clin Electrophysiol* 2008; 31: 1095–1099.

45 Gulizia MM, Piraino L, Scherillo M, *et al*. A randomized study to compare ramp versus burst antitachycardia pacing therapies to treat fast ventricular tachyarrhythmias in patients with implantable cardioverter defibrillators: The PITAGORA ICD trial. *Circ Arrhythm Electrophysiol* 2009; 2: 146–153.

46 Santini M, Lunati M, Defaye P, *et al*. Prospective multicenter randomized trial of fast ventricular tachycardia termination by prolonged versus conventional antitachyarrhythmia burst pacing in implantable cardioverter-defibrillator patients – ATP Delivery for Painless ICD Therapy (ADVANCE-D) trial results. *J Interv Card Electrophysiol* 2010; 27: 127–135.

47 Fries R, Heisel A, Kalweit G, Jung J, Schieffer H. Antitachycardia pacing in patients with implantable cardioverter defibrillators: How many attempts are useful? *Pacing Clin Electrophysiol* 1997; 20: 198–202.

48 Gasparini M, Anselme F, Clementy J, *et al*. Biventricular versus right ventricular antitachycardia pacing to terminate ventricular tachyarrhythmias in patients receiving cardiac resynchronization therapy: The ADVANCE CRT-D trial. *Am Heart J* 2010; 159: 1116–1123 e1112.

49 Ridley DP, Gula LJ, Krahn AD, *et al*. Atrial response to ventricular antitachycardia pacing discriminates mechanism of 1:1 atrioventricular tachycardia. *J Cardiovasc Electrophysiol* 2005; 16: 601–605.

50 Brooks L, Zhang Y, Dendi R, Anderson RH, Zimmerman B, Kerber RE. Selecting the transthoracic defibrillation shock directional vector based on vf amplitude improves shock success. *J Cardiovasc Electrophysiol* 2009; 20: 1032–1038.

51 Jaarsma T, Beattie JM, Ryder M, *et al*. Palliative care in heart failure: A position statement from the Palliative Care Workshop of the Heart Failure Association of the European Society of Cardiology. *Eur J Heart Fail* 2009; 11: 433–443.

52 Lampert R, Hayes DL, Annas GJ, *et al*. HRS expert consensus statement on the management of cardiovascular implantable electronic devices (CIEDs) in patients nearing end of life or requesting withdrawal of therapy. *Heart Rhythm* 2010; 7: 1008–1026.

53 Kirkpatrick JN, Gottlieb M, Sehgal P, Patel R, Verdino RJ. Deactivation of implantable cardioverter defibrillators in terminal illness and end of life care. *Am J Cardiol* 2012; 109: 91–94.

54 Dyrda K, Khairy P. Implantable rhythm devices and electromagnetic interference: Myth or reality? *Expert Rev Cardiovasc Ther.* 2008;6:823–832

55 Kolb C, Schmieder S, Lehmann G, *et al*. Do airport metal detectors interfere with implantable pacemakers or cardioverter–defibrillators? *J Am Coll Cardiol* 2003; 41: 2054–2059.

56 Tandogan I, Temizhan A, Yetkin E, *et al*. The effects of mobile phones on pacemaker function. *Int J Cardiol* 2005; 103: 51–58.

57 Nazarian S, Roguin A, Zviman MM, *et al*. Clinical utility and safety of a protocol for noncardiac and cardiac magnetic resonance imaging of patients with permanent pacemakers and implantable–cardioverter defibrillators at 1.5 Tesla. *Circulation* 2006; 114: 1277–1284.

58 Roedig JJ, Shah J, Elayi CS, Miller CS. Interference of cardiac pacemaker and implantable cardioverter–defibrillator activity during electronic dental device use. *J Am Dent Assoc* 2010; 141: 521–526.

59 Crossley GH, Poole JE, Rozner MA, *et al*. The Heart Rhythm Society (HRS)/American Society of Anesthesiologists (ASA) expert consensus statement on the perioperative management of patients with implantable defibrillators, pacemakers and arrhythmia monitors: Facilities and patient management. This document was developed as a joint project with the American Society of Anesthesiologists (ASA), and in collaboration with the American Heart Association (AHA), and the Society of Thoracic Surgeons (STS). *Heart Rhythm* 2011; 8: 1114–1154.

60 Ladouceur VB, Khairy P, Beland MJ, Bhanji F. "Magnetic attraction" in the pediatric emergency department: The case of a malfunctioning implantable cardioverter–defibrillator. *Pediatr Emerg Care* 2012; 28: 562–565.
61 Diemberger I, Martignani C, Biffi M, *et al*. Arrhythmia discrimination by physician and defibrillator: Importance of atrial channel. *Int J Cardiol* 2012; 154: 134–140.
62 Mansour F, Guash E, Berruezo A, Brugada J, Tolosana JM, Mont L. Inappropriate shocks or inappropriate programming? A review of guidant's reconfirmation algorithm. *Europace* 2009; 11: 1120–1122.
63 Swerdlow CD, Friedman PA. Advanced ICD troubleshooting: Part I. *Pacing Clin Electrophysiol.* 2005; 28: 1322–1346.
64 Anderson KP. Sudden cardiac death unresponsive to implantable defibrillator therapy: An urgent target for clinicians, industry and government. *J Interv Card Electrophysiol* 2005; 14: 71–78.
65 Lehmann MH, Thomas A, Nabih M, *et al*. Sudden death in recipients of first-generation implantable cardioverter defibrillators: Analysis of terminal events. Participating investigators. *J Interv Cardiol* 1994; 7: 487–503.
66 Glikson M, Beeman AL, Luria DM, Hayes DL, Friedman PA. Impaired detection of ventricular tachyarrhythmias by a rate-smoothing algorithm in dual-chamber implantable defibrillators: Intradevice interactions. *J Cardiovasc Electrophysiol* 2002; 13: 312–318.
67 Cooper JM, Sauer WH, Verdino RJ. Absent ventricular tachycardia detection in a biventricular implantable cardioverter–defibrillator due to intradevice interaction with a rate smoothing pacing algorithm. *Heart Rhythm* 2004; 1: 728–731.
68 Michaud J, Horduna I, Dubuc M, Khairy P. ICD-unresponsive ventricular arrhythmias. *Heart Rhythm* 2009; 6: 1827–1829.
69 Mansour F, Khairy P. Electrical storm due to managed ventricular pacing. *Heart Rhythm* 2012; 9: 842–843.
70 Nayak HM, Verdino RJ, Russo AM, *et al*. Ventricular tachycardia storm after initiation of biventricular pacing: Incidence, clinical characteristics, management, and outcome. *J Cardiovasc Electrophysiol* 2008; 19: 708–715.

11 CHAPTER 11

Follow-up of the patient with a CIED

Harish Doppalapudi,[1] *Mark L. Blitzer,*[2] *and Mark H. Schoenfeld*[2]

[1] University of Alabama at Birmingham, Birmingham, AL, USA
[2] Yale University School of Medicine, Yale-New Haven Hospital, New Haven, CT, USA

Introduction

Cardiovascular implantable electronic devices (CIEDs) include cardiac pacemakers, implantable cardioverter–defibrillators (ICDs), implantable cardiovascular monitors, and implantable loop recorders (ILRs). This chapter outlines the general principles of the follow-up of CIEDs, with a specific focus on pacemakers and ICDs. Various sources of electromagnetic interference (EMI) encountered by the CIED patient in the medical and non-medical environments are briefly reviewed, along with suggestions to mitigate the adverse effects from these interactions. The management of CIEDs in other special situations, such as in the perioperative period, and in patients nearing end of life or requesting withdrawal of therapy, is also summarized. Finally, there is a brief discussion on device advisories and their management.

Goals of CIED follow-up assessment

The follow-up evaluation of a patient with a CIED begins in the immediate post-implantation period and extends throughout the patient's life, rather than throughout the life of the device system *per se*. The original indications for device insertion require periodic review, and new indications for modification of the existing system also warrant continuing evaluation. The device physician needs to assess those symptoms not satisfactorily treated by the device as well as those symptoms potentially caused by the device. Systematic record keeping is an important part of this process, particularly in following end-of-life parameters and in tracking patients whose systems may be subject to product recall or failure.

It remains a challenge to optimize the functioning and longevity of a device system in the face of constantly changing patient needs, whether those changes are in lifestyle, medical circumstances, cardiac function, or electrophysiological milieu. The issue of who should perform device follow-up evaluations remains an ongoing debate—what is clear is that the relevant skills must be continuously and finely maintained.[1] This chapter explores these issues and examines the methodology of device follow-up evaluation.[2,3]

Immediate post-implantation period

Following implantation of a new pacemaker or ICD system, the patient is generally observed on a

Cardiac Pacing and ICDs, Sixth Edition. Edited by Kenneth A. Ellenbogen and Karoly Kaszala.
© 2014 John Wiley & Sons, Ltd. Published 2014 by John Wiley & Sons, Ltd.

cardiac monitor for 24 h. Generator replacements are performed on an ambulatory basis. The Heart Rhythm Society (HRS) is developing guidelines for clinical scenarios in which less than 24-h monitoring for primary implants may be considered without inpatient admission (i.e. observational status).

Prophylaxis with a parenterally administered antibiotic that has *in-vitro* activity against staphylococci is recommended before the procedure (IV cefazolin within 1 h or IV vancomycin within 2 h, before skin incision).[4] A portable chest radiograph may be obtained immediately following implantation to exclude a pneumothorax. Posteroanterior (PA) and lateral chest radiographs are obtained within 24 h to confirm satisfactory positioning of the pacing and/or ICD lead(s) and to serve as a baseline for subsequent comparisons. A twelve-lead electrocardiogram (ECG), ideally with pacing, is obtained before discharge.

Most essential in the immediate post-implantation period is education of the patient. The importance of always carrying a device identification card must be stressed. Medical alert bracelets are often recommended as well. The patient is asked to refrain from vigorous activity involving the ipsilateral arm for a period of approximately 4 weeks to minimize the possibility of lead dislodgement and minimize undue stress on the incision. The patient should also keep the incision completely dry for 5–7 days to minimize the chance of infection. Precautions to minimize interference from various household, industrial, and medical sources of electromagnetic energy should be discussed; equally important, the patient should be reassured regarding use of common household appliances such as microwave ovens. Temporary driving restrictions (usually for 6 months) may be appropriate for patients presenting with syncope or those undergoing ICD implantation for secondary prophylaxis until the follow-up assessment confirms that the device is functioning normally; otherwise driving may be resumed in 1–2 weeks. Plans are made for outpatient wound evaluation and suture or staple removal if needed, generally to occur within 2–4 weeks. Patients are asked to be attentive to any signs of fever or infection, such as pain, redness, swelling, or drainage at the incision site.

The follow-up clinic and record keeping

The personnel necessary for the device follow-up assessment include a supervising physician, a device nurse or technician, and clerical staff for record keeping and outpatient scheduling. Personnel directly involved in device follow-up evaluation must be thoroughly familiar with all aspects of device function. The site of the device follow-up evaluation should allow history taking and patient examination, and should be fully equipped to allow for analysis of device function (Table 11.1). This includes capabilities for 12-lead ECG (with and without a magnet), radiography (and fluoroscopy, if possible), trans-telephonic and ambulatory ECG monitoring, and availability of the programmer's and physician's manual for every model of device encountered. The telephone numbers for technical

Table 11.1 Essential components of a device clinic

Clinic personnel	Device physician Device nurse or technician Clerical staff
Device and patient data	Patient's name, age, identification, address, phone number Pulse generator data: model, serial number Lead(s): model, serial number Operative note from implant with implant data Complete follow-up records Telephone numbers for device technical support
Equipment	Examination room Pacemaker or ICD programmers Magnet Physician manuals for each model device followed ECG machine External defibrillator and transcutaneous pacemaker Code cart
Ancillary requirements	X-ray and fluoroscopy Tilt table Blood chemistry laboratory Holter/event monitoring

support of all device manufacturers should be available. Depending on the number of different device models employed by the clinic, extensive familiarity with a wide variety of programming devices may be necessary because of the lack of universal programming.[5] A resuscitation cart, defibrillator, and transcutaneous pacemaker should be immediately available. The clinic staff should be capable of performing advanced cardiac life support.

Record keeping is an indispensable component of a device clinic. Its purpose is to record accurately such patient demographics as name and address, to identify specifics of the device system used (model and serial numbers, implant values), to track patient symptoms and various parameters of pacemaker or ICD function (e.g. sensing and pacing thresholds, identified changes in magnet rate), and to update any changes in programmed parameters. Such records may be computer stored and allow for the generation of comprehensive updated reports. Record keeping also allows for organization and maintenance of strict schedules for patient follow-up assessments. This promotes identification of potential problems with device function well before they are actualized, rather than having patients drop in only after the problem has manifested.

The establishment of a federal pacemaker registry was mandated by Medicare guidelines, wherein specifics of pacemaker data, such as patient demographics and model and serial numbers, are reported at the time of implantation. The National Cardiovascular Data Registry (NCDR) has been mandated by the Centers for Medicare and Medicaid Services (CMS) to collect data on all ICD generators and lead implants. Such registries, coupled with manufacturer-generated patient lists and accurate record keeping by the device physician, should facilitate contacting patients if a systematic problem with a particular type of device system is identified or if a product advisory/recall is issued. If the physician has observed a problem, such as premature battery depletion, the manufacturer can then be consulted to determine whether others may have made similar observations.

Independent of a formal recall, it is the responsibility of the device physician to decide whether corrective measures are warranted in a particular case. If a recall or advisory on a particular device product has been issued, the nature of the potential malfunction should determine the timing of the device system revision, if required at all. If the reported component failure is random and unpredictable, then replacement should be undertaken more rapidly, especially in those patients who are deemed "pacemaker dependent" [see "Pacemaker dependence" and "Device advisories (alerts and recalls)"]. Unfortunately, as of this writing, there is no manufacturer-independent, large-scale national device/lead database that allows physicians and their patients to be notified in a timely fashion of pacemaker system malfunctions.[6] Thus, the device physician must be ever vigilant as to trends of potential device malfunction in their practice as well as to reports from others, whether via other physician's or manufacturers' notifications.

The outpatient visit

Even a routine pacemaker or ICD follow-up visit is a labor-intensive encounter with much to be accomplished in a timely manner, including a brief history, examination, device evaluation, troubleshooting, reprogramming, and record keeping. By keeping the goals of the visit in focus and maintaining an orderly approach to follow-up, the process can be made efficient (Table 11.2).

The first visit, approximately 2–4 weeks subsequent to implantation, is primarily directed toward evaluation of the healing wound. This is particularly important in patients with diabetes, chronic renal insufficiency, impaired cardiac perfusion due to depressed ejection fraction, or smokers, all of

Table 11.2 Elements of the outpatient visit

History
Physical examination
Chest X-ray and fluoroscopy
Electrocardiography
Magnet application
Device interrogation
Communication with other physicians as needed (e.g. heart failure specialist, radiation therapist, surgeon for preoperative assessment)

whom are prone to slower healing, as well as in patients requiring anticoagulation (warfarin, dabigatran, rivaroxaban, etc.) or antiplatelet agents (aspirin, clopidogrel, prasugrel, etc.), in whom pocket hematomas can prove catastrophic. Symptoms are reviewed as at any visit. Chest radiographs (PA and lateral) and ECGs with and without pacing can be repeated at this time. Most problems arising within 2 weeks of implantation relate to either lead dislodgement, exit block, or healing of the incision or pocket. Arrangements for transtelephonic or other type of remote monitoring are made, as well as for the 3-month check-up. At that point, the inflammation associated with the tissue–electrode interface has generally resolved, allowing for assessment of chronic pacing and sensing thresholds. Subsequent visits should focus on device maintenance, optimization of function, and evaluation of patient complaints. After the 3-month check-up, patients are generally seen once or twice yearly, or as otherwise dictated by their clinical needs. With increasing reliability and automaticity built into modern pacemakers, and with the availability of reliable remote monitoring systems, less frequent in-office checks have become more feasible. Guidelines for the frequency of in-person and remote follow-up of CIEDs are discussed later.

History

The elicitation and evaluation of symptomatology require careful sleuthing on the part of the device physician. Perceptions of pain, well-being, or vigor may vary widely from patient to patient, depending on an individual's "threshold" for discomfort or malaise. These may also be a function of a patient's fears and expectations. If the patient does not feel "100% better" after pacemaker insertion, does this reflect malfunction, or were the patient's original symptoms multifactorial in etiology and not preventable by pacing alone? As such, it is sometimes difficult to distinguish symptoms that warrant only reassurance from those that may be subtle clues to underlying pacemaker malfunction, malprogramming, or "*patient–pacemaker mismatch*." The latter is a term applied to the situation when the pacing system may be functioning perfectly appropriately, but fails to result in optimal patient functioning and indeed may even produce symptoms. For example, in an older patient who develops angina, it may be important to make the system less sensitive to activity, lower the upper rate limit, and have a relatively quicker decline of pacing rate once activity ceases.

Patients may have systemic or local symptoms (Table 11.3). Systemic symptoms include dyspnea, edema, chest pain, palpitations, dizziness, or syncope. These symptoms may be present at baseline, be exertional or postural, or be random and episodic.

Pacemaker syndrome is an important cause of baseline symptoms.[7,8] This phenomenon, commonly observed during single chamber ventricular pacing, results in hemodynamic compromise from retrograde activation of the atria in some cases and from cyclic losses of synchrony between the atria and ventricles in other cases (Figure 11.1). Patients may present with pre-syncope, syncope, malaise, fatigue, palpitations, or dyspnea. Loss of atrioventricular (AV) synchrony during pacing may produce systemic hypotension, AV valvular regurgitation, reduction in cardiac output, pulmonary congestion, and unpleasant neck pulsations (cannon A waves due to atrial contraction against a closed AV valve). In the worst-case scenario of AV dyssynchrony, retrograde 1:1 ventriculoatrial (VA) conduction may occur with ventricular pacing. Retrograde VA conduction is observed in approximately 80% of patients with sick sinus syndrome and even in a small minority of patients (15%) with antegrade high-grade AV block. The presence of retrograde VA conduction should be ascertained with electrocardiography, particularly in the inferior leads (e.g. II, III, and aVF), and/or telemetered intracardiac electrograms (EGMs). Blood pressure determinations should be made in the supine and erect positions with both ventricular pacing and during a non-paced rhythm if possible. Rarely, cardiac output determinations may also be required to demonstrate hemodynamic compromise associated with ventricular pacing. If pacemaker syndrome is identified, consideration should be given to reprogramming the pacemaker to reduce pacing dependence (e.g. decrease the lower rate), but ultimately revision to a dual chamber system may be required. Pacemaker syndrome should be considered not only with VVI pacing but also in any situation when

Table 11.3 Common symptoms in patients with CIEDs

		Symptoms	*Causes*
Systemic	Baseline	Edema, dyspnea, chest pain	Pacemaker syndrome Angina Pericarditis Pericardial effusion Pulmonary thromboembolism Lead perforation
	Exertional	Dyspnea, palpitations	Chronotropic incompetence Inadequate rate response Aggressive rate response Upper rate behavior Exercise-induced arrhythmias Pacemaker-mediated tachycardias Pacemaker syndrome
	Postural	Dizziness, syncope	Orthostatic syncope Loss of capture (insufficient lead slack)
	Random	Palpitations, dizziness, syncope	Pacemaker malfunction Inappropriate inhibition of pacing Inappropriate tracking (of myopotentials) Pacemaker-mediated tachycardias SVT or VT Vasodepressor syncope
Local	Pulse generator pocket	Pain, swelling, discharge, erosion	Infection Hematoma Seroma
	Extremity	Arm edema	Venous thrombosis Inflammatory arthritis (gout) Reflex sympathetic dystrophy
	Muscle stimulation	Pectoral, diaphragmatic, intercostal	(See Table 11.4)
Other	ICD shocks		

SVT, supraventricular tachycardia; VT, ventricular tachycardia.

AV synchrony is deranged; it can occur with AAI pacing secondary to long PR intervals and with DDD pacing in the setting of loss of atrial capture, inappropriate mode switching, pacemaker-mediated tachycardia (PMT), etc. The widespread and often insidious expression of pacemaker syndrome has led to a reappraisal of the choice of dual versus single chamber pacemaker implantation, as recently codified in an official HRS consensus statement.[9]

Baseline symptoms may occur from other causes. Some patients develop angina at baseline following device implantation, and might require the lower rate to be decreased. Sharp, pleuritic chest pain can result from pericarditis. Dyspnea can result from pericardial effusion or from pulmonary thromboembolism (PTE).

Exertional dyspnea or fatigue can occur due to lack of rate-adaptive pacing or inadequate rate response in a patient with chronotropic incompetence. On the other hand, an older patient might experience exertional angina due to an over-aggressive rate response. Upper rate behavior can account for exertional symptoms; e.g. a previously vigorous patient who receives a dual chamber system for complete heart block may be exertionally limited with an upper tracking rate of only 120 bpm, especially if electrical Wenckebach or 2:1

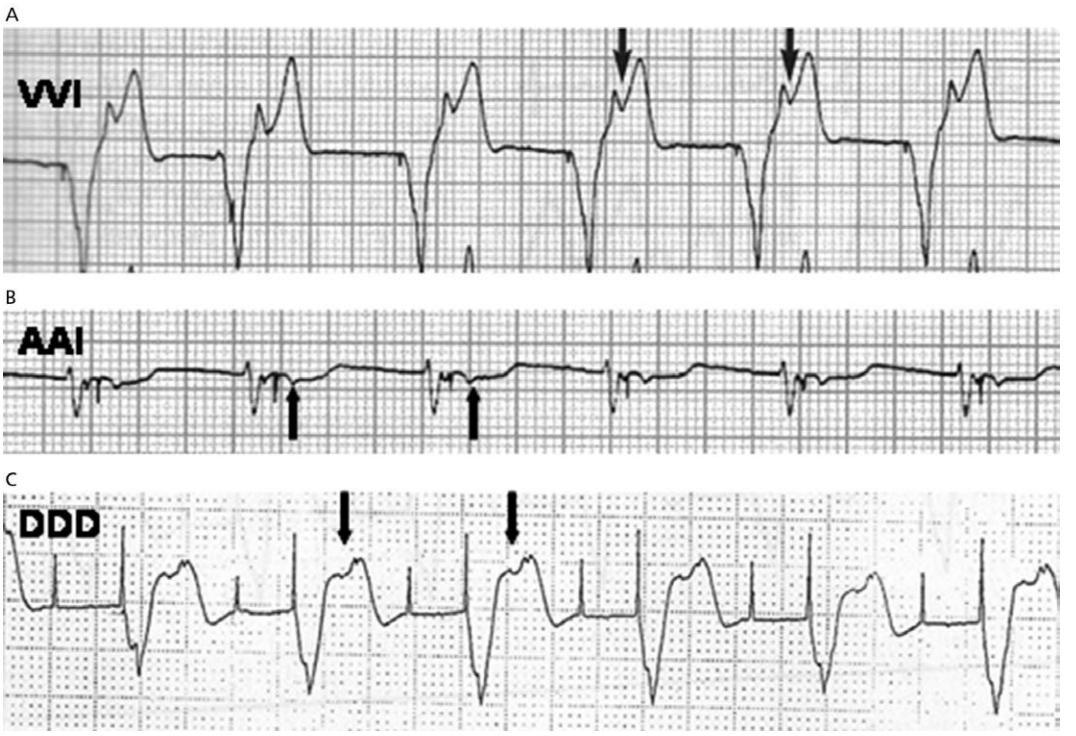


Figure 11.1 Paced ventriculoatrial activation sequences associated with pacemaker syndrome. The P waves are shown by the arrows. (A) VVI, VVI pacing with retrograde conduction. (B) AAI, atrial pacing at about 80 bpm with a very long PR interval. (C) DDD, AV sequential pacing with retrograde conduction due to loss of atrial capture.

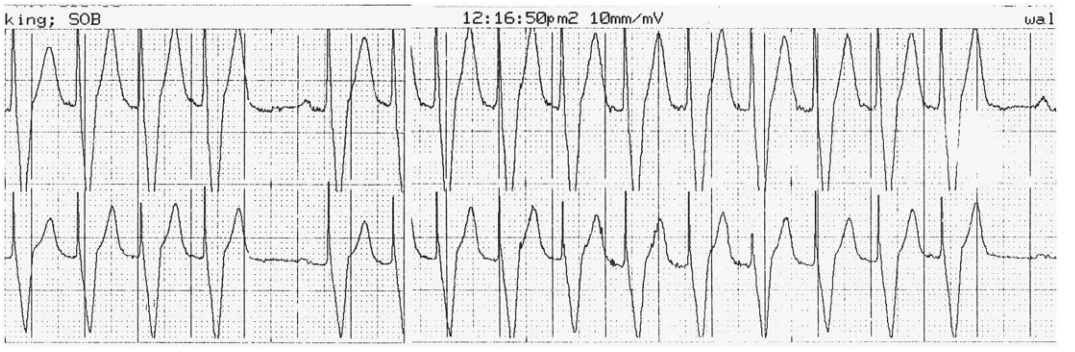


Figure 11.2 Holter transmission in a dual chamber system with ventricular tracking at the upper rate of 120 bpm associated with electrical Wenckebach phenomenon. This vigorous patient reported exercise limitation and dyspnea in association with this upper rate limitation.

heart block develops at the pacemaker's upper rate limit (Figure 11.2). Symptoms may result from exercise-induced arrhythmias potentially contributing to PMTs.

Treadmill testing may be useful in assessing exercise tolerance, chronotropic competence, and maximal heart rates achievable, either independent of pacing or in the setting of specifically programmed parameters. In rate-adaptive systems it is particularly useful to assess activity-sensing thresholds as well as the rapidity of pacing rate increases and decreases with activity. Upper rate behavior in

dual chamber systems may also be appreciated with exercise testing (e.g. Wenckebach vs. 2:1 block); exercise-induced arrhythmias potentially contributing to pacer-mediated tachycardias may rarely be observed.

Postural symptoms can be due to orthostatic syncope, but intermittent loss of capture due to inadequate lead slack should also be considered.

Intermittent but *random* symptoms can be due to pacing system malfunction, inappropriate inhibition of pacing (due to oversensing of myopotentials, EMI, noise, or cross-talk) or tracking of myopotentials. This requires careful evaluation, including, determination of sensing and pacing thresholds, review of stored EGMs for oversensing, and performing special maneuvers to evaluate for myopotential inhibition or tracking. PMTs may also arise and generate symptoms. Reprogramming options to address this are discussed later. Problems unrelated to the pacing system such as spontaneous atrial or ventricular arrhythmias, and vasodepressor syncope should also be considered. Most devices have sophisticated diagnostics, often storing the actual EGM from any such tachycardia. This greatly simplifies evaluation. Many pacemakers allow the clinician to attempt to terminate supraventricular tachycardias (SVTs) with rapid pacing if the patient is in persistent tachycardia at the time of a follow-up visit. Additionally, certain pacemakers even allow for the programming of atrial antitachycardia pacing (ATP) to be automatically delivered for SVTs. Tilt testing may prove useful in revealing the presence of vasodepressor syncope. Under such circumstances, medical therapy with volume expansion, β-blockers, selective serotonin reuptake inhibitors, mineralocorticoids, or vasoconstrictors, such as midodrine, may prove useful. Pacemaker reprogramming may also be beneficial. Increasing the lower pacing rate or activating certain specialized "rate-drop" algorithms may provide assistance. There is evidence that certain rate-adaptive sensors responsive to cardiac contractility may be particularly efficacious in minimizing recurrent vasovagal spells.[10] The extent to which any pacing system can improve on vasovagal syncope remains a source of controversy.[11]

Patients may complain of *local* pain, swelling, discharge, or erosion at the pulse generator site or of edema of the ipsilateral limb. In addition, stimulation of the diaphragmatic, pectoral, or intercostal muscles may be reported.

All patients with ICDs should be questioned about *ICD shocks*. Shocks can be appropriate (due to ventricular arrhythmias) or inappropriate (due to rapidly conducted SVT or oversensing). Symptoms preceding a shock can be very useful in discerning the etiology. Patients may perceive shocks that never occurred (phantom shocks). Troubleshooting of ICDs is discussed in Chapter 10.

Physical examination

The physical examination is a critical aspect of device follow-up evaluations. Most attention will be directed toward the healing incision and device pocket, looking for erythema, tenderness, incipient or overt erosion, or pocket swelling.

Pulse generator pocket

Swelling over the pulse generator may represent hematoma formation, seroma, or pocket infection. Pocket hematomas occur in approximately 20% of patients who receive subcutaneous or intravenous heparin shortly post procedure.[12] While a hematoma does not imply an infection, the risk of subsequent infection is heightened, and most would advocate prolonging the period of prophylactic antibiotics until the hematoma has resolved. Conservative management is all that is usually required, with temporary cessation of anticoagulants and more frequent follow-up to look for signs of pressure necrosis. Percutaneous aspiration of the pocket may actually be counter-productive, diminishing the tamponading effect and increasing the chances of further bleeding and infection.

Patients may note caudal migration of the generator or superficiality of the pacemaker leads, but these phenomena are infrequent and of concern only rarely. In a healthy pocket, the generator is freely mobile beneath the skin. An immobile generator, especially when firmly adherent to the overlying skin, raises the possibility of occult infection or pre-erosion. Erosion of a generator or a lead is potentially quite serious and may result in systemic infection (Figure 11.3). A variety of approaches to "salvaging" an eroded system have been advocated, although ideally the entire system



Figure 11.3 Pacemaker erosion.

Table 11.4 Inadvertent muscle stimulation with CIEDs

	Causes
Pectoral (pocket)	• Placement of uninsulated can against pectoral muscle (unipolar pacing system) • Lead insulation breach close to the pocket • Lead dislodgement and retraction to the pocket
Diaphragmatic	• Lead in coronary venous system (left phrenic nerve) • Misplaced/dislodged lead in superior vena cava (right phrenic nerve) • Thin ventricular wall (direct muscle stimulation) • Lead perforation of right ventricle (direct muscle stimulation)
Intercostal	• Lead perforation through free wall of right ventricle

(including leads) should be explanted and replaced with a new system after an appropriate period of intravenous antibiotics. A fluctuant pocket should not be aspirated, as this may introduce infection into a sterile process and will not treat an infection if present. Suspected pocket infections should be surgically opened to confirm the diagnosis and to remove all hardware if the pocket is infected. Pacemaker infections are not adequately treated by prolonged courses of antibiotics alone.

Muscle stimulation

Unanticipated stimulation of the pectoral, diaphragmatic, and rarely, intercostal muscles can occur from CIEDs (Table 11.4). Myopectoral stimulation may be appreciated at the pocket site and is almost exclusively seen in unipolar systems. Certain generators are manufactured with one insulated side intended to be placed against the pectoral muscle. Myopectoral stimulation may be attributed to placement of such a generator can with the uninsulated side down against the pectoral muscle (or the patient may have reversed the can by "twiddling"), leading to anodal stimulation of the underlying muscles; it may thus be corrected by inversion of the generator. Frequently, no problem is identifiable, but the situation may be corrected by reprogramming to a lower output to avoid invasive revision to a bipolar system. Reduction of voltage is often effective in eliminating muscle stimulation—far more so than reduction of pulse width duration. Pectoral muscle stimulation may also indicate lead insulation failure close to the muscle layer. Rarely, a dislodged lead that has retracted all the way to the pocket is the cause. The last two causes can result in myopectoral stimulation in unipolar or bipolar systems.

Diaphragmatic stimulation, if present, is usually apparent on physical examination, but rarely requires fluoroscopy for confirmation. It can occur as a result of right or left phrenic nerve stimulation, or by direct stimulation of the diaphragm. This problem is becoming more frequent with the use of biventricular pacing systems, where the lead placed in the coronary venous tributary is often in close proximity to the left phrenic nerve. Most current devices allow the left ventricular stimulation vector to be re-programmed; in most cases an alternate pacing vector decreases or eliminates phrenic stimulation. Direct stimulation of the diaphragm may occur through a thin ventricular wall,

or, less commonly, through a perforated ventricle. In the former case, reduction of output may alleviate the problem. Another cause for diaphragmatic stimulation is (right) phrenic nerve stimulation with a misplaced or dislodged atrial or ventricular lead. Depending on which lead is responsible, the corrective approach may entail inactivation of the atrial channel, reduction of atrial output, or repositioning of the displaced lead.

General aspects

Other important aspects of the physical examination include vital signs, with particular emphasis on pulse and blood pressure. The latter may vary significantly as a function of pacing mode (e.g. VVI vs. DDD) or pacing rate. Neck veins should be evaluated for the presence of cannon A waves. Cardiac examination should confirm paradoxical splitting of the second heart sound in most cases of right ventricular (RV) pacing, and should exclude the presence of a pericardial friction rub suggestive of cardiac perforation. The arm ipsilateral to the lead insertion site should be examined for edema, perhaps reflecting venous thrombosis, which is usually a spontaneously resolving phenomenon and rarely responsible for thromboembolism. Arm elevation is often helpful while endogenous thrombolysis and recruitment of collateral circulation take place. If symptoms are more marked, short-term anticoagulation with warfarin may speed the process. Edema coupled with inflammation may, less commonly, represent a gouty attack precipitated by the recent surgical implantation of a device system.

Dynamic maneuvers

Carotid sinus massage may be employed to induce slowing to the lower rate limit, thereby confirming the ability of the pacemaker to capture. Rarely, carotid massage-induced slowing of the sinus node may be useful in dual chamber systems to differentiate SVT from physiological sinus tachycardia with ventricular tracking near the upper rate limit. In rate-adaptive systems dependent on sensing vibration, the generator may be tapped to demonstrate increases in the pacing rate. Physical manipulation of the pacing system should be undertaken to evaluate the integrity of the leads and their connections to the generator can. Traction applied to the generator or abduction of the arm ipsilateral to the generator may expose a previously unsuspected malconnection or lead fracture and result in loss of capture or myopectoral stimulation. Confirmation of continued capture should be made with the patient in the erect as well as supine position in cases where inadequate or insufficient lead "slack" may be present.

Myopotential sensing can result in pacing inhibition in single or dual chamber systems, triggering of ventricular pacing in dual chamber systems, or inappropriate shocks in patients with ICDs. Pectoral myopotentials may be elicited by isometric exercise involving the arm ipsilateral to the generator, whereas diaphragmatic myopotentials are elicited by deep respiration, coughing, or performing the Valsalva maneuver. The ability to observe real-time intracardiac signals as well as the universal adaptation of marker channels has greatly eased this evaluation. This is ordinarily an issue only for unipolar systems. If myopotential inhibition is elicited and clinically significant, reprogramming to a reduced sensitivity, to an asynchronous pacing mode, or to a triggered pacing mode may be undertaken to ensure continuous pacing in the pacemaker-dependent patient. Consideration of changing the unipolar system to a bipolar system is another option. However, myopotential sensing can occur in bipolar systems due to lead insulation breach, or in ICDs with an integrated bipolar lead, due to reversal of coil connections or a loose setscrew to the distal coil. Selected intermittent problems that may be revealed by special maneuvers are listed in Table 11.5.

Radiography and fluoroscopy

The chest radiograph (PA and lateral using the dorsal spine technique) remains an important feature of pacemaker and ICD follow-up evaluation, conveying a wealth of information. Following implant, it serves to delineate lead positioning and screw tip advancement in active fixation leads. Inadvertent positioning of a ventricular pacing lead in the middle cardiac vein or in the left ventricle through a patent foramen ovale may become apparent (Figure 11.4). Lead dislocation is rare beyond the first month after implantation; coronary sinus leads may be particularly prone to this due to the specific anatomic situation. Subsequent

Table 11.5 Intermittent problems revealed by special maneuvers

Problem	*Major consequence(s)*	*Dynamic maneuver during physical exam*
Myopotential sensing	Oversensing	Diaphragmatic: Cough Valsalva maneuver Deep respiration Pectoral: Ipsilateral arm (isometric) exercise
Lead or connector problems	Oversensing Loss of capture	Traction on pulse generator Ipsilateral arm movements (abduction)
Problems at electrode-tissue interface: Insufficient slack Excessive motion	Loss of capture	Positional changes (supine, erect)
Diaphragmatic stimulation		Positional changes

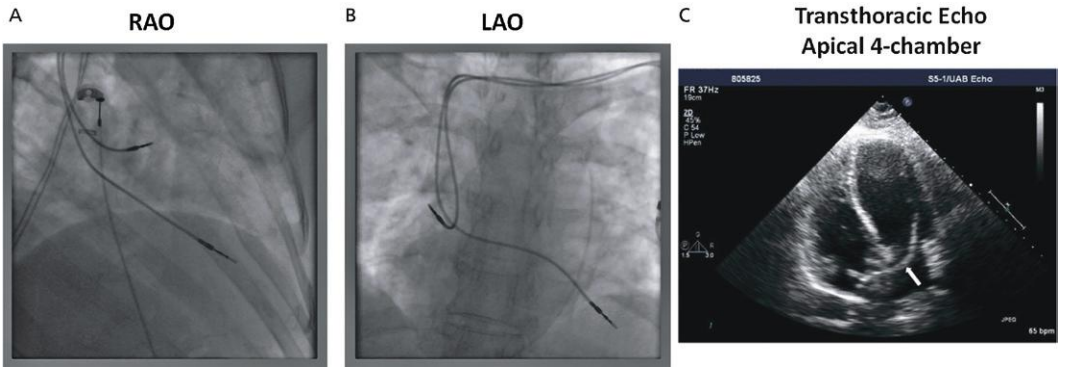


Figure 11.4 (A) Right anterior oblique (RAO) and (B) left anterior oblique (LAO) fluoroscopic images of a pacing lead inadvertently placed in the left ventricle through a patent foramen ovale. (C) An apical four chamber view on transthoracic echocardiography which confirms the course of the pacing lead (arrow).

radiographs may be scheduled on a periodic basis or only if specific questions are to be addressed.

In particular, lead conductor fractures may sometimes be identified in cases of lead failure in the setting of elevated lead impedance. These typically occur at sites of acute angulation or at sites of increased external stress, such as the first rib–clavicular junction in leads placed via subclavian vein puncture or at anchoring sites if a protective sleeve was not applied at the time of implant. Fluoroscopy, in conjunction with traction on the lead and generator, may be required to delineate the fracture. Previously, a manufacturer's advisory on potential fracture of an inner J-shaped retention wire has recommended periodic ciné-fluoroscopy to evaluate for fracture in certain active fixation J-shaped atrial leads (Telectronics Accufix™ series). Recently, outer insulation breach resulting in exteriorization of conductors has been reported in the St. Jude Medical Riata™ leads, which can be identified on fluoroscopy (Figure 11.5).[13]

The venous insertion site may be apparent on the film; jugular venous cut-down, for example, entails lead entry superior to the clavicle. Anatomical variants (such as a persistent left superior vena cava) may also be appreciated.

Clues to the polarity of the lead(s) may be appreciated by analyzing either the distal tip for the presence of a ring electrode or the header block, although whether the generator is actually

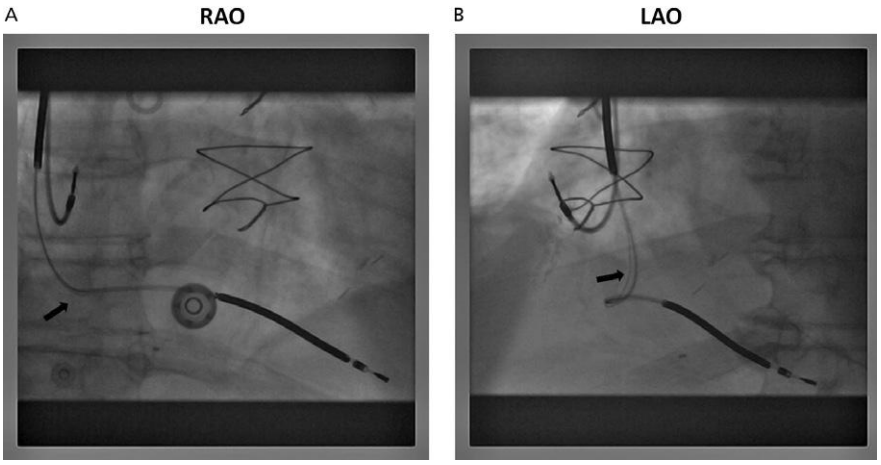


Figure 11.5 (A) Right anterior oblique (RAO) and (B) left anterior oblique (LAO) fluoroscopic images showing exteriorization of conductors (arrows) of a Riata ICD lead (St. Jude Medical, Inc.) due to "inside–out" insulation breach.

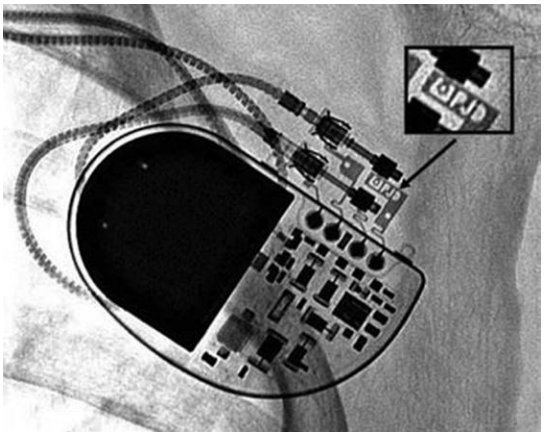


Figure 11.6 Radiographic identification of a pacemaker generator has been facilitated by the use of device-specific identification codes. The code appears horizontally in the upper right corner of the device. The code "PJD" following the Medtronic logo identifies the device as a Medtronic Sigma 303 pacemaker (insert).

programmed to bipolar or unipolar pacing remains to be determined. Examination of the connector block may disclose retraction of the lead pin or inadvertent reversed connection of the lead pins.

The generator may also be examined for position and, importantly, to identify the specific model in patients with an unknown system. Various radiographic identification codes exist that are manufacturer specific and facilitate recognition of the specific device in question (Figure 11.6). Comprehensive references exist to assist in this process.[14] Older systems not employing such radiographic codes may be identified on the basis of generator shape or battery configuration on the radiograph.

Electrocardiography

It is beyond the scope of this chapter to provide a detailed discussion of pacemaker electrocardiography. Rather, a general approach to the use of

Table 11.6 Responses and uses of magnet application over pacemakers and ICDs

	Pacemakers	*ICDs*
Typical magnet response	• Asynchronous pacing (rate specific to manufacturer)	• Suspension of tachycardia detection and therapies • Bradycardia function unaffected
Programmability	• Yes (BS, SJM, Biotronik)	• Yes (BS, SJM)
Special functions	• Electrogram storage • Threshold search	
Uses	• Device identification • Evaluation of battery status (ERI) • Diagnosis and prevention of pacing inhibition from inappropriate sensing (e.g. EMI) • Confirm capture during asynchronous pacing • Termination of pacemaker-mediated tachycardias	• Prevention of therapies from inappropriate sensing (e.g. EMI)

BS, Boston Scientific; EMI, electromagnetic interference; SJM, St. Jude Medical.

electrocardiography in assessing pacemaker functioning will be addressed. The 12-lead ECG, both with and without pacing, is a useful tool in pacemaker follow-up assessments. Aside from confirming the pacemaker's ability to sense and capture, the ECG can provide important information on lead integrity and position. For example, the typical morphology of a RV-paced complex is that of left bundle branch block (LBBB), whereas right bundle branch block (RBBB) morphology may suggest left ventricular (LV) pacing, whether intentional (e.g. epicardial wires or coronary sinus pacing) or otherwise (e.g. perforation or lead placement in the LV through a patent foramen ovale or the arterial system). A superior axis is common in leads in the RV apex, whereas intermediate or inferiorly directed axes are suggestive of leads high on the septum or in the outflow tract.

The ECG is especially important in follow-up of CRT devices, to determine the presence or loss of LV capture. Since the morphology of LV and biventricular pacing can be quite variable in different patients, it is essential to keep a record of the post-implantation ECGs for comparison.

Fusion and pseudofusion can be identified on the ECG. This information can be valuable in appropriate programming. The atrioventricular (AV) delay may be lengthened to minimize pacing and conserve battery life, or it may be shortened to force pacing [e.g. in CRT devices or in hypertrophic cardiomyopathy (HCM) patients with obstruction].

Magnet application

The response to magnet application differs between pacemakers and ICDs (Table 11.6). Within pacemakers or ICDs, it varies between different manufacturers, and even among various models of a single manufacturer.[15] A doughnut magnet with a strength of around 90 Gauss is typically used for this purpose.

For pacemakers, magnet application typically results in asynchronous pacing by closing a magnetic switch (mechanical reed switch, Hall sensor, or giant magnetoresistive sensor). It is a frequent misconception that magnets "turn off" pacemakers when quite the opposite ensues. The magnet pacing rate and other elements of the magnet response are manufacturer specific and sometimes vary among different models of a single manufacturer. The magnet pacing rate decreases in all pacemakers (the exact value is manufacturer and device specific) when the device reaches elective replacement

indicator (ERI), and decreases further at end of life (EOL). This has long been the basis of transtelephonic monitoring for battery depletion in pacemakers. ERI in some models may be elicited only in the magnet mode. In such instances, routine magnet application may be especially important for determining the need for replacement of a depleting pacemaker generator. Magnet response is programmable in some pacemakers.

Although multi-programmability and telemetered data through the programmer have supplanted magnet application for detailed pacemaker analysis in most cases, magnet application remains an important aspect of pacemaker evaluation. In the absence of a programmer, magnet application with ECG monitoring confirms the ability to capture a cardiac chamber during asynchronous pacing. This may otherwise not be apparent if the patient's intrinsic rhythm inhibits pacemaker firing. Because pacemakers typically respond to magnet application by asynchronous pacing, magnets may also be employed, both diagnostically and therapeutically, in cases where potential pacemaker malfunction is attributed to sensing problems. Magnet application can be therapeutic to terminate PMT or to restore pacing in cases of oversensing. In cases of pacemaker dependence, rapid magnet conversion to asynchronous pacing may be critical in preventing asystole due to oversensing or cross-talk inhibition (particularly if the appropriate pacemaker programmer is unavailable). In some contemporary pacemakers, however, magnet application may instead trigger specialized pacemaker functions, such as threshold search, EGM storage, or no response in programmable devices with the magnet response turned "off."

For ICDs, magnet application suspends tachyarrhythmia detection and therapy, but typically does not affect pacing (the exception is Sorin devices). With most current ICDs, tachyarrhythmia detection and therapies are restored upon removal of the magnet. However, with some older devices (Boston Scientific) magnet application for a certain period of time may result in permanent deactivation of tachyarrhythmia functions. As with pacemakers, magnet response is programmable in some ICDs.

The application of a magnet over the generator is rarely associated with adverse effects. On occasion, ventricular ectopy may result from asynchronous ventricular pacing, but this is seldom sustained.

Pacemaker dependence

Pacemaker dependency is defined as the absence of a life-sustaining rhythm without the pacing system. Cessation of pacemaker function in these patients may result in symptomatic bradycardia or ventricular asystole that endangers the life of the patient. The term is problematic for a variety of reasons. First, it is often misused in cases when 100% pacing is observed. In this sense any patient with a pacemaker may be rendered "pacemaker dependent" by having the device programmed to a rate greater than their intrinsic heart rate. Second, in patients with conduction abnormalities such as AV block, the degree of impairment may vary from one point in time to another. That is, the ability to conduct 1:1 from atrium to ventricle may be somewhat "whimsical" and may also vary with the application of various medications that facilitate or depress conduction (Figure 11.7). Finally, with reprogramming of pacemakers to slower rates, gradual slowing of the pacing rate is more likely to allow the emergence of an escape rhythm than is a sudden cessation of pacing (Figure 11.8).

In patients in whom gradual reprogramming of the generator to slower rates still results in 100% pacing at the slowest programmable rate, it is still possible to determine the presence (or absence) of an underlying rhythm if the output is temporarily inhibited or programmed to subthreshold values. This practice may result in prolonged asystole during programming and should be attempted only if temporary programming is available that is rapidly reversible. Alternatively, chest wall stimulation may be applied with alligator clip cables from a temporary pacing device via skin electrodes (one situated directly over the generator can) in an effort to produce EMI and thereby inhibit pacer output. This technique is particularly well suited to unipolar systems with limited programming capabilities for rate or output.

Functional pacemaker dependence is a term that is sometimes applied to patients with CRT devices who develop acute hemodynamic deterioration when CRT is inhibited, because of reversion to a

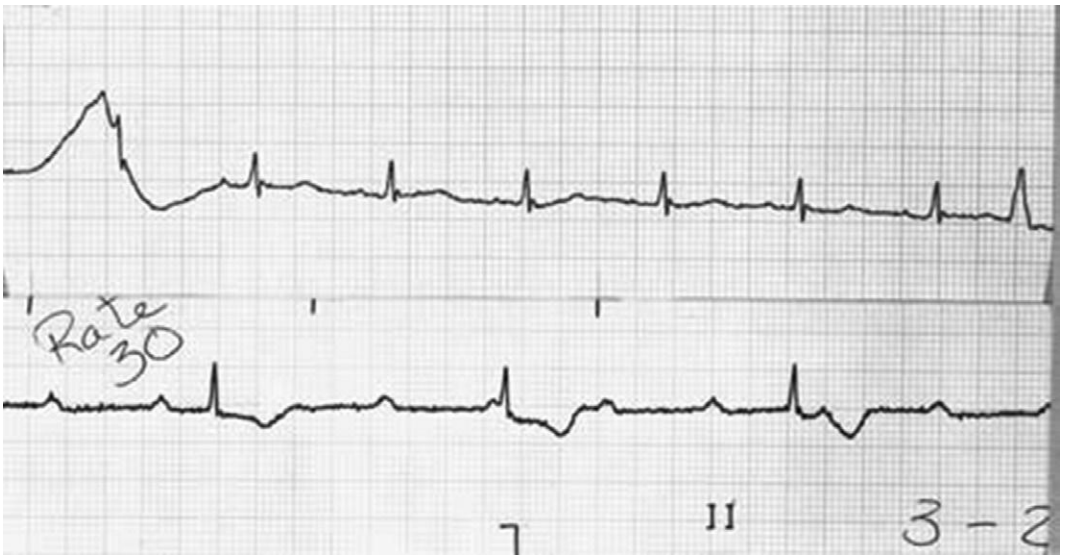


Figure 11.7 Top: Intact atrioventricular conduction in a pacemaker patient with resulting inhibition of pacemaker output. The pacemaker was originally inserted for complete heart block. Bottom: Underlying rhythm in the same patient several months later demonstrating recurrent complete heart block.



Figure 11.8 Emergence of escape rhythm in a 56-year-old woman 3 days after mitral valve replacement. (A) The patient has been paced with temporary wires at 90 bpm since her surgery. Abrupt termination of pacing results in asystole lasting a total of 9 s. (B) Hours after gradually decreasing the pacing rate to 50 bpm, sinus rhythm at 70 bpm with normal atrioventricular conduction is noted. The patient was discharged from the hospital 2 days later without permanent pacing.

dyssynchronous state of electrical activation. The term may also be used for patients who are not usually pacemaker dependent, but may become pacemaker dependent in certain situations (such as sedation, vagal stimulation, anesthetic use, etc.).

Device interrogation

Programmers and telemetry

Pacemaker and ICD programmers are complex devices with which the device physician must be thoroughly familiar.[5] All programmers, independent of the manufacturer, share certain architectural features. All modern programmers are computer based. There is an input section that allows operator interface with the computer programmer via a keyboard, light pen, and/or touch-sensitive screen. There is a telemetry interface associated with the programmer, usually in the form of a handheld wand that transmits signals to and receives data from the pulse generator. Wireless communication between the programmer and the device is

available for some devices. The programmer is also associated with a printer for hardcopy printouts of pacemaker data. The printer may be physically integrated with the programmer or be a separate component.

Telemetry is the ability to transmit information from one device to another. Current programmers enable bidirectional telemetry (two-way communication) with the device. There are broadly two modes of communication between the device and the programmer. First, near-field or inductive telemetry requires placement of a handheld wand connected to the programmer directly over the device. Communication is based on inductive coupling between two closely placed coils, one in the device and the second in the wand. Second, several current devices are capable of wireless telemetry with the programmer up to a distance of about 10–20 feet from the device without needing a wand; however, initial communication between the device and the programmer through the handheld wand is required as a security measure before wireless telemetry can be established. Both near-field and wireless telemetry utilize radiofrequency (RF) for transmission. The longer range wireless telemetry utilizes either the ISM band (902–928 MHz) or the MICS band (402–405 MHz) of the RF spectrum; the carrier frequencies depend upon the manufacturer.

The ability to undertake telemetry, as in the case of programming, is device specific and requires manufacturer-specific programmers and/or modules. Inability to perform telemetry has several potential explanations, including using the wrong programmer, using the correct programmer but without the software updates to communicate with the present model of device, an older model of device incapable of providing telemetry, or a device that has a circuit malfunction[16] or is at end of life.

Spurious programming remains a problem that may present in a variety of forms. "Phantom programming" refers to the reprogramming of a device by another physician unbeknown to the original physician programmer. "Dysprogramming" is spurious programming due to an anomalous interference source such as electrocautery. "Misprogramming" is reprogramming of a device by a programmer in unanticipated fashion due to faulty program emission counts. Rarely, "cross-programming" may be observed as the unpredictable reprogramming of one manufacturer's pacemaker or ICD by another manufacturer's programmer. For this reason, a pacemaker or ICD must be interrogated and programmed only with the specific manufacturer's programmer.

Table 11.7 Data obtained by telemetry

Administrative data (patient information)
Programmed parameters
Measured (real-time and stored) data
Diagnostics (stored data)
Electrograms and event markers (real-time and stored)

Table 11.8 Approach to device interrogation

1 Review of programmed parameters and patient information
2 Display of real-time electrograms, event markers, and ECG
3 Evaluation of measured data (real-time and historical), pacing and sensing thresholds
4 Review of patient diagnostics (stored data)
5 Special considerations and maneuvers
6 Programming changes

Approach

Programmers enable both programmability and telemetry of a host of data, including programming commands, administrative data, programmed data, measured data and diagnostic data (Table 11.7). Device follow-up assessments can be performed efficiently using a systematic approach (Table 11.8).

Review of programmed parameters

Even before any reprogramming is undertaken or thresholds are determined, the device should be interrogated to document the current programmed settings. All modern devices have such telemetry available. It should be emphasized that independent confirmation of parameters such as mode and rate should be made electrocardiographically after all interventions, because telemetry will not always

reflect true programmed settings, although this is rare. This is particularly true in the case of device systems that have come into contact with extreme environmental noise (such as electrocautery or defibrillation), causing subsequent resetting of the device or device malfunction—in these cases, what one sees (via telemetry) is not always what one gets.

Some models allow both programmers and generators to have actual times displayed, which is important in programming certain circadian features, as well as in identifying when certain events, such as automatic mode switching, have occurred since the last interrogation.

Display of real-time EGMs, marker channels, and ECG

Real-time intracardiac EGMs and marker channels may be available, depending on the system used; they facilitate the physician's ability to diagnose appropriate, or inappropriate, device function. Displaying the appropriate real-time EGMs and marker channels along with one or more ECG leads facilitates device interrogation.

Intracardiac EGMs

Intracardiac EGMs are the signals recorded by electrodes located on the pacing leads. They may be displayed in real-time (real-time EGMs), or the signals from past events stored by the device may be telemetered (stored EGMs). It is important to note that the telemetered EGM may not always be the same as the signal used by the sense amplifier. The size of the intracardiac EGMs may give the physician a rough idea of the sensing capabilities of the system and may also delineate the amplitude of far-field signals. During device interrogation, it is important to ensure that the appropriate real-time EGMs from the chamber of interest (atrial, RV, or LV) for the particular situation are displayed. With most devices, one can choose from various options such as bipolar, unipolar tip, and unipolar ring EGMs. The clinical utility of intracardiac EGMs includes identifying retrograde conduction, measuring VA conduction time, assisting rhythm identification, evaluating unusual sensing phenomena, evaluating lead connector integrity, assisting threshold determinations, and evaluating myopotential sensing.

In addition to real-time EGMs, with some devices the patient may freeze and store EGMs with external magnet application during symptomatic events, or the device may automatically store EGMs in response to high heart rates (Figure 11.9). This corresponds to an event monitor function of the device. These stored EGMs are discussed later in "Review of patient diagnostics."

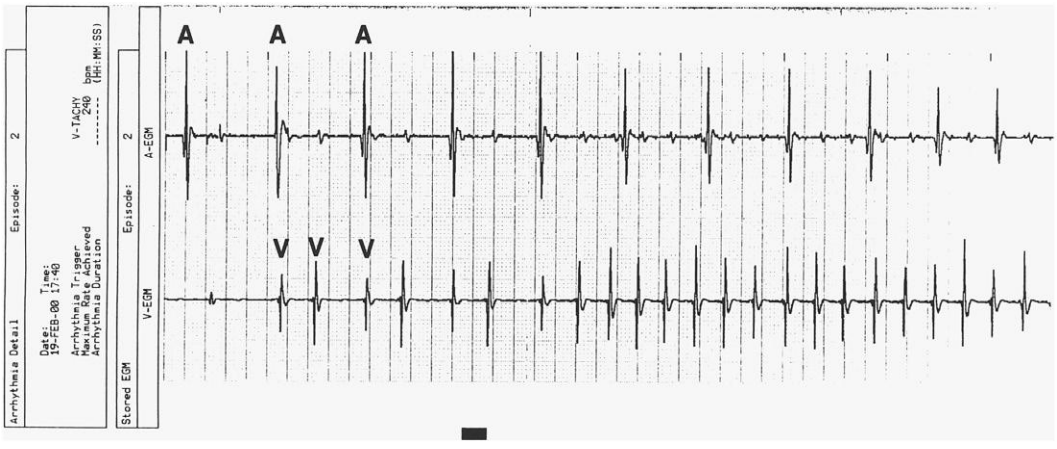


Figure 11.9 Stored atrial (top) and ventricular (bottom) electrograms (EGMs) from a pacemaker with automated EGM capture triggered by a high ventricular rate. The patient experienced syncope at the time the EGMs were recorded. The documentation of atrioventricular dissociation is diagnostic of ventricular tachycardia.

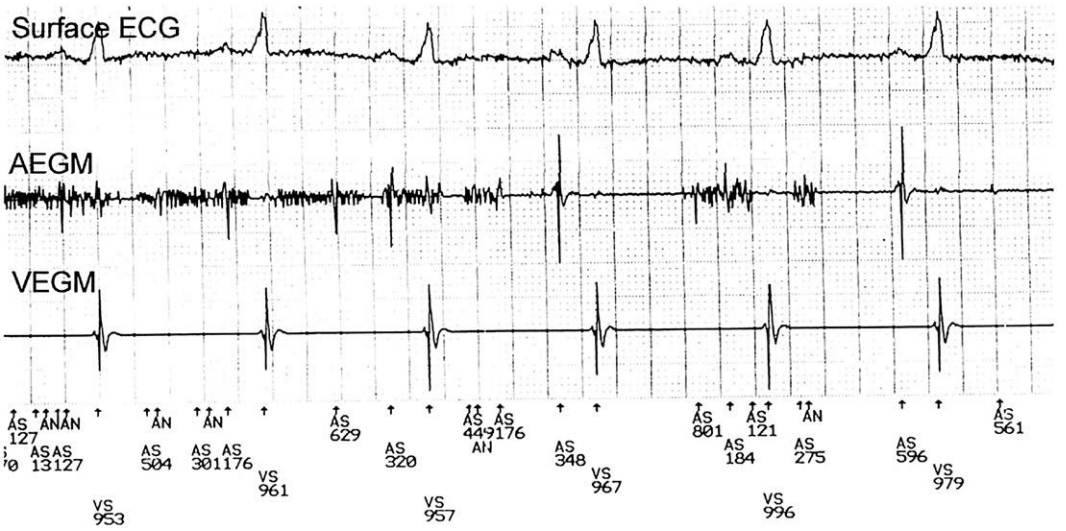


Figure 11.10 Surface ECG, atrial (AEGM), and ventricular (VEGM) intracardiac electrograms, and marker channel (bottom) demonstrating "noise" and oversensing on the atrial lead of a Guidant ICD. This resulted from an insulation break from subclavian crush.

Marker channels (event markers)

Marker channels (event markers) are potentially more useful than EGMs, and denote when a particular channel (atrial or ventricular) is sensing activity or emitting a paced output (Figure 11.10). By telling the physician what the device is "seeing and doing," certain phenomena, such as cross-talk inhibition, may be more easily defined. However, event markers do have their limitations. They describe device behavior, but not its appropriateness; in addition, a stimulus output report does not necessarily imply capture. Event markers are best used in conjunction with a simultaneously recorded surface ECG and/or EGM. Just like EGMs, marker channels may be displayed in real time or for stored episodes.

ECG

It is useful to record at least one real-time ECG lead during device interrogation. This is especially important in pacemaker-dependent patients during threshold testing where local myocardial capture seen on the intracardiac EGM may not necessarily imply global capture. In addition, the ECG is useful in confirmation of oversensing in conjunction with the intracardiac EGM and event markers. Evaluation of CRT devices often requires a 12-lead ECG to assess the degree of electrical resynchronization.

Most programmers have the capability to display multiple ECG leads using skin electrodes. ICDs can display far-field EGMs (shock EGMs) of different configurations that can serve as a surrogate for a surface ECG lead. Several newer devices use these far-field EGMs to generate a "leadless ECG" without requiring placement of skin electrodes. An external ECG machine may be used, especially if a 12-lead ECG is warranted.

Evaluation of measured data, and pacing and sensing thresholds

Measured data include parameters that indicate the status of the battery and of the lead(s). Sensing and pacing thresholds, which are in fact a type of measured data, indicate lead status. Measured data (including thresholds) can be evaluated in real time; in addition, historical data can be stored and displayed as "trends" in most devices. The retrieval of stored and real-time data indicating battery and lead status is an important part of each follow-up visit (Table 11.9).

Table 11.9 Indicators of battery and lead status

	Battery	*Lead*
Measured (real-time) data	Battery voltage Internal resistance (pacemakers) Charge time (ICDs) Current drain	Pacing impedances Shock impedances
Thresholds		Sensing thresholds Pacing thresholds
Historical data (trends and episodes)	Voltage trends Battery impedance trends	Lead impedance trends Electrogram amplitude trends Pacing threshold trends Episodes indicating lead noise (short VV intervals)

Table 11.10 Indicators of battery status of pacemakers and ICDs

	Pacemakers	*ICDs*
Voltage	Yes	Yes
Internal resistance	Yes	Not predictable
Charge time	Not relevant	Yes
Magnet rate	Yes	No
Estimated longevity (based on current drain)	Yes	Yes

Battery status

The main indicators of the battery status of a pacemaker include battery voltage and internal resistance. Battery voltage and charge time indicate the status of an ICD battery (Table 11.10). In addition to real-time measurement of these parameters, most devices also provide a graphic display of these trends over time. Current drain is also reported by most devices; devices may provide an estimate of longevity based on the remaining battery capacity and the current drain for the programmed settings.

Most pacemakers are powered by a lithium–iodine (LiI) battery. The voltage of a new LiI battery is around 2.8 V and decreases gradually over the course of the device in a predictable manner, until the end of life when it sharply falls. The internal resistance of a LiI battery to current flow (battery impedance) also follows a predictable curve, sharply increasing toward the end of life. With time, pacemaker battery voltage declines and battery impedance rises, allowing projections of device longevity. Telemetry of battery voltage and impedance helps diagnose impending device depletion. ICDs typically have a lithium–silver vanadium oxide battery whose voltage curve is less predictable and is characterized by an initial drop and a plateau, followed by a second sharp decline toward the end of life (Figure 11.11). The internal resistance of ICD batteries does not behave in a predictable fashion. The charge times, however, are more predictable and gradually increase toward the end of life in ICDs.

Various stages in the life of a pacemaker or ICD battery are recognized (Table 11.11). A new battery is said to be at beginning of life (BOL) or beginning of service (BOS). With progressive battery depletion, most devices have a certain point designated as the *elective replacement indicator (ERI), elective replacement time (ERT), or recommended replacement time (RRT)*, when replacement is recommended within a short period (about 3 months). Beyond the ERI, devices reach *end of life (EOL) or end of service (EOS)*, when immediate replacement of the generator is warranted since the functions become unpredictable. It is important to distinguish EOL from ERI. The former connotes gross device malfunction or lack of function; the latter strives to indicate a time when generator replacement should be considered within a period of a few weeks to months. At or near EOL, transient high current drain from the battery may further reduce the output voltage. This may result in temporary or persistent loss of device function (Figure 11.12). Some devices identify an earlier

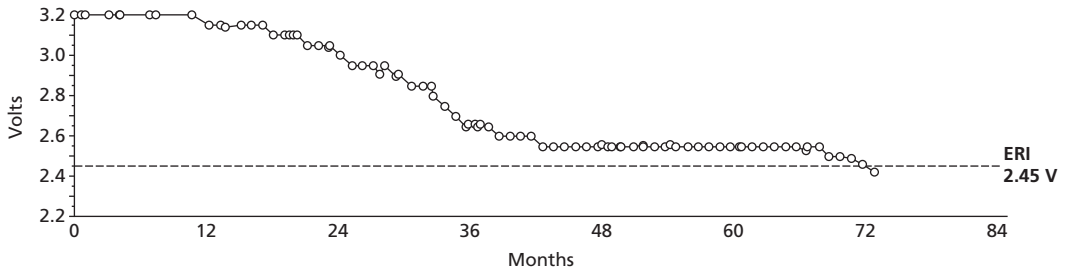


Figure 11.11 Graphic display of change in battery voltage over time of a St. Jude Medical ICD. Battery voltage drops gradually from an implant value of around 3.2 V to around 2.6 V, where it plateaus during the middle of life (MOL) of the device, and declines again as the device reaches elective replacement indicator (ERI).

Table 11.11 Nomenclature for various stages in the life of a pacemaker or ICD battery

Stage of battery	*Description*
• Beginning of life (BOL) or beginning of service (BOS)	A new battery that has not been significantly used
• Elective replacement indicator (ERI), or elective replacement time (ERT), or recommended replacement time (RRT)	Battery replacement recommended within a short period Basic functions are supported
• End of life (EOL), or end of service (EOS)	Immediate battery replacement recommended Not reliable to support basic functions
• Elective replacement near (ERN)	A stage before ERI, recognized in some devices, when closer follow-up than usual is recommended
• Middle of life (MOL)	Stage in ICD batteries, characterized by a plateau in voltage following the drop from initial value
• Power-on reset (POR)	Back-up mode due to loss of volatile memory from exposure to strong EMI

point before ERI called ERN, when close follow-up is recommended. ICD batteries (lithium–silver vanadium oxide) have a middle of life (MOL) when they reach a plateau following the initial dip in voltage.

The behavior of devices approaching battery depletion is highly variable among different manufacturers and even among different models from the same manufacturer. Importantly, with all pacemakers (but not with most ICDs), the pacing rate in response to magnet application is altered at ERI and provides the primary means of discerning the triggering of ERI, particularly in patients followed trans-telephonically. Other device functions may be altered at ERI that are specific to the manufacturer and the device. With all manufacturers, rate response and certain diagnostic and storage features are disabled at ERI. With certain manufacturers, the mode of pacing at ERI is changed as well, i.e. DDD to VVI. These changes may produce symptoms of pacemaker syndrome in some patients; in such patients, it may be important to schedule generator replacement before ERI is triggered.

True ERI or EOL behavior must be distinguished from electrical reset or *"power-on reset" (POR)* mode that results from loss or corruption of the device's volatile electronic memory due to exposure to strong EMI. POR mode is a simple back-up pacing mode (typically VVI or VOO) that is stored in non-volatile, read-only memory and allows the device to function after loss of programmable memory. In ICDs, electrical reset typically results in VVI pacing and maximal energy shocks. The

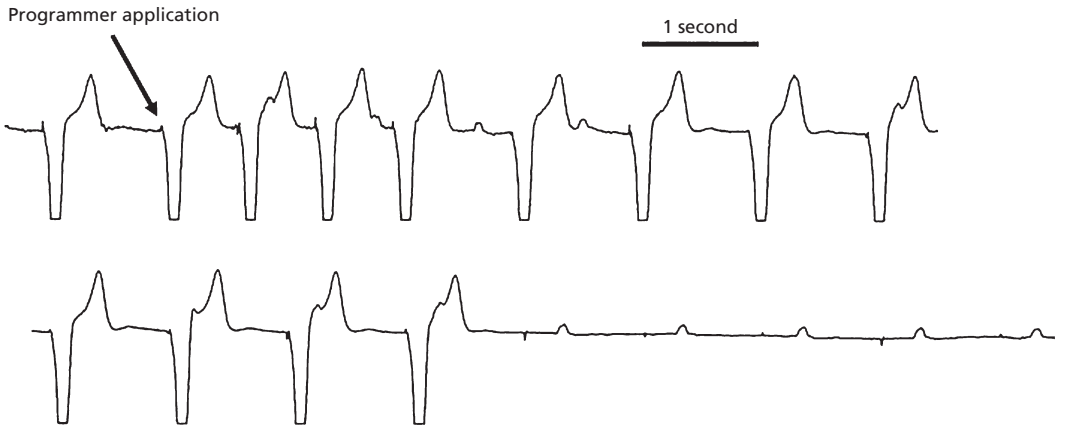


Figure 11.12 Loss of capture during programmer head (magnet) application in a pacemaker at end of battery life. The pacemaker telemetry was non-functional. Three paced beats at 100 bpm denote magnet application. With continued application of the programmer head, capture was lost due to increased current demand on the battery. A temporary pacemaker was in place anticipating such an occurrence.

POR mode and ERI modes, and rates of operation may or may not be identical for a given device. If identical, POR may be distinguished from ERI by a satisfactory battery voltage in POR and a low battery voltage in ERI. The reset mode does not automatically revert back, but requires a specific programmer command. It should be recognized that there may be different levels of "reset" (that are manufacturer and device specific) based on the degree of corruption of the device. Therefore, it is important to consult the manufacturer's technical support for all types of reset.

Lead status

Lead performance is evaluated by measurement of impedance, and sensing and pacing thresholds.

Impedance Evaluation of lead impedance is useful in diagnosing problems with lead integrity. A very low telemetered lead impedance may suggest problems with lead insulation, whereas a very high telemetered impedance may indicate conductor fracture or a loose set-screw, which may not be apparent radiographically. Pacing lead impedances normally range from 200 to 2000 Ω. High voltage lead impedances range from 20 to 100 Ω. Trends in impedance, where available, should be analyzed because a single "snapshot" of impedance during an office visit may not always identify incipient problems with lead integrity (Figure 11.13). In addition, if a problem is suspected, impedances may be evaluated while having the patient undertake dynamic physical maneuvers that place traction on the lead and/or generator.

Sensing and sensing thresholds For manual sensing threshold determination, the device should first be programmed below the intrinsic rate to assess sensing. In single chamber devices, ventricular sensing thresholds may be determined by then decreasing sensitivity (i.e. increasing the millivolt values) in the VVI mode to determine at what value pacemaker output is no longer inhibited. The same approach may be applied for establishing atrial-sensing thresholds using the AAI mode. The triggered modes may also be used in their respective chambers to evaluate sensing and determine sensing thresholds. Failure to trigger a pacemaker stimulus at a given sensitivity value indicates undersensing (Figure 11.14). Alternatively, triggered pacing by signals other than the P wave or QRS, such as T waves or myopotentials, indicates oversensing. In dual chamber systems, atrial sensing can be confirmed by programming to a P-synchronous ventricular triggered mode, shortening the AV interval so as to trigger ventricular pacing, and reducing atrial sensitivity progressively

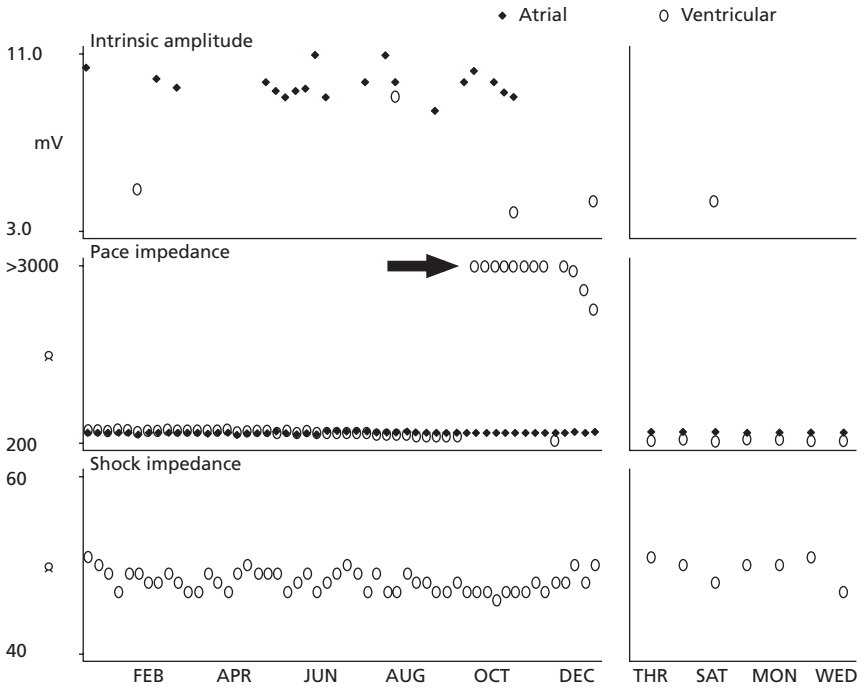


Figure 11.13 Graphic 6-month trend report of atrial and ventricular electrogram amplitudes, pacing lead, and high-voltage lead impedances in a Guidant ICD. From August to December, high ventricular lead impedances (open circles) were documented (arrow), but returned to normal at the time of the interrogation. The patient was demonstrated to have a fractured ventricular lead.

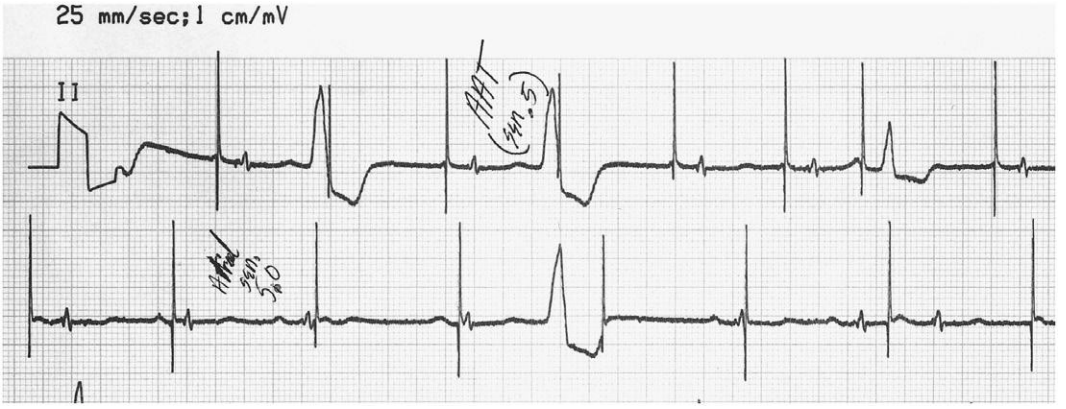


Figure 11.14 Atrial triggered pacing mode. Top: At maximal sensitivity of 0.5 mV, atrial sensing is appropriate. Bottom: With reduction of atrial sensitivity to 5.0 mV, there is a failure of atrial sensing with atrial spikes that do not coincide with native P waves.

until paced ventricular events no longer result. Ventricular sensing can either be checked in the VVI mode with the rate set lower than the intrinsic rate or, alternatively, in the DDD mode as long as the AV delay can be set sufficiently long to inhibit ventricular pacing.

Newer devices provide other techniques to evaluate sensing. Some automatically check atrial and ventricular EGM amplitudes on a regular basis. The results are available for review upon interrogation. Others require running a sensing protocol that automates the process described above. Finally, in certain devices, the intracardiac signal can be printed on calibrated paper that allows direct reading of the size of the sensed signal. With this technique, small variations may exist compared with the signal measured by the device due to differences in filters between the telemetry circuit and the sensing circuit. In patients with atrial electrical standstill or complete heart block without a viable escape mechanism, sensing thresholds will not be obtainable.

Sensing evaluation should always include evaluation of oversensing. For unipolar systems, particularly in pacemaker-dependent patients, the possibility of myopotential inhibition of ventricular output should be investigated. At increasing ventricular sensitivities, the patient is asked to perform isometric exercise using the arm ipsilateral to the generator, such as pushing the hands together in front of the chest (Figure 11.15). One should look for "noise" on the surface lead and EGM with inappropriate sensing of R waves on the marker channel and ventricular pacing inhibition. Likewise, the possibility of myopotential triggering of ventricular pacing from atrial oversensing in a dual chamber system should be evaluated by having the patient perform deltopectoral isometric exercises at increasing atrial sensitivities. Atrial oversensing of myopotential or far-field R waves is a frequent cause of inappropriate mode switching. In general, the chronic atrial and ventricular sensitivity settings should be set to a twofold to fourfold safety margin unless oversensing occurs (i.e. for an atrial sensing threshold of 2 mV, a sensitivity setting of 0.5–1.0 mV would be appropriate).

Pacing and pacing thresholds The pacing threshold determination is an important feature of device follow-up evaluations, because generator longevity may be significantly enhanced if the output can be programmed to the lowest value that will provide an adequate safety margin for pacing. Particular longevity may be obtained if outputs can be programmed to 2.5 V, i.e. less than the LiI battery voltage of 2.8 V. At this output, the energy inefficient voltage doubling circuit can be avoided. Further decreases in output beyond this point provide diminishing energy savings. In practice, doubling the voltage threshold (at a pulse width of 0.4 or 0.5 ms) or tripling the pulse width threshold (as long as the threshold is <0.3 ms) will usually provide an adequate safety margin. Energy consumption is directly proportional to the pulse width, but increases with the square of voltage. If tripling the pulse width results in an interval of less than 0.9 ms, this is usually more energy efficient



Figure 11.15 Two-channel Holter (simultaneous V1 and modified V5) showing symptomatic inhibition of pacing by myopotentials.

than doubling the voltage. Programming larger safety margins is typical immediately after implant to allow for the usual post-implant threshold increases. This process is almost always complete by 2–3 months, allowing chronic thresholds to be programmed at that point. Programming larger safety margins should also be considered in the ventricular channel of pacemaker-dependent patients given the possibility of late unexpected threshold rises.[17]

Determination of pacing thresholds should be made for all chambers where applicable. In patients with intact 1:1 AV conduction, determination of *atrial* stimulation threshold is easiest measured in the AAI mode with the pacing rate set 10–20 bpm above the intrinsic rate. Atrial output (or pulse width) is progressively lowered until a QRS complex is "dropped," indicating loss of atrial capture. In patients with AV block, atrial capture must be measured in a DDD mode. The threshold may then be determined by noting the loss of a P wave on a surface tracing, the appearance of atrial-sensed events on a marker channel, or a spontaneous atrial signal on an EGM tracing. The latter two findings indicate return of spontaneous sinus node function after loss of atrial capture. *Ventricular* stimulation thresholds are most cleanly performed in the VVI mode. Patients should be forewarned that such testing will be taking place because some will feel ill with the loss of AV synchrony during VVI pacing. Under such circumstances, the DDD mode may be used as an alternative for threshold testing; the AV delay must be set sufficiently short to "force" ventricular pacing and minimize fusion and pseudofusion, which can obscure detection of loss of ventricular capture and result in a falsely low perceived stimulation threshold. In pacemaker-dependent patients, loss of ventricular capture may result in asystole. Fortunately, most modern programmers permit rapid restoration of pre-programmed outputs with temporary pacing modes or automated threshold algorithms. It is helpful to alert the patients as to what they may feel as threshold is approached during testing. The operator must remain vigilant though to terminate the test immediately after loss of capture is first noted. Estimation of *LV* stimulation threshold is an important part of follow-up of CRT devices. LV threshold estimation can be challenging. Almost all current devices use the sensed RV EGM for bradycardia and tachycardia timing, but most devices allow display of the LV EGM during LV threshold estimation; if this is not available, careful scrutiny of the RV EGM or the ECG is essential. Many devices offer multiple configurations for LV pacing; typically the cathode is an electrode located on the coronary sinus (CS) lead, whereas the anode can involve an electrode on the CS lead, the ring, or distal coil of the RV lead, or the pulse generator itself. Anodal capture (of the RV) in configurations utilizing the RV lead can confound LV threshold determination. If patients complain of diaphragmatic stimulation, the phrenic nerve stimulation threshold must be assessed in various LV pacing configurations, in multiple positions. The optimal LV pacing configuration is chosen based on the LV threshold and the margin between LV and phrenic nerve stimulation thresholds.

Automaticity is a feature that has been applied to a number of pacemaker parameters to allow for device regulation without the need for continual clinician input. This is particularly the case with ventricular capture determinations (Figure 11.16). Most auto-capture algorithms have concentrated on the ventricle due to the relative ease of measuring the large evoked response with capture; however, devices capable of automatically measuring atrial capture and LV capture are also available. Auto-capture algorithms function on a continuous (beat-to-beat) or periodic basis. In these devices, the generator may be programmed to automatically determine the pacing threshold continuously or at periodic intervals and reset the output so as to ensure an adequate safety margin and simultaneously optimize device longevity. Certain devices that check capture on a beat-to-beat basis allow programming the output to as little as 0.25 V over the stimulation threshold. This option is being used increasingly to facilitate device follow-up.[18]

Lead performance trends

Historical information (including initial implant values) regarding lead impedance, EGM amplitude, and pacing threshold may be recorded in some devices and be available for recall via telemetry (Figure 11.17). Lead conductor or insulation problems can also be identified by the

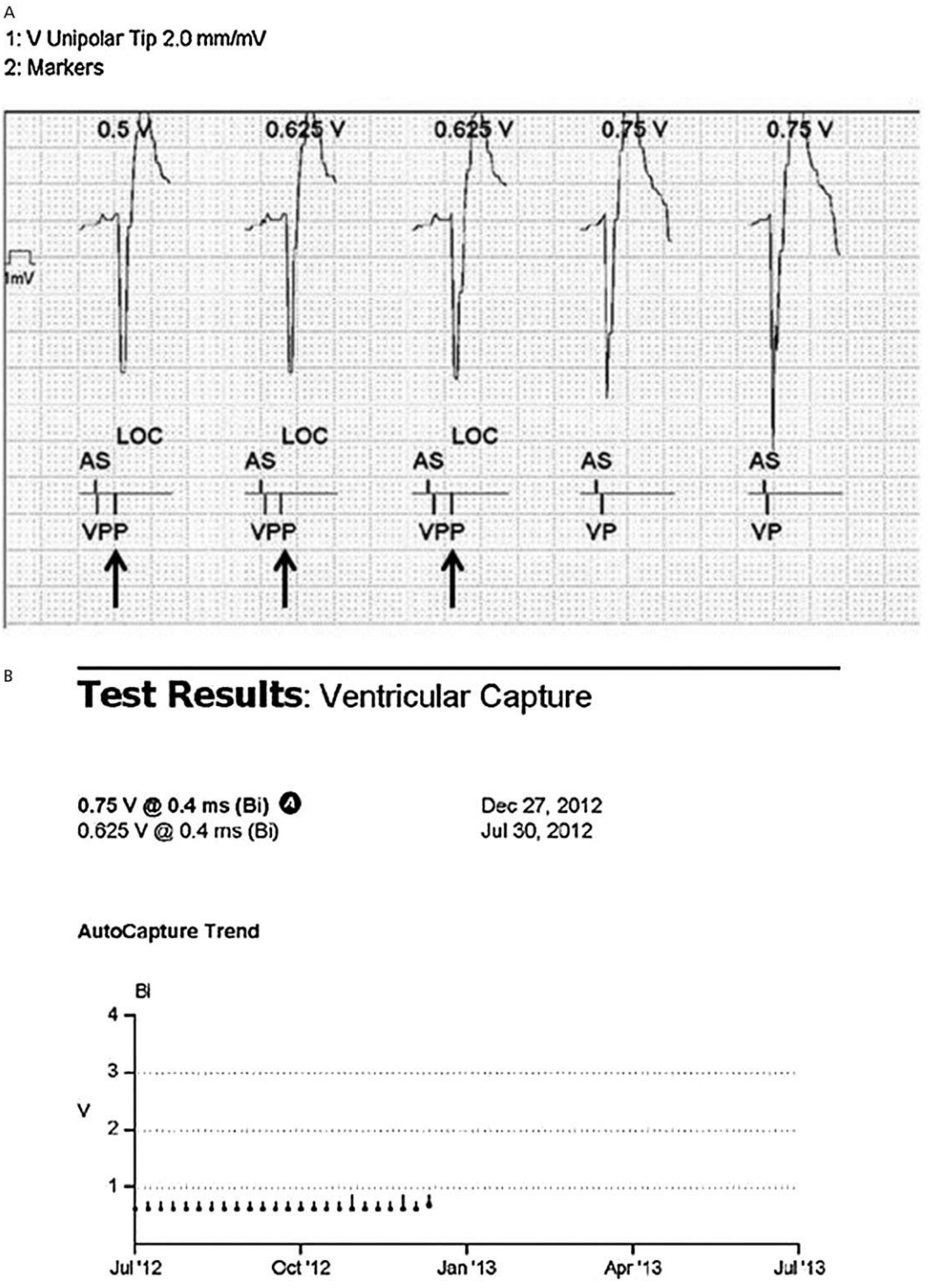


Figure 11.16 Ventricular auto-capture in a St. Jude Medical pacemaker. (A) Tracing stored during automatic determination of ventricular threshold. There is loss of capture (LOC) at 0.5 and 0.625 V, and appropriate capture at 0.75 V. Whenever there is loss of capture, a back-up safety pulse, P (arrows), is delivered. (B) Graphic display of ventricular pacing threshold over time as determined by the auto-capture algorithm.

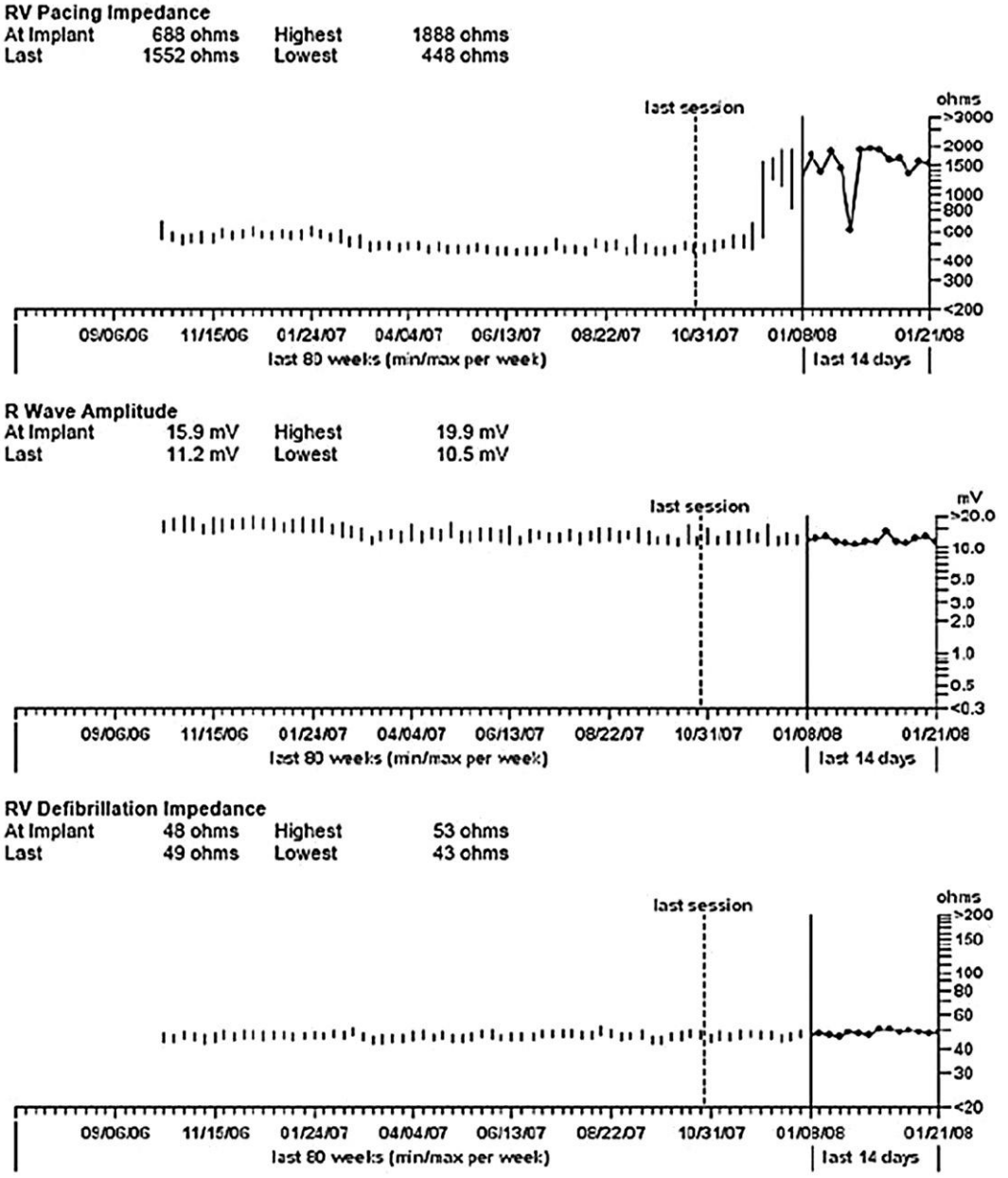


Figure 11.17 Lead performance report of a Medtronic Sprint Fidelis ICD lead from a patient implanted with a Medtronic ICD system, showing trends in pacing impedance, electrogram amplitude, and high voltage (defibrillation) impedance. Lead fracture was diagnosed based on the sudden elevation in pacing impedance.

recording of non-physiologically short intervals between intracardiac events, which indicate lead noise. Algorithms incorporating several of these parameters may be useful in early identification of lead problems, e.g. the lead integrity alert from Medtronic has proven to be useful in early identification of Sprint Fidelis™ lead fractures.[19]

Programmability of polarity has become increasingly available in current pacemakers and, unfortunately, is not infrequently required. Problems with insulation defects in certain polyurethane leads subject to the "subclavian crush" syndrome, resulting in low impedance values, may be temporarily addressed by reprogramming from bipolar to unipolar mode. Some devices will automatically reprogram the lead configuration to unipolar polarity when bipolar impedances are abnormal. This maneuver generally will increase the lead impedance in these situations and prevent loss of capture and possible undersensing, but will not prevent oversensing from make–break electrical transients arising from contact between the two conductors. Ultimately, lead replacement is required in the pacemaker-dependent patient. Occasionally, pacing or sensing thresholds will be significantly better in one polarity compared with the other. This may be helpful in the setting of marginal threshold values. General guidelines for chronic programming of common pacemaker parameters are given in Table 11.12.

Review of patient diagnostics

Telemetry of data stored in the device memory (stored data) is possible with current systems. This includes patient-specific diagnostics such as event counters and episodes. Some of this information may be available in a rolling time-window (temporal trends). These data may assist in diagnosing certain problems reported by the patient and in optimizing device function. Stored data also include historical information regarding battery and lead status, which has been discussed in the previous section; original implant values, model and serial numbers, and implant indications may also be available as stored data.

Overall event counters

Bradycardia counters provide an assessment of the pacing system over time. The percentage of events in each pacing state (A paced; V paced, A paced; V sensed, A sensed; V paced, A sensed; V sensed, premature ventricular events) and the overall percentage of pacing in each chamber is reported. With recent information regarding the deleterious effects of RV apical pacing, especially in patients with LV dysfunction, it is important to ensure that RV pacing is minimized if possible. On the other hand, in patients with CRT devices, biventricular pacing rates should be above 90% for effective resynchronization.

Heart rate histograms further separate the pacing states by rate. Atrial, ventricular, and AV conduction histograms are available in most devices. Histograms may also demonstrate how often different rates occur during rate-adaptive pacing at a particular activity-sensing threshold. The determination of such events (or predicted events) may enable the physician to reprogram the device settings so as to achieve rates thought to be more appropriate or "physiological" for the patient (sensor-indicated rate histogram) (Figure 11.18).

Episodal counters (episodes)

Episodal information is also available. This includes atrial and ventricular tachycardic (high rate) episodes, mode switch episodes, sudden rate drop episodes, PMT episodes, etc., which are triggered by specific device settings. In addition, some devices allow patient-activated memory storage, which can be triggered by placement of a magnet. In this way, the device can function as an event monitor.

The information available during each episode varies. The most basic description involves the time and duration of the episode with atrial and ventricular rates. Storage of EGMs and marker channels with cycle lengths is also possible in most devices as a programmable option. Interval plots reported in some devices can also be very useful.

Atrial high rate and *mode switch episodes* deserve particular mention. Storage of these episodes is particularly helpful in patients with atrial tachyarrhythmias, as it allows fine tuning of antiarrhythmic and AV nodal blocking medications, as well as rational assessment as to the necessity of anticoagulation. Not infrequently, a patient with a dual chamber device will present with new-onset atrial

Table 11.12 General guidelines for programming common bradycardia parameters

Parameter	*Situation*	*Chronic setting*	*Comments*
Lower rate limit	General	50–70 bpm	
	Heart failure	70–90 bpm	Benefit of high-rate pacing not proven
Upper rate limit	General	85% maximal predicted heart rate [(220 − age) × 0.85] bpm	Based on average levels of activity
	Children/athletes	(220 − age) bpm	May require programming short refractory periods
	Coronary artery disease/ angina	110–120 bpm	Approximates peak heart rates on maximal β-blockade
Pacing output	Fixed voltage	3× pulse width threshold	Minimizing voltage output is most efficient
	Fixed pulse width	2–3× voltage threshold	Use autothreshold functions
Sensitivity	Atrium	25–50% of threshold value	Need <1 mV setting for mode switching
	Ventricle	25–50% of threshold value	Evaluate oversensing in unipolar systems
AV delay	AV block	150–180 ms paced AV delay, sensed AV delay 25–40 ms lesser	Turn on rate-adaptive AV delay in active patients
	Intrinsic AV conduction (no CHF)	Maximize AV delay	Longer AV delays may compromise hemodynamics Use AV interval hysteresis to promote intrinsic conduction
	Hypertrophic cardiomyopathy	Approximately 100 ms	Optimize by Doppler Use negative hysteresis to force ventricular pacing
	Risk for CHF	Atrial non-tracking modes (VVI, DDI, DVI)	Minimize ventricular pacing Lower rate limit 40 bpm Hysteresis Long AV delay/AV search algorithm Minimal ventricular pacing algorithm Inactivate rate response Activate sleep rate Inactivate rate-adaptive AV delay Ensure appropriate atrial capture, mode switching, etc.
	CHF with CRT device	100–130 ms	Ensure >90% biventricular pacing Use negative hysteresis

AV, atrioventricular; CHF, congestive heart failure.

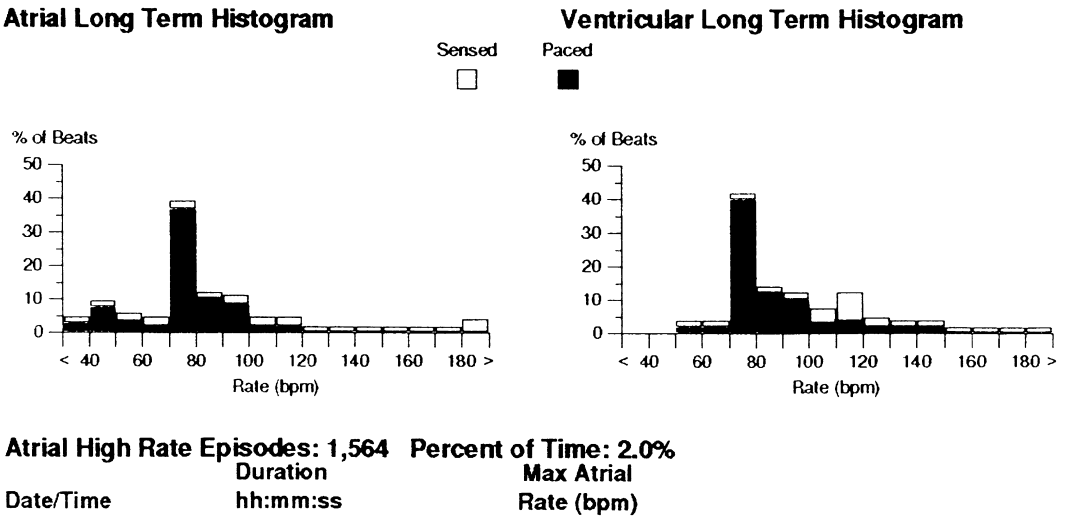


Figure 11.18 Telemetry of stored rate histogram for a patient with a rate-adaptive dual chamber pacemaker. The histograms display long-term data for the atrial- and ventricular-paced and -sensed rates.

fibrillation or flutter. The atrial fibrillation or flutter waves may be sensed and trigger rapid ventricular responses, often irregularly (Figure 11.19). Automatic mode switching is a very important feature incorporated into many dual chamber pacemakers for the management of atrial arrhythmias. It allows reversion from dual chamber pacing to single chamber ventricular pacing [or to a non-atrial tracking mode such as DDI(R)] when atrial arrhythmias are recognized, and a return to dual chamber mode when sinus rhythm has been restored. In general, this algorithm works well, but occasional undersensing of fibrillatory waves may result in frequent switches back to DDD mode for several seconds before re-recognizing the atrial dysrhythmia and again mode switching. This often results in the reporting of hundreds or even thousands of mode switch events corresponding to a single or just a few more sustained episodes of atrial fibrillation (AF). Separately, one occasionally sees oversensing in the atrial channel during sinus rhythm from far-field R waves. This can result in "double counting," which can spuriously trigger mode switch. Episodes of mode switching due to far-field R wave sensing are typically less than 5 min in duration; nonetheless, reprogramming sensitivity or refractory periods may occasionally be warranted under such circumstances. In non–mode-switching devices, the upper tracking rate limit may be reduced to minimize rapid ventricular tracking, but it is often more effective to reprogram the device to a DDIR or VVIR mode. The DDIR mode works particularly well for patients with significant sinus node dysfunction but intact AV conduction, who spend much of their time in sinus rhythm with atrial pacing. In some devices, atrial flutter may be converted to sinus rhythm by temporary burst pacing from the atrial channel manually or as part of automated atrial ATP therapies.

In ICDs, the tachycardia episodes are classified by the zone in which they are binned (VF, VT, SVT). The administration of therapies (ATP, high-voltage shock) and their effect (successful or not) is also reported. In some CRT devices, ventricular-sensing episodes are reported.

Temporal trends Multiple patient-specific arrhythmic and non-arrhythmic parameters can be trended over time in several devices. Atrial arrhythmia burden, ventricular arrhythmia burden, and ventricular rate during atrial arrhythmias and device therapies are some of the arrhythmic parameters that are available (Figure 11.20). In addition, trends of heart rate, activity, heart rate variability, respiratory rate, thoracic impedance, etc. are also

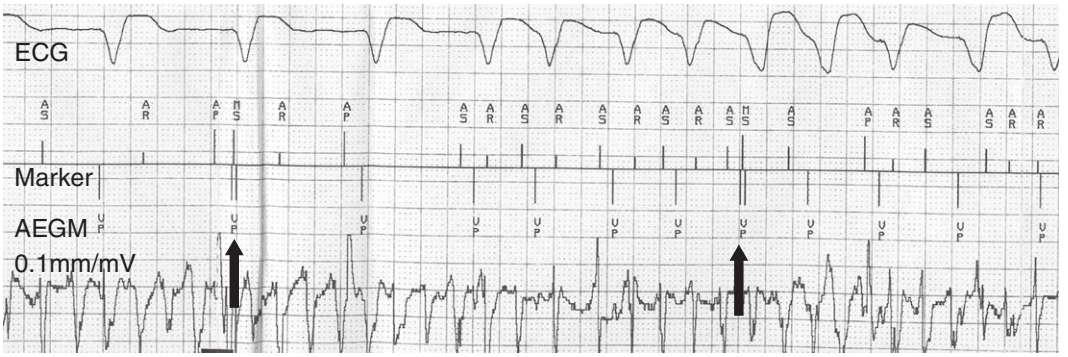
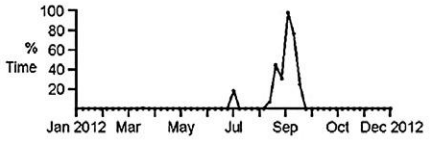


Figure 11.19 Rhythm strip showing intermittent ventricular tracking of atrial flutter/atrial fibrillation resulting in irregular ventricular pacing near the upper rate limit in the DDD mode. At the start of the tracing, the device is in mode switch non-atrial tracking mode with a slow paced ventricular rate. At the first arrow, the device exits mode switching to DDD mode because of atrial undersensing (MS on marker annotations). The second arrow identifies re-activation of mode switch behavior due to consistent atrial sensing with brief tracking at the upper rate limit. AEGM, atrial electrogram.

Diagnostics Summary	Since Aug 29, 2011
AP	86 %
VP	7.6 %
AMS Episodes	1190
Mode Switch	4.8%
AT/AF Burden	5.0%

VT/VF Episodes: 16	Since Oct 1, 2012
	VF
Episodes	16
ATP Delivered	
Shocks Delivered	25
SVT Episodes: 0	

AT/AF Burden	5.0%	Since Aug 29, 2011
Total AT/AF Burden	5.0%	Since Jun 6, 2011



VT/VF Episodes

Date / Time	Type	Rate (bpm)	Duration (M:S)	Therapy Delivered
Dec 29, 2012 5:52 am	VF	171	00:08	
Dec 29, 2012 4:56 am	VF	181	00:16	830V
Dec 29, 2012 4:56 am	VF	169	00:10	
Dec 29, 2012 4:54 am	VF	173	00:18	
Dec 29, 2012 3:23 am	VF	176	00:18	
Dec 29, 2012 3:18 am	VF	181	00:18	830V
Dec 29, 2012 3:17 am	VF	171	00:12	
Dec 29, 2012 2:30 am	VF	171	00:10	
Dec 29, 2012 12:49 am	VF	179	00:18	
Dec 24, 2012 3:29 am	VF	181	00:20	
Dec 22, 2012 8:43 pm	VF	171	00:12	
Dec 22, 2012 3:30 pm	VF	171	00:10	
Dec 22, 2012 3:29 pm	VF	169	00:10	
Dec 14, 2012 1:57 pm	VF	222	00:24	830V
Dec 11, 2012 2:12 pm	VF	190	00:08	
Oct 16, 2012 7:00 pm	VF	230	00:24	830V

Figure 11.20 Follow-up evaluation of a patient with a dual chamber ICD revealing both atrial tachyarrhythmia (AT/AF) burden and episodes of ventricular tachyarrhythmia (VT/VF) with ICD therapies.

available in several devices, which can provide valuable clinical information. For instance, the OptiVol fluid index in Medtronic devices that is derived from the transthoracic impedance may be a useful marker of incipient heart failure.

With some devices, the counters are automatically reset following each device interrogation. In others, it is important to manually "clear diagnostics" at each interrogation; failure to do so may result in the counters being frozen after reaching their storage limit. The patient-specific trends typically encompass a rolling time window of several months, and usually do not need to be manually cleared.



Figure 11.21 Cross-talk in a unipolar dual chamber pacemaker. (A) This patient was referred for loss of capture on the ventricular lead. The ECG shows atrial pacing consistently but ventricular output in only some cardiac cycles. Telemetry showed ventricular sensing within 40–60 ms of the pacing output that inhibits ventricular pacing. (B) After reducing ventricular sensitivity from 2.8 to 5.6 mV, inhibition of ventricular output was corrected. This device did not have programmable post-atrial pacing ventricular blanking intervals or safety pacing, which would have also resolved the cross-talk.

Special considerations and maneuvers

In dual chamber systems several problems may require evaluation during follow-up visits as the clinical situation arises. The possibility of *cross-talk*, i.e. inappropriate sensing of the atrial pacing artifact on the ventricular channel, resulting in ventricular pacing inhibition, can be assessed by programming the ventricular channel to its highest sensitivity and the atrial output to its highest value (Figure 11.21). The programmed rate should exceed the native rate so as to require continuous atrial pacing, and the programmed AV interval should be shorter than the native PR interval. Cross-talk is most likely to occur with unipolar pacing systems. The absence of cross-talk inhibition at maximal atrial output and maximal ventricular sensitivity suggests that this problem is not likely to be encountered at usual settings. Fortunately, cross-talk is much less of a problem with modern pulse generators that incorporate various techniques to minimize this problem, such as ventricular blanking periods and cross-talk sensing windows. Assessment of this phenomenon should be undertaken cautiously in patients with heart block, because ventricular asystole may occur. Identification of cross-talk warrants reprogramming, when possible, to lower atrial output or ventricular sensitivity, prolongation of ventricular blanking period, or consideration of another mode such as VDD.

The propensity for *PMT* in the DDD mode may be explored by shortening the post-ventricular atrial refractory period (PVARP) to its minimum and programming atrial output to subthreshold levels. If retrograde ventriculoatrial conduction is present, PMT may be observed if it is triggered by a spontaneous PVC or if loss of atrial capture occurs. In the latter case, AV sequential pacing fails to capture the atrium, but captures the ventricle, with retrograde conduction leading to activation of the atrium and setting up PMT. PMT may be managed by decreasing the upper ventricular tracking rate, extending the PVARP (which may limit the desired upper tracking limit), changing to

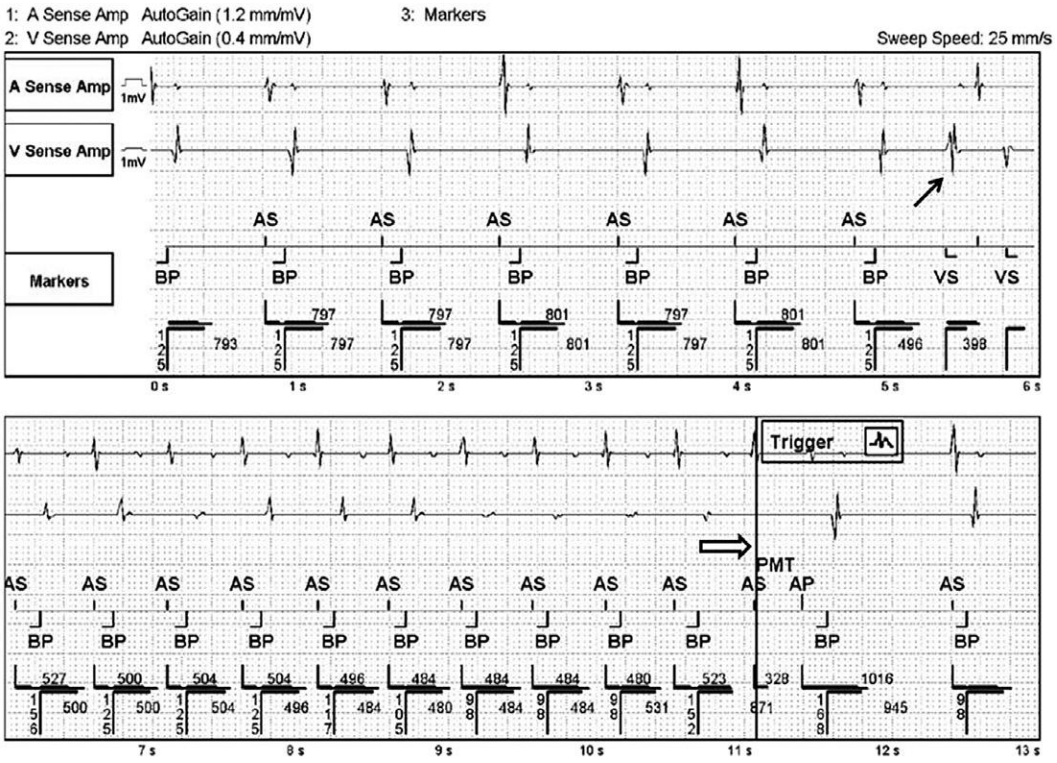


Figure 11.22 Episode of pacemaker-mediated tachycardia (PMT) retrieved during routine follow-up of a St. Jude Medical CRT-D. A premature ventricular complex (arrow) initiates a run of PMT. When the device detects PMT (open arrow), ventricular pacing is inhibited for one beat, which terminates the episode.

a non-atrial tracking mode such as DDI or activating PMT intervention algorithms. These can include an increase in the PVARP after a PVC, which will minimize the chance of initiating PMT, or periodically "dropping" a ventricular-paced beat with any tachycardia near the upper rate limit (Figure 11.22). The tachycardia will be terminated if it is indeed a PMT, but only a brief pause created if the pacemaker is tracking an intrinsic atrial rhythm that the pacemaker was tracking, i.e. sinus tachycardia. Many devices allow programming of a rate-adaptive PVARP that shortens the PVARP at more rapid rates, permitting a long PVARP at rest without unduly imposing limits on the upper rate.

In addition to the above considerations in dual chamber pacing systems, special maneuvers may be performed as dictated by the clinical situation [see Table 11.5 and "Dynamic maneuvers (during physical examination)"]. This includes testing for myostimulation (pectoral and diaphragmatic), for oversensing of myopotentials (pectoral and diaphragmatic), or for intermittent loss of capture due to lead or connector issues, excessive lead tip motion, or insufficient lead slack.

Programming considerations

Atrioventricular interval

Data[20] suggesting that RV pacing may worsen symptoms of congestive heart failure in those with underlying cardiomyopathy have refocused attention on appropriate programming of the AV interval. Studies suggest that the risk of heart failure in patients with sinus node dysfunction can be related to the cumulative percentage of ventricular pacing and the paced QRS duration.[21] The highest risk of heart failure occurs at greater than 40% cumulative ventricular pacing in the DDD mode.[21] Certainly, in those with diminished LV function and narrow intrinsic QRS duration, one should make attempts to prolong the AV delay

sufficiently to minimize RV pacing. This can be accomplished in several ways. Programming a long fixed AV delay is one option. A second option is enabling an AV search hysteresis feature, which is available in many devices. With this feature, a back-up AV interval is set as well as a further delay that is added to the programmed value, allowing additional time to encourage native conduction. If no intrinsic R wave has been sensed by the end of the summed interval, the programmed "physiological" AV delay will become active, but with periodic searches for native conduction. Some devices have newer algorithms that allow programming to a minimal ventricular pacing mode.[22] This provides pacing in an AAI(R) mode with beat-to-beat analysis checking for antegrade conduction. If there is failure of AV conduction, the device will automatically mode switch to DDD(R) (Figure 11.23). Programming the device to DDI(R) mode is sometimes worthwhile as well.

Patients with normal LV function are rarely able to distinguish between native conduction and P-synchronous pacing. Nevertheless, the above techniques to minimize ventricular pacing may still be worthwhile, if only to maximize battery duration. However, there is clearly an AV delay sufficiently long that the benefits of inhibiting ventricular pacing are outweighed by the adverse hemodynamic effects that can result with marked first-degree block. Much of this detrimental effect may be linked to atrial contraction occurring during or immediately after ventricular systole, creating "*pseudo-pacemaker syndrome*." Certain studies have demonstrated that this detrimental effect is seen with PR intervals of longer than 220–240 ms.[23] In occasional patients who continue to complain of breathlessness after a pacemaker is implanted, an attempt at AV optimization using Doppler echocardiography or impedance cardiography may be warranted. Both AV as well as LV/RV optimization is a subject of particular interest in those with biventricular devices. Traditional mitral inflow and aortic outflow Doppler measurements as well as tissue Doppler techniques may be utilized.[24] Optimization of AV and VV intervals may be useful in selected patients, but randomized trials have thus far failed to demonstrate any benefit of algorithmic AV and/or VV optimization on outcomes in CRT patients.

In contrast to the previous situations, there are also situations in which ventricular pacing is desired. This is particularly true when dual chamber pacemakers are placed for symptom relief in those with hypertrophic obstructive cardiomyopathy. Programming a short fixed AV delay is one option, although more sophisticated algorithms such as negative AV interval hysteresis can be effective in allowing for the longest AV interval that still provides 100% ventricular pacing. Patients with biventricular pacemakers represent another group where continuous ventricular pacing is desired. This is often difficult when these patients develop

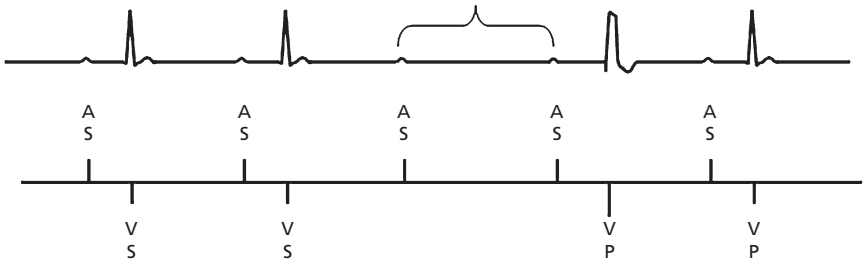


Figure 11.23 Schematic of Medtronic's managed ventricular pacing (MVP) algorithm. AAI(R) pacing is operative until a PP interval occurs without containing a sensed ventricular event (bracket). AS, atrial-sensed event; VP, ventricular-paced event. Ventricular pacing occurs after the P wave. AAI(R) pacing then resumes until two of four PP intervals occur without sensed ventricular events. This triggers DDD(R) pacing for a preprogrammed number of intervals, then the AAI pacing may again become operative. Because the sensed ventricular event may occur at any time in the PP interval, minimization of ventricular pacing may occur at the cost of atrioventricular synchrony.

rapid AF. New algorithms are being developed to assist in this situation. One such algorithm automatically increases the ventricular pacing rate after every sensed ventricular event. Another provides a "triggered" mode where each sensed RV beat immediately results in LV pacing, resulting in a fused QRS complex that is more synchronized than the intrinsic beat would be alone. Finally, in patients with a "traditional" dual chamber pacemaker, underlying cardiomyopathy, and a baseline RBBB, biventricular pacing can often be simulated. To accomplish this, one carefully programs the AV delay so as to create fusion between the RV-paced complex and the native QRS (which, due to the RBBB, is activating the LV first) and thus create some measure of resynchrony.

A *differential AV delay* is now incorporated into virtually all dual chamber devices. This allows for programming of a shorter AV delay for the sensed AV interval (sAV) compared with the paced AV interval (pAV). This accounts for the fact that the pacemaker does not recognize a sensed atrial event (and start the sAV timer) until atrial depolarization is well under way. The differential AV delay thus keeps the time between atrial and ventricular contraction constant regardless of the presence of atrial pacing. A differential value of 25–40 ms is considered appropriate. Most devices also now have a *rate-modulating AV delay* feature. This provides for a shortening of the AV interval during exercise, mimicking the normal positive dromotropic effect seen in those with normal AV conduction. This feature provides a hemodynamic benefit as well as allowing for the programming of a higher maximum tracking rate. This feature should ordinarily be programmed "on" in those with AV conduction disturbances.

Other specific functions should be programmed as indicated. Rate-adaptiveness may be enabled or adjusted based on the heart rate histograms. Sleep rate, hysteresis rate, rate drop response, rate smoothing, etc. can be considered on an individual basis. Guidelines for chronic programming of basic dual chamber pacemaker parameters are shown in Table 11.12.

Implantable loop recorders

Implantable loop recorders (ILRs) are diagnostic devices typically implanted in the subcutaneous tissue of the left chest, and record a high fidelity bipolar ECG signal from two sensing electrodes on the device. ILRs have been used for the investigation of recurrent unexplained syncope following initial negative work-up. They are also being used for the detection of silent arrhythmias such as AF, either to quantify the atrial arrhythmia burden following left atrial ablation or to identify the etiology of cryptogenic embolic stroke. ILRs are interrogated in clinic using the same manufacturer-specific programmers used for pacemaker and ICD interrogation. Some devices enable home monitoring using the manufacturer-specific remote monitoring system.

The patient can trigger EGM storage by using a hand-held activator, at the onset of symptoms. The device can be also programmed to automatically store high and low heart rate episodes and pauses. The episodes retrieved from the device should be carefully examined. Undersensing may be the cause of bradycardic episodes or pauses. Likewise, T wave oversensing can be the cause of tachycardia detection. The sensitivity may be adjusted in clinic if several episodes of over- or under-sensing are noted. When diagnosis of an arrhythmia responsible for the patient's symptoms leads to pacemaker or ICD implantation, the ILR should be explanted at the same time as implantation.

Outpatient monitoring

In addition to in-person evaluation of the CIED in the clinic, there are several ways in which CIEDs can be monitored remotely.

Trans-telephonic monitoring

A variety of electrocardiographic techniques enable ambulatory determinations of pacemaker function between clinic visits. The most important of these is trans-telephonic monitoring (TTM) of the patient's free-running and magnet rates. This technique does not supplant the direct outpatient visit with the device physician. It does, however, reduce the frequency of outpatient visits, which may be particularly burdensome for patients who are frail, are unable to travel, or live remote from medical facilities. Despite its limitations, TTM enables the device physician to determine changes in free-running or magnet pacing rates indicative of



Figure 11.24 Intermittent loss (arrows) of ventricular capture documented on ambulatory Holter monitoring.

battery depletion and may indicate problems with pacemaker sensing or capture. Certain device models only allow for this modality of ambulatory monitoring and not the newer forms of remote monitoring described below.

Holter and event recorders

As an extension of this approach, 24-h Holter monitoring may be useful for uncovering problems with pacemaker malfunction that are potentially responsible for a patient's symptoms (Figure 11.24). The approach is limited by sampling error in patients with infrequent symptoms, as no abnormalities may be identified if the patient is "having a good day." Rather, the technique is more often useful in demonstrating previously unsuspected and asymptomatic malfunctions, such as intermittent undersensing or myopotential triggering. Activity-related rate trends warranting reprogramming, particularly with dual chamber or rate-adaptive pacing, may be observed with Holter monitoring. Patients with infrequent symptoms may benefit from 30-day event monitoring. As noted previously, many devices have the ability to store episodes with EGMs in response to patient activation, thereby serving as an event monitor.

Remote monitoring

All manufacturers of pacemakers and ICDs have released enhanced outpatient remote monitoring systems, which vastly increase the amount of data available to the clinician. These systems include an external monitoring device that can communicate with the implanted device and provide information equivalent to that when interrogating a device in the office, including stored EGMs from high-rate events in pacemakers as well as printouts from VT/VF events in ICDs.[25] This technology is already being expanded to provide additional data on non-arrhythmic variables, such as transthoracic impedance measurements, from one manufacturer that may provide preclinical information on incipient heart failure and the inclusion of a blood pressure cuff and scale with the system from another manufacturer. These systems are being created to allow specialized datasets so that the general cardiologist or heart failure specialist can access certain data streams, while the electrophysiologist can access others. With the increased automaticity of many devices, pacing and sensing thresholds are often available.

Many new ICDs and some pacemakers incorporate transmitters/receivers to allow communication with the monitoring device wirelessly. Usually the patient has to be within 15 feet of the receiver, making placement of the device on the nightstand in a patient's bedroom ideal. Once set up, there is often no need for any patient involvement. With implanted devices lacking wireless technology, an antenna similar to a programmer

head is placed directly on top of the generator.[26] The monitoring device is typically plugged into a traditional phone line and the information is then uploaded to a password-protected internet website. Other modes of transmission, such as use with cell phones or with voice-over-internet telephony, are being actively addressed. Some devices (Biotronik's Home Monitoring transceiver) are themselves cellular units, capable of independent transmission.

With wireless communication, the remote monitoring process is automatic, whereas when a wand is required, it has to be patient activated. The system can be set up to transmit information on a pre-specified schedule, i.e. every 3 months. Certain "alert" situations such as battery at ERI, lead impedances out of range, multiple defibrillator shocks, or onset of AF can trigger immediate transmissions. Depending on the system being used, the clinician can be advised of these "alert" transmissions via page, fax, phone, or internet review. These systems often allow the patient to "trigger" a transmission if concerned about a possible shock, a symptom such as syncope, or an audible alert.

These monitoring devices are usually portable, i.e. patients can take them when they travel or go to second homes, etc. These enhanced outpatient monitoring devices are predominantly being utilized for ICDs. The technology is becoming available for PPMs as well and may well supplant traditional TTM in the future. Updated guidelines for the application of this technology are being developed.[27] Although the technology is already available for the physician to remotely reprogram the device, safety concerns limit access to this feature at present. Similar to stand-alone programmers, manufacturers are using proprietary technology and thus the chance for universal equipment appears remote.

The TRUST trial, which randomized about 1500 people implanted with Biotronik ICDs between conventional in-office follow-up and remote monitoring, demonstrated that home monitoring reduced total hospital encounters for device interrogation by nearly 50%. In addition, remote monitoring facilitated earlier physician evaluation of all arrhythmias and of silent events.[28] Remote pacemaker follow-up has been shown to identify clinically actionable events earlier and more frequently than TTM, though surprisingly there remains a significant delay between identification of an event and actual intervention by the clinician.[29,30]

Table 11.13 Follow-up recommendations for CIEDs

	In person	*Remote**
Pacemakers, ICDs, CRT devices		
Initial		
	Before discharge	N/A
	2–4 weeks	N/A
	4–12 weeks	N/A
Subsequent:		
Pacemakers and CRT-P	6–12 months	3–6 months
ICDs and CRT-D	3–6 months	3–6 months
At signs of battery depletion	1–3 months	1–3 months
Implantable loop recorders	1–6 months	1–6 months
Implantable hemodynamic monitors	1–6 months	1–6 months

*All patients with CIEDs, including those followed remotely need at least an annual in-person evaluation.
CRT-D, CRT ICDs; CRT-P, CRT pacemakers.

Frequency and mode of follow-up

With increasing availability of reliable remote monitoring, and the time constraints imposed on physicians by in-person follow-up, there has been a recent paradigm shift in follow-up monitoring of CIEDs.[31] This is reflected in an expert consensus document, which is summarized in Table 11.13.[27]

In-person follow-up is crucial in the immediate post-implantation period for pacemakers and ICDs (before discharge, in 2–4 weeks, and in 4–12 weeks) to evaluate wound healing and recognize early complications. Subsequent follow-up can be predominantly clinic based (every 6–12 months for pacemakers, every 3–6 months for ICDs) or remote (every 3–6 months). Intensified follow-up (every 1–3 months) is recommended as the device nears

battery depletion. For ILRs, in-person or remote follow-up every 1–6 months is recommended. Patients with implantable hemodynamic monitors may also be followed up on a similar schedule, although some might need more frequent follow-up. *Any person with a CIED should be assessed in person at least once a year*, including those followed remotely.

Trans-telephonic remote follow-up is limited to pacemakers. Given its limitations to detect device system problems, this should not be the sole means of pacemaker follow-up, but should rather supplement clinic follow-up. TTM is typically performed every 3 months, with increased frequency (every 1–2 months) as the device nears ERI.

Deviations from the recommended schedules may be needed for pacemaker-dependent patients, devices under recall or alert, or for changes in the patient's clinical condition. Patients experiencing symptoms potentially related to pacemaker function or malfunction are encouraged to transmit their rhythm when they are symptomatic, independent of the above scheduling guidelines.

Special situations encountered by the CIED patient

Electromagnetic interference

EMI can occur from radiated or conducted energy. Sources of EMI are found in the medical and non-medical environment. Various effects of EMI on CIEDs are summarized in Table 11.14. Oversensing is common to all sources of EMI (Figure 11.25). The most important concern is that oversensing of EMI can lead to inhibition of pacing, which can result in asystole in the pacemaker-

Table 11.14 Electromagnetic interference (EMI) and CIEDs

Effects	
Effect	*Consequence*
Oversensing	Pacing inhibition
	Inappropriate tracking (atrial channel)
	Inappropriate mode switch (atrial channel)
	Safety pacing (ventricular channel)
	Asynchronous pacing (noise response/noise reversion)
	Inappropriate therapies (ICD)
Magnet mode (response)	Asynchronous pacing (pacemakers)
	Inhibition of tachycardia functions (ICDs)
Power-on (electrical) reset	Change in bradycardia parameters (pacemakers and ICDs)
	Change or loss of tachycardia functions (ICDs)
Device malfunction	Unpredictable failure of device function
Lead–tissue interface damage	Elevated pacing thresholds
	Induction of arrhythmias
Other	
Activation of rate response	Rapid pacing
Direct myocardial capture	Rapid pacing
Spurious programming	
General management strategies	
Reduce exposure	Avoid known sources if possible
	Keep source as far away as possible
	Minimize time of exposure
Minimize consequences (of oversensing)	Magnet application
	Reprogramming

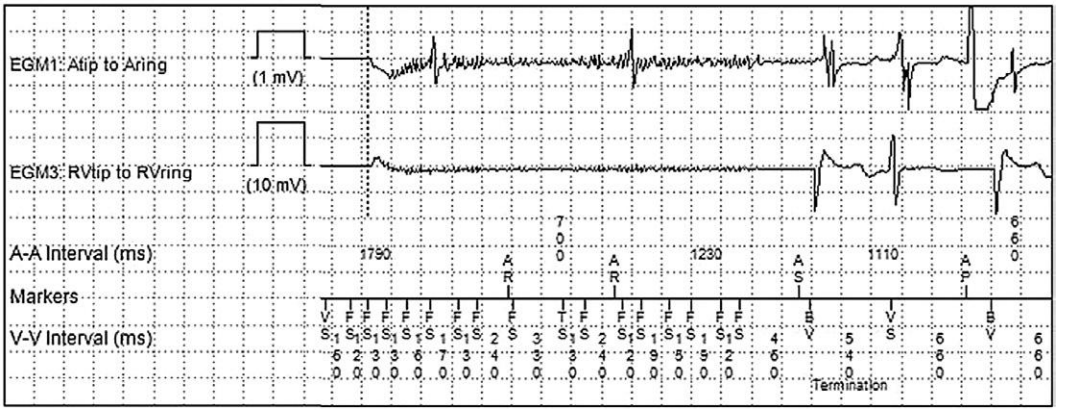


Figure 11.25 An episode of oversensing of electromagnetic interference (EMI) retrieved during device follow-up. Transient electrical noise artifact is seen on both the atrial and ventricular channels.

dependent patient. Most devices have noise response (noise reversion) algorithms, which can be triggered when EMI is oversensed, leading to asynchronous pacing. Asynchronous pacing may trigger an arrhythmia due to ventricular pacing in the vulnerable period. Oversensing of EMI can also result in inappropriate tracking, mode switch, or safety pacing. Oversensing of EMI by an ICD may result in inappropriate therapies, including ATP and shocks. In addition to oversensing, EMI can trigger the magnet mode, or the power-on reset mode, and can rarely cause device malfunction. Other effects of specific sources of EMI are discussed below.

General management strategies for EMI (Table 11.14) primarily focus on reducing the likelihood of exposure to EMI (avoiding known EMI sources if possible, keeping the source of EMI as far away as possible, and reducing the time of exposure) or minimizing the consequences of EMI. The latter is targeted against oversensing of EMI, and may be accomplished by application of a magnet over the CIED, or by reprogramming. In general, magnet application results in asynchronous pacing (in a pacemaker) or disabling of tachycardia detection (in an ICD). Reprogramming of the device to an asynchronous pacing mode and/or disabling of tachycardia detection can be done instead of using a magnet. Either strategy is appropriate in a patient with a pacemaker or in a patient with an ICD who is not pacing dependent. However, reprogramming (to an asynchronous pacing mode along with disabling of tachycardia therapies) is essential in a pacemaker-dependent patient who has an ICD. It is important to note that either magnet application or reprogramming only minimizes the effects of oversensing of EMI, and other effects of EMI can still occur. Strategies to minimize some of these source-specific effects are briefly discussed below.

Non-medical sources

Anti-theft (electronic article surveillance, EAS) devices are becoming ubiquitous in retail centers. Several different technologies are used to detect metal alloy-containing tags on merchandise. These have been observed to potentially interact with implanted devices, resulting in inappropriate device triggering or, in the case of implanted defibrillators, inappropriate discharge. Device reset with reversion from dual chamber pacing to single chamber ventricular pacing with resultant pacemaker syndrome has been observed. These interactions appear to be clinically infrequent, particularly with diminishing use of acoustomagnetic technology. Since interactions are more likely with prolonged, close exposure, patients should be told to walk through the store threshold without either lingering or leaning directly against the gates.[32]

Walk-through or hand-held metal detectors are used at airports and other places requiring high security. The detector alarm will usually be triggered by the CIED, but device function is unlikely to be affected because of the transient nature of exposure to EMI. Patients may pass through security metal detectors without lingering. Patients with implanted devices should notify security staff of the presence of the device. The metal-detecting wand may be passed over the device quickly in a single stroke. Repeated back-and-forth motions over the device are to be avoided.

It has been recognized increasingly that cell phones may interfere with the function of implanted devices. In one study, the potential for any type of interference was 20%, with associated symptoms in 7.2%, when the phone was placed over the generator.[33] The most common pacemaker interactions include tracking interference on the atrial channel followed by asynchronous pacing and ventricular inhibition. Potential ICD interactions include reed switch activation leading to VT underdetection and erroneous shock therapy, although reports of the latter have been extraordinarily rare. Interference was more common in older devices without feed-through filters. Since most interactions occurred at distances of less than 10 cm, a reasonable recommendation would be to avoid placing cell phones in the breast pocket over the device.[34] Some advocate holding the phone over the ear contralateral to the device while using it. Particular care should be exercised with high-powered fixed cellular devices such as those in cars and boats.

Digital music players can cause interference with programmer telemetry but are unlikely to affect CIED function. Portable headphones use a magnetic substance that can cause EMI and interfere with device function. All reported interactions occurred when the headphones were within 3 cm of the device; so the headphones should be kept at a safe distance from the device.[35]

Common household appliances such as microwave ovens, toasters, and televisions, do not interact with CIEDs. When using electrical tools, such as drills and chainsaws, it is prudent to maintain a safe distance (6 inches or more) between the motor and the CIED. It is important to ensure that all electrical equipment is properly grounded. Arc welders can interact with CIEDs and special precautions are necessary. Magnetic mattresses or chairs, and devices that deliver electrical current through the body [such as body fat estimators (bioelectrical impedance analyzers)] should be avoided.

Some common non-medical sources of EMI and recommendations for patients with CIEDs are summarized in Table 11.15.

Tasers are sometimes used by law-enforcement agencies. These weapons use electrical current that can interefere with pacemaker or ICD function. Slot machines have been reported to cause EMI resulting in ICD shocks.

Medical sources

Interactions between CIEDs and various medical sources of EMI have been well described in the literature, and a recent document provides an excellent summary of these studies.[15]

Electrosurgery (electrocautery)

Electrosurgery is often required intraoperatively, and is the most common source of EMI in the medical environment. The monopolar configuration is commonly used and involves delivery of current between the cauterizing device and a return electrode placed on the skin. The bipolar configuration, which is sometimes used, involves delivery of energy between two electrodes at the tip of the device. Monopolar cautery can affect CIED function, whereas bipolar cautery does not cause any significant interaction.

Like any other source of EMI, electrocautery can cause oversensing, which can result in inhibition of pacing output or inappropriate ICD therapies. In addition, it can cause irreversible damage to the generator or resetting of the device to a back-up mode.

Procedures below the umbilicus are less likely to cause interference with a CIED located in the usual position in the upper chest if the return electrode is placed on the lower body. Interference should be anticipated with procedures above the umbilicus, and magnet application or reprogramming should be considered, especially if the patient is pacemaker dependent and/or has an ICD.

Table 11.15 Selected non-medical sources of EMI and recommendations for the CIED patient

Specific precautions	
Antitheft devices (EAS systems)	Walk through without lingering or leaning directly on the device
Airport metal detectors	Inform security personnel of device
	Walk through quickly (may trigger alarm)
	Hand-held wand may be passed quickly over the device
Cell phones	Do not place cell phone in breast pocket over (ipsilateral to) CIED
	Hold cell phone over contralateral ear
	Keep fixed high-output phones (car and boat phones) at least 15 cm away from device
Portable headphones	Keep at least 3 cm away from device
Electric tools	Proper grounding
	At least 15 cm distance between motor and device
Arc welding	Wear non-conductive gloves
	Keep welding cables away from device
	At least 1 meter between welding arc and device
No specific precautions required (minimal to no interactions)	
Household appliances (microwave, TV, toasters, electrical can openers, food processors)	
Remote control devices	
Electric blankets	
Digital music players (iPods)	
To be avoided	
Devices that pass electrical current through the body (e.g. body fat estimators)	
Magnetic mattresses or chairs	

It is important to maximize the distance between the site of cautery and the CIED. It is ideal to avoid cautery entirely near the pulse generator, if possible. Bipolar cautery should be considered if required near the CIED. For monopolar cautery, the grounding pad should be placed as far as possible from the CIED and in a location where the vector from the cautery tip to the pad moves directly away from the pulse generator. Short bursts of cautery and the least required power settings are recommended. Surface ECG monitoring becomes unreliable when cautery is used, and an alternative mode of rhythm monitoring, such as arterial pressure or plethysmography, is essential. The device should be interrogated after the procedure.

Defibrillation/cardioversion

Transient undersensing and both acute and chronic rises in pacing threshold have been observed with defibrillation and cardioversion (Figure 11.26).[36] Some of this may relate to transmission of current down the lead(s) causing injury at the tissue–electrode interface, resulting in the potential for exit block. The majority of problems seen after electrical cardioversions are encountered with unipolar pacemakers implanted in the right pectoral fossa. To minimize these types of phenomena, cardioversion or defibrillation should be performed via AP rather than anteroapical paddles. Minimizing the defibrillating energy by using more efficient biphasic defibrillators is desirable. In addition, pacing and sensing thresholds should be checked following external defibrillation. Finally, equipment for temporary pacing should be close to hand, especially for a pacemaker-dependent patient.

Both electrocautery and defibrillation can produce irreversible damage to the generator. This is more likely in older devices that lack protective mechanisms such as Zener diodes, which shunt energy away from the delicate device circuitry. They may also result in resetting of the generator to a back-up mode.

Endoscopy

Certain endoscopic procedures require the use of cautery, including treatment of bleeding ulcers and



Figure 11.26 (A) Loss of capture in a VVI pacemaker following DC cardioversion for atrial fibrillation. (B) Tracing obtained 3 min after the shock (arrow) showing persistent loss of capture at the paced rate of 60 bpm. The threshold increased transiently from 0.6 to 3 V, but returned to baseline within 10 min.

the removal of colonic polyps. Although there is a paucity of reports in the literature regarding interactions during these procedures, a cautious approach still seems rational. With endoscopic procedures where cautery will be used, placing a magnet over the generator in pacemaker-dependent patients and using a magnet or temporarily turning off tachycardia detection in patients with an ICD are reasonable approaches. Capsule endoscopy is an increasingly used novel system for visualizing the small intestine. The labeling of the device reports it is contraindicated in patients with ICDs. The contraindication was based more on theoretical concerns rather than hard data. Several publications have reported absolutely no effect of the capsule on pacemaker function. The largest report involved 100 pacemaker patients tested with an external device simulating the capsule transmissions and moved over the generator and along the chest wall. The distances between device and simulator were closer than those that would occur *in vivo*. There were no dangerous interactions. In four patients, the device briefly switched to a noise reversion, asynchronous pacing mode.[37] In rare instances, the output of the cardiac device can interfere with the video acquisition from the capsule, i.e. with an abdominal pacemaker generator.

Magnetic resonance imaging

Magnetic resonance imaging (MRI) presents a particularly noxious environment for cardiac devices. All components of MRI—the static magnetic field, gradient magnetic field, and pulsed RF field—can interfere with device function. The static magnetic field can cause reed switch closure, resulting in magnet mode, and can cause unpredictable

magnetic sensor activation. In addition, it can exert sufficient torque on the device within the pocket, but with diminishing amounts of ferrous material in recently constructed systems much less rotational and translational force is brought to bear.[38] The alternating magnetic field and rapid RF pulses can result in oversensing of EMI, which can cause pacing inhibition, noise response, inappropriate tracking, or inappropriate ICD shocks. Heating can occur at the electrode–myocardial interface as a result of the RF field, resulting in thermal injury, increase in pacing thresholds, or myocardial perforation. This heating is more pronounced with abandoned leads than with leads connected to a pulse generator. Rapid pacing corresponding to the pulse frequency can occur due to the effects on the output circuits.

The presence of a pacemaker or ICD should be considered a relative contra-indication to MRI. This caution is encouraged by device labeling, and recommended by MRI manufacturers and the FDA,[39] which continues to follow this subject with significant interest. Before device placement, the implanter should give careful thought to the potential need for MRI and, when feasible, complete the imaging before implant. It has been estimated that 50–75% of patients with implanted devices will have an MRI exam recommended over the lifetime of the device. In addition to the effect of MRI on CIED function, it should also be noted that the MR image quality may be affected by the presence of a CIED.

In spite of these concerns, there is a growing body of literature reporting on the potential safety of cardiac devices and MRI. So far, about 2000 patients with CIEDs have undergone MRIs with no significant effects.[40] Recent studies have not reported any examples of pacemaker inhibition, arrhythmia induction, lead dislodgement (chronic implants), or generator failure.[41–43] Small, clinically insignificant decreases in sensed EGMs and increases in capture threshold have been observed in a few patients. Power-on reset occurred in a few patients; the reed switch was activated only in a portion of the exams. This holds out the theoretical possibility of potentially life-threatening pacing inhibition in a pacemaker-dependent patient whose device is programmed asynchronously but undergoes a POR to VVI. The reed switch may not be activated and the pacemaker may then be subject to inhibition by EMI from the MRI.

The American Heart Association (AHA), European Society of Cardiology (ESC), and American College of Radiology (ACR) have published guidelines regarding use of MRI in patients with CIEDs.[40] Careful patient selection is important. The device should be interrogated in detail immediately before and after the exam is completed. Prior to the MRI scan, the device should be programmed to an asynchronous mode in pacemaker-dependent patients or to a non-sensing or non-tracking mode in patients who require pacing support only rarely. Tachycardia therapy should be disabled in ICD patients. Rate modulation should be disabled. Careful monitoring of the patient, including continuous verbal communication, ECG, and pulse oximetry, is essential as is the presence of emergency resuscitation equipment, a radiologist, and a cardiologist. Although MRIs with CIEDs are coming closer to acceptance, referral to a center experienced in these exams is advocated until more specific protocols for the correct spin sequences, maximum specific absorption rate (SAR), and acceptable MRI machines and CIED models are developed.

Pacing systems specially designed for the MRI environment (MR-conditional or MR-compatible pacing systems) have recently been developed.[44] These incorporate several features, such as replacement of the reed switch by a Hall sensor, changing the lead input–filtering capacitance to minimize energy induced on leads, internal power supply circuit protection, reduction in ferromagnetic components, and lead geometry changes to reduce lead heating. Two such systems (Medtronic's Revo SureScan and Biotronik's pro-MRI) have been tested in clinical trials, and a third (from St. Jude Medical) is undergoing clinical testing. An MR-compatible ICD system based on Biotronik's pro-MRI platform was tested in clinical trials in Europe. Limitations with these MR-compatible devices should be noted; clinical trials so far have been limited to a static magnetic field strength of 1.5 T, and have excluded imaging of the chest.

Left ventricular assist devices

Left ventricular assist devices (LVADs) may be used as a bridge to transplant or as destination therapy in

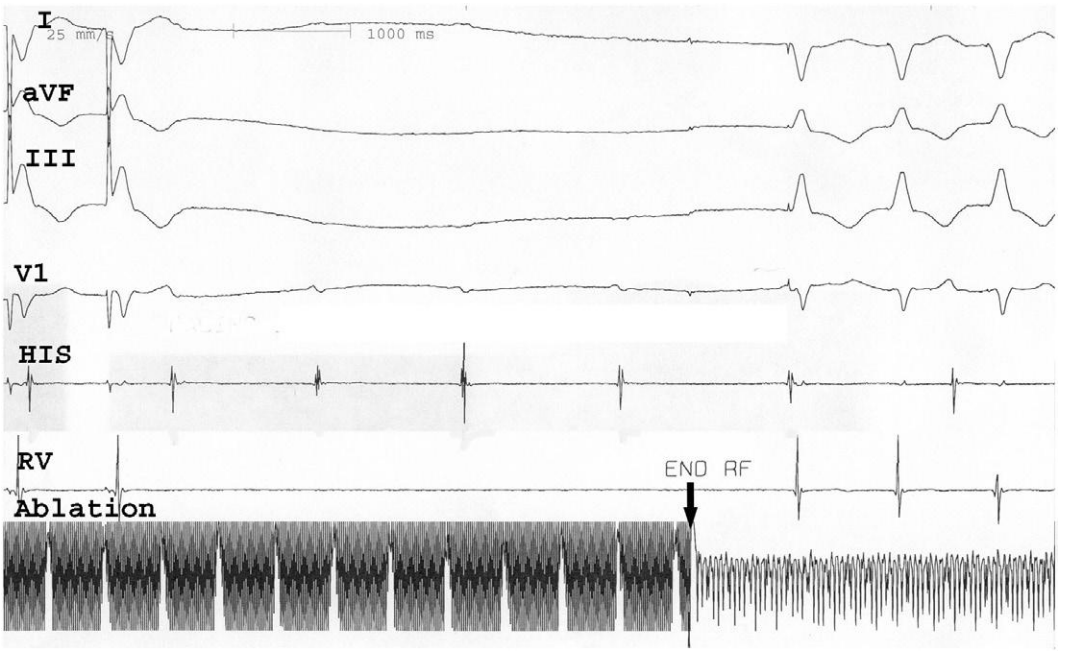


Figure 11.27 Multichannel recording of a patient with a single-lead ICD undergoing radiofrequency (RF) ablation of the atrioventricular node. The ablation is successful, but the RF energy results in ventricular oversensing, with resulting inhibition of ventricular pacing and complete heart block without escape. When the RF delivery is stopped, ventricular pacing resumes.

patients with end-stage heart failure. Following LVAD placement, certain changes may be observed in lead function, including a decrease in sensed ventricular EGM amplitude, rise in capture threshold, and decrease in lead impedance. EMI between a LVAD and CIED resulting in oversensing is rare, but has been reported. A unique interaction occurs between the HeartMate™ II LVAD and St. Jude Medical ICDs, resulting in loss of telemetry.[45] This occurs because the LVAD pulse width modulator operates at approximately the same frequency as used for telemetry by the St. Jude Medical programmer. Metal shielding may be necessary to restore communication between the programmer and the ICD. Replacement with a device that communicates on a different frequency may be required.

Radiofrequency catheter ablation

This is often undertaken in the electrophysiology lab for various atrial and ventricular tachyarrhythmias. Potential interactions include asynchronous pacing due to noise reversion, pacing inhibition, inappropriate ICD therapies, and device reset to the back-up mode. Rarely, threshold rises may be observed. Pacing inhibition is particularly relevant in the patient undergoing AV node ablation, which results in complete heart block and pacemaker dependency (Figure 11.27). Reprogramming the device to an asynchronous mode will prevent this issue from arising. Tachycardia detection should be disabled in ICDs.

Therapeutic radiation

Therapeutic radiation has a unique effect in addition to oversensing. Ionizing radiation can result in random component failure and premature battery depletion. This is due to the direct effect of radiation on CIED circuitry. The use of complementary metal oxide semiconductors (CMOSs) in current devices makes them more vulnerable to this. Though the effect is cumulative, the mode of device failure is random and unpredictable. All major manufacturers recommend against radiation therapy if the CIED is within the radiation field. However, radiation therapy to the chest (e.g. for breast or lung cancer) may be unavoidable in certain patients with pacemakers and ICDs. To minimize this risk, appropriate methods of shielding the generator and

limiting the field of radiation should be discussed with the radiation therapist. In rare instances, a newly placed contralateral system or generator repositioning using lead extenders should be considered. If included in the radiation field, the device should be interrogated after each treatment; however, device malfunctions may sometimes become manifest late after radiation exposure. Damage may result in sudden loss of output, alterations in programmed parameters, and rate runaway.

Lithotripsy

Lithotripsy has the potential to cause pacing inhibition, triggered pacing at the upper rate limit, and activation of rate modulation.[46] The pacemaker circuitry, particularly piezoelectric crystals, may be damaged if within several inches of the lithotripter focal point. Great care should be taken with abdominal implants. Lithotripsy synchronized to the R wave is less frequently used nowadays, particularly as it can add to the length of the procedure. This mode should be strongly considered in those with significant ventricular irritability, as the synchronized pulses are less likely to result in ventricular arrhythmias. If the lithotripter is used in a synchronized mode, care should be taken to ensure that the pulses are synchronized to the R wave and not the P wave or atrial spike, which can result in oversensing and ventricular pacing inhibition. In general, rate modulation should be disabled and consideration given to programming to an asynchronous mode, particularly with pacemaker-dependent patients.

Transcutaneous electrical nerve stimulation

Transcutaneous electrical nerve stimulation (TENS) units do not readily interfere with modern bipolar pacemakers. In pacemaker-dependent patients, particularly those with unipolar leads, the ECG tracing should be monitored during treatment or reprogrammed to an asynchronous mode. TENS units have clearly resulted in inappropriate defibrillator shocks (Figure 11.28).[47] Patients with ICDs who absolutely require TENS should have the marker channel observed with the device in a "monitor-only" mode with the first treatment to rule out any interference.

Other therapy

Electroconvulsive therapy (ECT) is safe in the pacemaker patient. Neurostimulators (deep-brain stimulators and spinal cord stimulators) may be

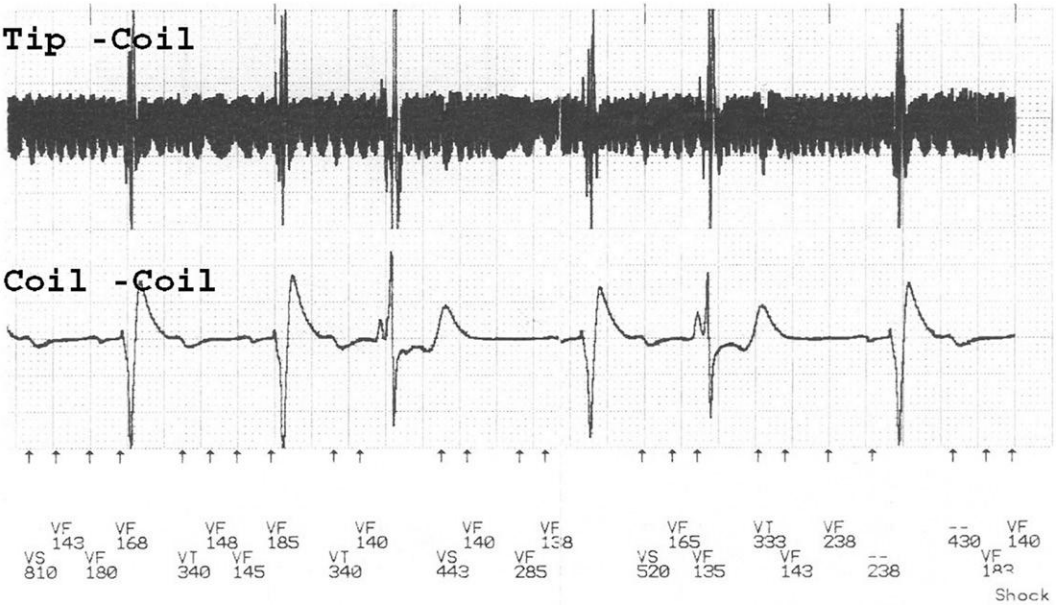


Figure 11.28 Intracardiac electrogram from a patient with a single-lead ICD undergoing transcutaneous electrical nerve stimulation. In the hope of achieving better pain relief, the patient independently turned up the output to maximum. This resulted in inappropriate detection of ventricular fibrillation and high-output shock delivery.

used concomitantly in patients with pacemakers or ICDs, but testing for interactions is recommended. Medical diathermy should be avoided in patients with pacemakers or ICDs.

Table 11.16 summarizes some common medical sources of EMI and recommendations for patients with CIEDs to minimize interference from these sources.

Perioperative (periprocedural) management

The device physician is often asked to evaluate a CIED patient before surgery or other procedures. The main concern in this situation is EMI from various sources: most procedures involve use of electrocautery and cardioversion/defibrillation; other sources of EMI are specific to the procedure being performed. The periprocedural management of the CIED patient is essentially recognition and management of various sources of EMI pertinent to the procedure; these have been discussed in detail above (see "Medical sources" and Table 11.17). A recent expert consensus statement provides general guidelines for perioperative management of patients with CIEDs.[15]

Most patients will not require a *de-novo* preoperative evaluation. Review of records should be sufficient to provide recommendations as long as the device has been interrogated recently (within the past 12 months for pacemakers and within the last 6 months for ICDs and CRT devices). Patient factors (pacemaker dependency, programmed parameters), procedural factors (type of surgery, whether cautery will be used), and device factors (battery life, chronicity of leads, magnet response) should all be taken into consideration. Recommendations for use of a magnet during surgery or for device reprogramming should be individualized based on this. It is essential to have equipment for cardioversion/defibrillation and external pacing readily available; placement of pads for this purpose should be considered in most patients. Given potential interaction of electrocautery and other sources of EMI with ECG monitoring, an alternative method of rhythm monitoring (plethysmography or invasive arterial pressure) should be used.

Post procedure, the device must be interrogated prior to discharge or transfer from telemetry if the device was reprogrammed prior to the procedure, following major vascular or cardiothoracic surgeries, if significant events including cardiac arrest occurred intraoperatively, or if there was exposure to significant EMI (cardioversion or defibrillation, RF ablation, or therapeutic radiation). In some situations with moderate exposure to EMI (monopolar cautery, ECT, lithotripsy), device follow-up within a month is recommended. In other situations, routine follow-up should be sufficient.

Patients nearing end of life or requesting withdrawal of therapy

The device physician may be called upon to assist in the management of patients nearing end of life or requesting withdrawal of therapy. It has been estimated that 20% of ICD patients receive shocks in the last weeks of their lives, which are painful and diminish quality of life. Recently, a multidisciplinary group developed an expert consensus statement that addresses these issues.[48] Some of the views of this group are highlighted here.

Ethically and legally, there is no difference between refusing CIED therapy and requesting withdrawal. This informed refusal, a corollary of informed consent, is considered a personal right of the patient. The consensus of the group is that CIED deactivation is neither physician-assisted suicide nor euthanasia. The group however acknowledges that though there is general agreement regarding ICD deactivation, there is less agreement about pacemaker deactivation, especially in a pacemaker-dependent patient. Even though pacemaker therapy is life sustaining, the prevailing consensus is that it is not replacement therapy (like kidney transplantation), but rather a substitutive therapy (like hemodialysis). The ultimate decision-making authority rests with the patient. However, the clinician cannot be compelled to perform device deactivation if it conflicts with his/her personal values. In such situations, the clinician should not abandon the patient but should involve a colleague who is willing to carry out this request.

Communication about CIED deactivation is essential and should be an ongoing process, starting prior to device implantation and continuing over time as the patient's health status changes. Device deactivation is not "all-or-none," but rather, various levels of deactivation are available, ranging

Table 11.16 Selected medical sources of EMI and recommendations for the CIED patient

Source	*Specific effects*/comments*	*Recommendations*
Electrosurgery	Most common medical cause of EMI Device reset or malfunction can occur	Reprogramming or magnet application for procedures above the umbilicus Place grounding pad away from device Use short bursts of cautery Limit power settings Use bipolar cautery if close to device Monitor pulse with arterial line or oximetry
Cardioversion and defibrillation[#]	Undersensing and elevated thresholds Device reset or malfunction can occur	Use anteroposterior pads, away from device Use biphasic shocks 5-min interval between successive shocks
Cardiac RF ablation[#] Radiation therapy[#]	Random component failure and premature battery depletion	Reprogramming or magnet application Discuss with therapist to minimize total dose to CIED: Shield device Consider device repositioning (lead extenders) Continuous ECG monitoring during treatment (esp. in pacemaker-dependent patients) Interrogate device frequently
MRI[#]	Thermal injury Lead dislodgment and induction of torque on device Rapid pacing Magnet mode and magnetic sensor activation	Avoid in pacemaker-dependent patients and patients with ICDs. Routine use is strongly discouraged in most patients Reprogram prior to scan (asynchronous mode, disable ICD therapies, disable rate response) Weakest necessary field strength: Limit specific absorption rate Monitor pulse with arterial line or oximetry
Left ventricular assist devices (LVADs)	Interaction between Heart Mate II LVAD and some St. Jude Medical ICDs	Metal shielding Generator replacement
Lithotripsy		Reprogram device (asynchronous mode, disable ICD therapies, disable rate response) Synchronize pulses to R wave Avoid submersion of generator
Transcutaneous electrical nerve stimulation (TENS)		Avoid in patients with ICDs; if required, test ICDs in monitor mode with first session Turn off impedance based sensor
Deep-brain stimulators and spinal cord stimulators		Test for interactions with CIED
Electroconvulsive therapy (ECT) Medical diathermy		Disable ICD therapies *Contraindicated*
No significant interference Bipolar cautery Diagnostic radiation (X-ray, CT) Capsule endoscopy Nerve conduction studies (EMG) Dental equipment Wireless technology (RFID, wireless telemetry, flow pumps)		

*Oversensing of EMI is common to all sources.

[#]Interrogation of the CIED is recommended soon after exposure to these sources, in most cases.

EMG, electromyogram; RFID, radiofrequency identification.

Table 11.17 FDA Class I recalls of pacemaker and ICD generators and leads (since 2004)

Device	*Problem*	*Date of recall*
Pulse generators		
Kappa and Sigma pacemakers (Medtronic)	May fail due to separation of wires that connect electronic circuit to other components such as the battery	May 2009
Multiple pacemaker models (Guidant)	Loss of hermetic seal, allowing moisture to affect electronic circuits	July 2005
Prizm and Contak Renewal ICDs (Guidant)	Deterioration in insulation causing short circuit and inability to deliver shocks	June 2005
Micro Jewel II and Gem DR ICDs (Medtronic)	Defective high-voltage capacitor causing longer charge times near EOL	April 2004
Leads		
Riata and Riata ST ICD leads (St. Jude Medical)	Failure associated with insulation abrasion causing externalization of conductors, failure to deliver shock, lead fracture	November 2011
Sprint Fidelis ICD leads (Medtronic)	Lead fracture	October 2007

EOL, end of life.

from disabling shocks to disabling all therapies to not replacing a depleting device. While disabling shocks may reduce patient discomfort, disabling pacing therapy in the pacemaker or CRT patient who is not pacemaker dependent may actually provoke symptoms due to intermittent bradycardia or cardiac desynchronization. Before deactivating a device, it is important to confirm that the patient (or surrogate) has requested this, although written consent is not required. Deactivation of pacing will require reprogramming, whereas antitachycardia therapies may be deactivated by reprogramming or magnet application. Industry-employed allied professionals (IEAPs) may assist in device deactivation, but should work under direct supervision of medical personnel. Like clinicians, they too cannot be compelled to participate in device deactivation if it conflicts with their personal values.

Other clinical situations

Device interrogation or reprogramming for diagnosis and treatment of arrhythmias

The device physician may be called upon to terminate tachyarrhythmias acutely, preferably without the need for cardioversion or defibrillation. Some devices allow for temporary high-rate pacing to above 300 bpm, allowing for the pace termination of atrial flutter. Rarely, application of a magnet with resultant asynchronous pacing may be successful in terminating a tachyarrhythmia. Reprogramming the device to faster rates for overdrive pacing, or using the triggered mode with chest wall stimulation to "program in" extra stimuli, may also prove useful. Some devices allow for programmed stimulation in either chamber using the programmer. In all cases, the intervention should be undertaken cautiously with defibrillator back-up.

Review of atrial and ventricular EGMs in patients with dual chamber devices can be helpful in the diagnosis of wide complex tachycardias. In patients with acquired torsades de pointes, the device may be temporarily programmed to a high pacing rate to prevent recurrent episodes while measures to correct the QT interval are undertaken.

Diagnosis of myocardial ischemia/infarction in the pacemaker patient

The diagnosis of myocardial ischemia/infarction in the pacemaker patient is complicated by the LBBB pattern imposed by RV pacing and the classic findings of ischemia are frequently obscured. The presence of an anterior myocardial infarction, age undetermined, may be indicated by the presence of qR complexes in I, aVL, V_5, and V_6, and that of an inferior infarct by a qR, QR, or Qr in the inferior leads. The specificity for these signs is quite good, but the sensitivity is poor. Notching of the ascending S wave in mid-precordial leads is another

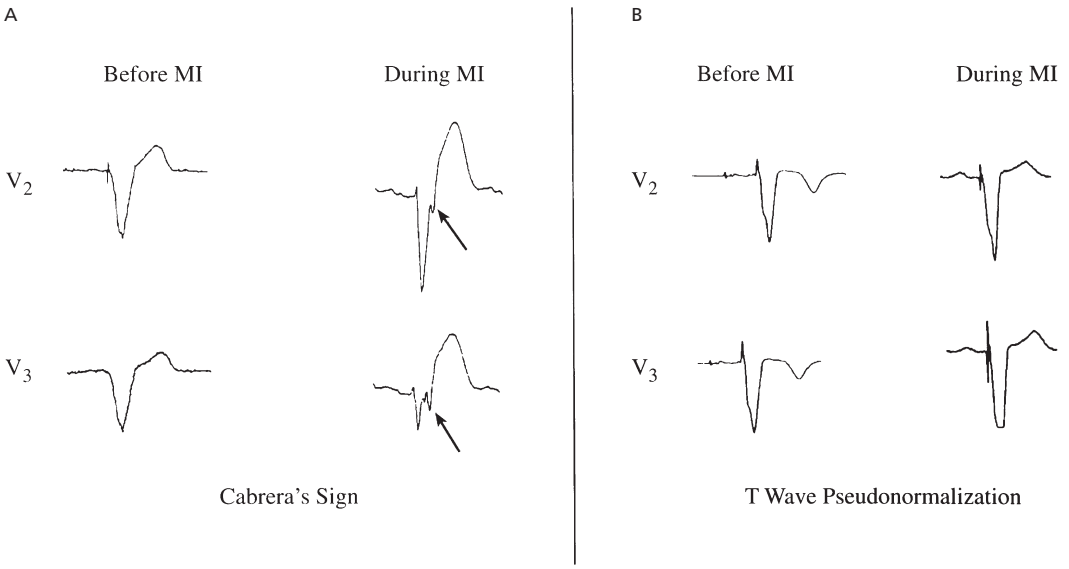


Figure 11.29 Diagnosis of myocardial ischemia/injury in the setting of continuous ventricular pacing. (A) Precordial leads V_2 and V_3 before and during a documented acute anterior myocardial infarction. Note the late terminal notching of the ascending limb of the paced QRS complex, known as "Cabrera's sign" (arrow). Also note the increased ST segment elevation in these leads during infarction. (B) Pseudonormalization of the T waves in leads V_2 and V_3 during an acute infarction.

specific finding (Cabrera's sign; Figure 11.29). An acute infarct can be diagnosed with reasonable specificity during RV apical pacing by the presence of ST elevation of 5 mm or more in leads with predominantly negative QRS complexes.[49] All of these changes are best appreciated by comparing a current ECG with those previously recorded.

Inhibition of the pacemaker with a programmer may reveal the patient's intrinsic QRS for a clearer diagnosis of ischemia/infarction. T wave changes alone should be interpreted with caution in this setting because ventricular pacing may produce T wave abnormalities, which are persistent after the discontinuation of pacing (T wave memory). However, these post-pacing repolarization changes do not produce ST segment elevation or depression.

Device advisories (alerts and recalls)

Recently, there has been increased concern over pacemaker and ICD generator reliability. A meta-analysis of device registries demonstrated that while both pacemaker and ICD reliability improved during the study period, there was a transient late increase in ICD malfunction, whereas pacemaker reliability steadily improved.[50] The overall annual malfunction rate was 20-fold higher for ICDs compared to pacemakers. The most common cause of device failure was battery malfunction. Lead performance is more challenging to assess because malfunctioning leads are not routinely explanted. In general, pacing lead survival is better than ICD lead survival.

Warnings about the potential for device malfunction (in this context the term "device" refers to the generator or lead) may be issued by the device manufacturers or by the FDA within the US. Manufacturers are required to submit to the FDA annual performance reports on the reliability of all pacemakers and ICDs. These data are generated from voluntary physician reporting of device failures and post-market surveillance registries. Unfortunately, data on the performance of any device model are never complete due to the voluntary nature of the registries, physician under-reporting of malfunctions, and failure to return out-of-service devices for analysis (especially from deceased patients). Healthcare providers and institutions should also report malfunctions to the manufacturer and also directly to the FDA through the MedWatch program (www.fda.gov/medwatch). Reporting of device-related fatalities is mandatory. All device reports

since around 1995 are contained in the Manufacturer and User Facility Device Experience (MAUDE) database. This database can be accessed and researched by healthcare providers (http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfmaude/search.cfm; accessed December, 2013). In 2002, the FDA established the Medical Product Safety Network (MedSun) and HeartNet, which is an active surveillance system and two-way communication channel between the regulatory agency and clinical sites. The National Cardiovascular Data Registry (NCDR) has been mandated by the Centers for Medicare and Medicaid Services (CMS) to collect data on all ICD generators and lead implants.

When the FDA determines that there exists a significant risk of device failure, a safety alert or recall (together termed advisories) is issued (Figure 11.30). Advisories are classified into four

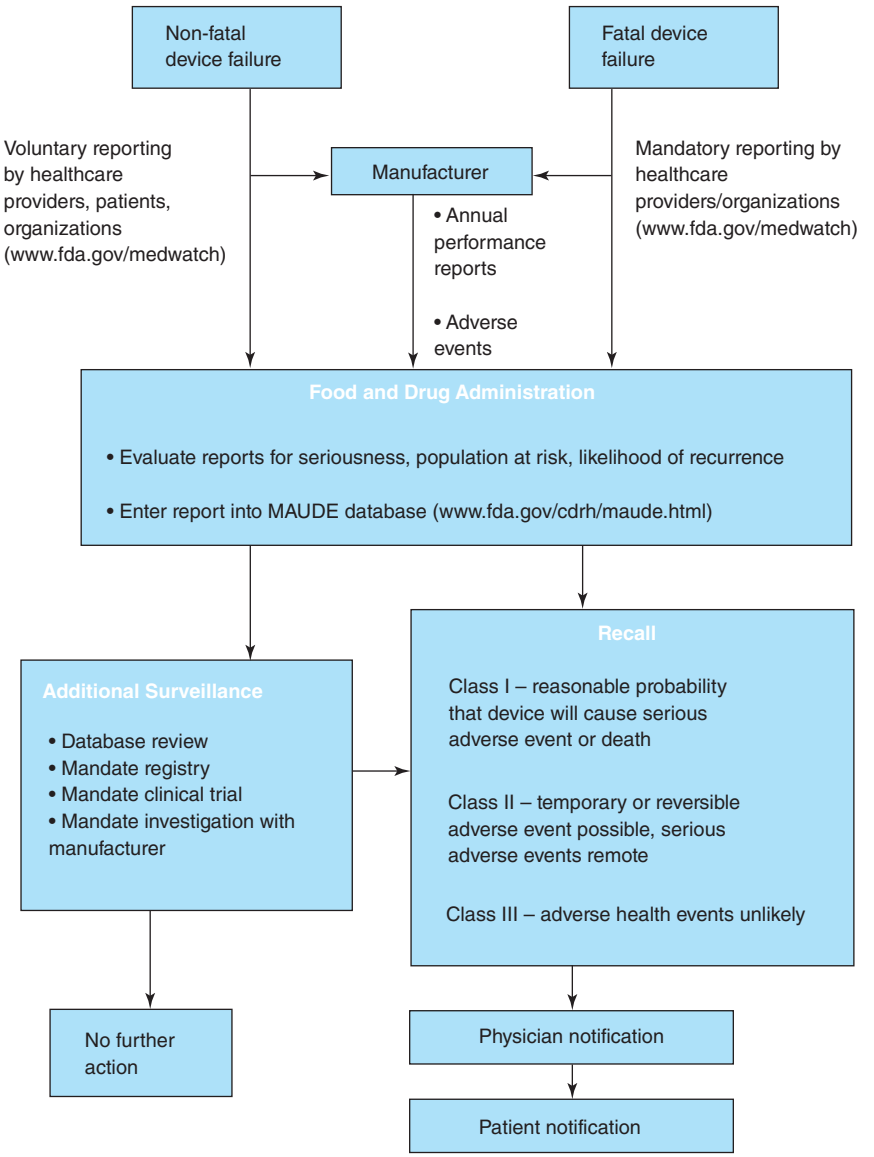


Figure 11.30 Schematic showing flow of information leading to device recalls or safety alerts. After Food and Drug Administration notification, the agency may initiate further surveillance or issue a recall directly. MAUDE, Manufacturer and User Device Experience.

categories: class I, class II, class III, and safety alerts. Device manufacturers may directly issue safety alerts (product notifications) as well. Recently, the FDA introduced a searchable Medical Device Recalls database (http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfRES/res.cfm; accessed December, 2013). Table 11.17 lists FDA class I generator and lead recalls since 2004.

The term recall is misleading, however, because removal of the device is not mandated, but left to the discretion of the physician who must determine the relative risks and benefits of device replacement. Whereas the manufacturer may offer a non-invasive reprogramming strategy to correct or minimize the likelihood of some malfunctions, the physician is otherwise left to make complex outcome decisions for each patient with an affected device. Not surprisingly, the rate of generator replacement in response to a particular advisory varies dramatically among physicians. The mortality and morbidity of generator change is probably underestimated by many physicians, leading to overly aggressive replacement practices.[51,52] Routine replacement of all devices under advisory (especially in non–pacemaker-dependent patients or low rates of device failure) probably results in more patient deaths than are caused by the device failure. In the case of the Telectronics Accufix™ lead, which was susceptible to fracture, more patients died from lead removal than from the fracture. To assist in making rational decisions in response to device advisories, decision analysis models have been created.[53] In general, non-invasive management should be considered when the risk of device malfunction is low, especially when the risk to the patient from device failure is low (non–pacemaker-dependent patients and patients with primary prevention ICDs). On the other hand, device replacement or system revision should be considered when the risk of device malfunction is high, especially if the malfunction is likely to seriously jeopardize the patient (pacemaker-dependent patients and patients with ICDs with a history of significant ventricular arrhythmias).

References

1 Schoenfeld MH. Quality assurance in cardiac electrophysiology and pacing: a brief synopsis. *Pacing Clin Electrophysiol* 1994; 17(3 Pt 1): 267–269.

2 Bernstein AD, Irwin ME, Parsonnet V, *et al*. Report of the NASPE Policy Conference on antibradycardia pacemaker follow-up: effectiveness, needs, and resources. North American Society of Pacing and Electrophysiology. *Pacing Clin Electrophysiol* 1994; 17(11 Pt 1): 1714–1729.

3 Schoenfeld MH. Contemporary pacemaker and defibrillator device therapy: challenges confronting the general cardiologist. *Circulation* 2007; 115(5): 638–653.

4 Baddour LM, Epstein AE, Erickson CC, *et al*. Update on cardiovascular implantable electronic device infections and their management: a scientific statement from the American Heart Association. *Circulation* 2010; 121(3): 458–477.

5 Schoenfeld MH. A primer on pacemaker programmers. *Pacing Clin Electrophysiol* 1993; 16(10): 2044–2052.

6 Schoenfeld MH. Recommendations for implementation of a North American Multicenter Arrhythmia Device/Lead Database. *Pacing Clin Electrophysiol* 1992; 15(11 Pt 1): 1632–1636.

7 Ausubel K, Furman S. The pacemaker syndrome. *Ann Intern Med* 1985; 103(3): 420–429.

8 Ellenbogen KA, Thames MD, Mohanty PK. New insights into pacemaker syndrome gained from hemodynamic, humoral and vascular responses during ventriculo-atrial pacing. *Am J Cardiol* 1990; 65(1): 53–59.

9 Gillis AM, Russo AM, Ellenbogen KA, *et al*. HRS/ACCF expert consensus statement on pacemaker device and mode selection. *J Am Coll Cardiol* 2012; 60(7): 682–703.

10 Deharo JC, Brunetto AB, Bellocci F, *et al*. DDDR pacing driven by contractility versus DDI pacing in vasovagal syncope: a multicenter, randomized study. *Pacing Clin Electrophysiol* 2003; 26(1 Pt 2): 447–450.

11 Connolly SJ, Sheldon R, Thorpe KE, *et al*. Pacemaker therapy for prevention of syncope in patients with recurrent severe vasovagal syncope: Second Vasovagal Pacemaker Study (VPS II): a randomized trial. *JAMA* 2003; 289(17): 2224–2229.

12 Michaud GF, Pelosi F Jr, Noble MD, Knight BP, Morady F, Strickberger SA. A randomized trial comparing heparin initiation 6 h or 24 h after pacemaker or defibrillator implantation. *J Am Coll Cardiol* 2000; 35(7): 1915–1918.

13 Erkapic D, Duray GZ, Bauernfeind T, De Rosa S, Hohnloser SH. Insulation defects of thin high-voltage ICD leads: an underestimated problem? *J Cardiovasc Electrophysiol* 2011; 22(9): 1018–1022.

14 Morse D, Parsonnet V, Gessman L, *et al*. *A Guide to Cardiac Pacemakers, Defibrillators, and Related Products*. North Carolina: Droege Computing Services, 1991.

15 Crossley GH, Poole JE, Rozner MA, *et al*. The Heart Rhythm Society (HRS)/American Society of Anesthesiologists (ASA) Expert Consensus Statement on the

perioperative management of patients with implantable defibrillators, pacemakers and arrhythmia monitors: facilities and patient management; this document was developed as a joint project with the American Society of Anesthesiologists (ASA), and in collaboration with the American Heart Association (AHA), and the Society of Thoracic Surgeons (STS). *Heart Rhythm* 2011; 8(7): 1114–1154.

16 Blitzer ML, Marieb MA, Schoenfeld MH. Inability to communicate with ICDs: an underreported failure mode. *Pacing Clin Electrophysiol* 2001; 24(1): 13–15.

17 Danilovic D, Ohm OJ. Pacing threshold trends and variability in modern tined leads assessed using high resolution automatic measurements: conversion of pulse width into voltage thresholds. *Pacing Clin Electrophysiol* 1999; 22(4 Pt 1): 567–587.

18 Schoenfeld MH, Markowitz HT. Device follow-up in the age of automaticity. *Pacing Clin Electrophysiol* 2000; 23(5): 803–806.

19 Tzogias L, Bellavia D, Sharma S, Donohue TJ, Schoenfeld MH. Natural history of the Sprint Fidelis lead: survival analysis from a large single-center study. *J Intervent Cardiac Electrophysiol* 2012; 34(1): 37–44.

20 Wilkoff BL, Cook JR, Epstein AE,*et al*. Dual-chamber pacing or ventricular backup pacing in patients with an implantable defibrillator: the Dual Chamber and VVI Implantable Defibrillator (DAVID) Trial. *JAMA* 2002; 288(24): 3115–3123.

21 Sweeney MO. Minimizing right ventricular pacing: a new paradigm for cardiac pacing in sinus node dysfunction. *Am Heart J* 2007; 153(4 Suppl): 34–43.

22 Sweeney MO, Shea JB, Fox V, *et al*. Randomized pilot study of a new atrial-based minimal ventricular pacing mode in dual-chamber implantable cardioverter-defibrillators. *Heart Rhythm* 2004; 1(2): 160–167.

23 Vardas PE, Simantirakis EN, Parthenakis FI, Chrysostomakis SI, Skalidis EI, Zuridakis EG. AAIR versus DDDR pacing in patients with impaired sinus node chronotropy: an echocardiographic and cardiopulmonary study. *Pacing Clin Electrophysiol* 1997; 20(7): 1762–1768.

24 Meluzin J, Novak M, Mullerova J, *et al*. A fast and simple echocardiographic method of determination of the optimal atrioventricular delay in patients after biventricular stimulation. *Pacing Clin Electrophysiol* 2004; 27(1): 58–64.

25 Theuns DA, Res JC, Jordaens LJ. Home monitoring in ICD therapy: future perspectives. *Europace* 2003; 5(2): 139–142.

26 Schoenfeld MH, Compton SJ, Mead RH, *et al*. Remote monitoring of implantable cardioverter defibrillators: a prospective analysis. *Pacing Clin Electrophysiol* 2004; 27(6 Pt 1): 757–763.

27 Wilkoff BL, Auricchio A, Brugada J, *et al*. HRS/EHRA expert consensus on the monitoring of cardiovascular implantable electronic devices (CIEDs): description of techniques, indications, personnel, frequency and ethical considerations. *Heart Rhythm* 2008; 5(6): 907–925.

28 Varma N, Epstein AE, Irimpen A, Schweikert R, Love C, Investigators T. Efficacy and safety of automatic remote monitoring for implantable cardioverter-defibrillator follow-up: the Lumos-T Safely Reduces Routine Office Device Follow-up (TRUST) trial. *Circulation* 2010; 122(4): 325–332.

29 Crossley GH, Chen J, Choucair W, *et al*. Clinical benefits of remote versus transtelephonic monitoring of implanted pacemakers. *J Am Coll Cardiol* 2009; 54(22): 2012–2019.

30 Schoenfeld MH. Transtelephonic versus remote monitoring of cardiovascular implantable electronic devices: is one approach to be preferred? *J Am Coll Cardiol* 2009; 54(22): 2020–2022.

31 Tracy CM, Epstein AE, Darbar D, *et al*. 2012 ACCF/AHA/HRS Focused Update of the 2008 Guidelines for Device-Based Therapy of Cardiac Rhythm Abnormalities: A Report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines. *J Am Coll Cardiol* 2012; 60(14): 1297–1313.

32 McIvor ME, Reddinger J, Floden E, Sheppard RC. Study of Pacemaker and Implantable Cardioverter Defibrillator Triggering by Electronic Article Surveillance Devices (SPICED TEAS). *Pacing Clin Electrophysiol* 1998; 21(10): 1847–1861.

33 Hayes DL, Wang PJ, Reynolds DW, *et al*. Interference with cardiac pacemakers by cellular telephones. *N Engl J Med* 1997; 336(21): 1473–1479.

34 Blitzer ML, Schoenfeld MH. Effects of electromagnetic interference on implanted cardiac devices. In: Raviele A, ed. *Cardiac Arrhythmias 2003*. Milan: Springer-Verlag Italia, 2004: 911–918.

35 Wolber T, Ryf S, Binggeli C, *et al*. Potential interference of small neodymium magnets with cardiac pacemakers and implantable cardioverter-defibrillators. *Heart Rhythm* 2007; 4(1): 1–4.

36 Levine PA, Barold SS, Fletcher RD, Talbot P. Adverse acute and chronic effects of electrical defibrillation and cardioversion on implanted unipolar cardiac pacing systems. *J Am Coll Cardiol* 1983; 1(6): 1413–1422.

37 Dubner S, Dubner Y, Gallino S, *et al*. Electromagnetic interference with implantable cardiac pacemakers by video capsule. *Gastrointest Endosc* 2005; 61(2): 250–254.

38 Gimbel JR, Johnson D, Levine PA, Wilkoff BL. Safe performance of magnetic resonance imaging on five patients with permanent cardiac pacemakers. *Pacing Clin Electrophysiol* 1996; 19(6): 913–919.

39 Faris OP, Shein M. Food and Drug Administration perspective: Magnetic resonance imaging of pacemaker and

implantable cardioverter-defibrillator patients. *Circulation* 2006; 114(12): 1232–1233.

40 Misiri J, Kusumoto F, Goldschlager N. Electromagnetic interference and implanted cardiac devices: the medical environment (part II). *Clin Cardiol* 2012; 35(6): 321–328.

41 Sommer T, Naehle CP, Yang A, *et al*. Strategy for safe performance of extrathoracic magnetic resonance imaging at 1.5 tesla in the presence of cardiac pacemakers in non-pacemaker-dependent patients: a prospective study with 115 examinations. *Circulation* 2006; 114(12): 1285–1292.

42 Nazarian S, Roguin A, Zviman MM, *et al*. Clinical utility and safety of a protocol for noncardiac and cardiac magnetic resonance imaging of patients with permanent pacemakers and implantable-cardioverter defibrillators at 1.5 tesla. *Circulation* 2006; 114(12): 1277–1284.

43 Nazarian S, Hansford R, Roguin A, *et al*. A prospective evaluation of a protocol for magnetic resonance imaging of patients with implanted cardiac devices. *Ann Intern Med* 2011; 155(7): 415–424.

44 Jung W, Zvereva V, Hajredini B, Jackle S. Initial experience with magnetic resonance imaging-safe pacemakers: a review. *J Intervent Cardiac Electrophysiol* 2011; 32(3): 213–219.

45 Mehta R, Doshi AA, Hasan AK, *et al*. Device interactions in patients with advanced cardiomyopathy. *J Am Coll Cardiol* 2008; 51(16): 1613–1614.

46 Cooper D, Wilkoff B, Masterson M, Castle L, Belco K, Simmons T, *et al*. Effects of extracorporeal shock wave lithotripsy on cardiac pacemakers and its safety in patients with implanted cardiac pacemakers. *Pacing Clin Electrophysiol* 1988; 11(11 Pt 1): 1607–1616.

47 Philbin DM, Marieb MA, Aithal KH, Schoenfeld MH. Inappropriate shocks delivered by an ICD as a result of sensed potentials from a transcutaneous electronic nerve stimulation unit. *Pacing Clin Electrophysiol* 1998; 21(10): 2010–2011.

48 Lampert R, Hayes DL, Annas GJ, *et al*. HRS Expert Consensus Statement on the Management of Cardiovascular Implantable Electronic Devices (CIEDs) in patients nearing end of life or requesting withdrawal of therapy. *Heart Rhythm* 2010; 7(7): 1008–1026.

49 Barold SS, Herweg B, Curtis AB. Electrocardiographic diagnosis of myocardial infarction and ischemia during cardiac pacing. *Cardiol Clin* 2006; 24(3): 387–399, ix.

50 Maisel WH. Pacemaker and ICD generator reliability: meta-analysis of device registries. *JAMA* 2006; 295(16): 1929–1934.

51 Gould PA, Krahn AD, Canadian Heart Rhythm Society Working Group on Device A. Complications associated with implantable cardioverter-defibrillator replacement in response to device advisories. *JAMA* 2006; 295(16): 1907–1911.

52 Schoenfeld MH. The "natural" history of implantable defibrillators under advisory. *Heart Rhythm* 2008; 5(12): 1682–1684.

53 Amin MS, Matchar DB, Wood MA, Ellenbogen KA. Management of recalled pacemakers and implantable cardioverter-defibrillators: a decision analysis model. *JAMA* 2006; 296(4): 412–420.

Index

Note: Locators in *italics* denote tables and figures (when outside page ranges)

AAI (atrial inhibited) pacing 213, *214*, 218, *220*, *221*
AAT (single chamber triggered mode, without inhibition) pacing 213–14
abandonment, lead 206–7
abrasion, lead 64–5
acceleration sensor, peak endocardial 76
accelerometers 74–5, 315
Accufix wire fragment retrieval 205–6
acidosis, temporary pacing 30
acquired atrioventricular block 7–11
  causes 7
  classification 7–8
  indications for permanent pacing 10–11
  level of block, identification 8, *9*
  symptoms 8–10
action potentials 34–5
active discrimination, SVT–VT *346*, 352
active fixation leads 51–4, 166–7
  ventricular lead positioning 169–71
activity sensors 74–5
  combination with minute-ventilation sensors 76
acute bacterial endocarditis, temporary pacing 30
acute myocardial infarction
  diagnosis in pacemaker patients 498–9
  permanent pacing, indications 25, *26*, *27*
  sinus node dysfunction 28
  temporary pacing, indications 25, 28–9
adolescents, permanent pacing 23–5
advisories
  device, follow-up assessments 499–501
  ICD 420
  leads 60–6
AEI (atrial escape interval) 226, 232
AFR (atrial flutter response) 251, *252*, *253*
air embolism, pacemaker implantation 183
airport metal detectors, electromagnetic interference 489, *491*
alerts, device 499–501
algorithms
  to allow intrinsic sinus rate 244, *245*, *246*
  to approach CRT non-responders 407–9
  for atrial arrhythmia detection and atrial pace/sense competition 251–5
  atrial fibrillation prevention 255, *256*
  automated capture 45–6
  for cardioinhibitory neurogenic syncope 244, *247*, *248*
  dual chamber, SVT–VT discrimination *see* dual chamber algorithms, SVT–VT discrimination
  to minimize right ventricular pacing 255, 257–9, *260*
  for pacemaker-mediated tachycardia 262–3, *264*, 313
  single chamber, SVT–VT discrimination *see* single chamber algorithms, SVT–VT discrimination
  special, unexpected/sudden rate changes 309–10, *311*
alignment errors, limitations of SVT–VT morphology discriminators 347
aluminium capacitors, ICD *332*, 333–4
amyloidosis, permanent pacing 18
anatomy, conduction system 1–3
anchoring sleeve, lead 60
anodal stimulation 42
antiarrhythmic drug therapy
  impact on stimulation threshold 47
  SVT discriminators 425
antibiotic prophylaxis
  ICD implantation 358
  pacemaker implantation 158–9
antibiotic therapy, pacemaker-associated infections 189–90, 191
anticoagulants, patient assessment 155–6
antiplatelet agents, patient assessment 155–6
antitachycardia pacing (ATP) 309–10
  diagnostic value 435, *436–8*
  fast VT 432–4
  ICD 309–10, 367, *368*, *369*, 432–5
  post-pacing interval variability, diagnostic value 435, *436–8*
  response pattern, diagnostic value 435, *436–8*
  slow VT 435
anti-theft devices, electromagnetic interference 439, 489, *491*
AOO (atrial asynchronous) pacing 212, *213*, 218
AOOR (atrial asynchronous rate-modulated) pacing 229

Cardiac Pacing and ICDs, Sixth Edition. Edited by Kenneth A. Ellenbogen and Karoly Kaszala.

© 2014 John Wiley & Sons, Ltd. Published 2014 by John Wiley & Sons, Ltd.

API (atrial protection interval) *252*, 254–5
arc welding, electromagnetic interference 489, *491*
arrhythmia
  atrial, detection algorithms 251–5
  detection, ICD 342, *343*, *344*
  device interrogation/reprogramming for diagnosis and treatment 498
  logbook *315*, 316, *320*
  during pacemaker implantation 183–4
  see also bradycardia; tachycardia
ARS (atrial rate stabilization) *239*, 240
assessment, patient *see* patient assessment
asynchronous pacing 212, *213*, 218, 296, *297*
  rate-modulated 229
  ventricular high rate episode 296, *297*
  see also pacing modes
asystole risk, patient assessment 157
ATP *see* antitachycardia pacing (ATP)
atrial arrhythmia, detection, algorithms 251–5
atrial asynchronous (AOO) pacing 212, *213*, 218
atrial asynchronous rate-modulated (AOOR) pacing 229
atrial-based timing 231
  effect on rate-modulated pacing modes 232–3, *235*
  hybrid systems 234, *236*
  ventricular-based timing *vs.* 231–2, *233*, *234*
atrial building blocks, SVT–VT discrimination *346*, 350–2
atrial contractions, premature, loss of biventricular pacing 268
atrial escape interval (AEI) 226, 232
atrial fibrillation
  before/during pacemaker implantation 183–4
  management in dual chamber systems 480, *481*
  prevention algorithms 255, *256*
  with ventricular response above lower rate limit (LRL) or sensor-indicated rate (SIR), loss of biventricular pacing 268–9
atrial flutter response (AFR) 251, *252*, *253*
atrial inhibited (AAI) pacing 213, *214*, 218, *220*, *221*
atrial lead implantation 172–4
atrial-paced atrioventricular interval, atrial-sensed atrioventricular interval *vs.* 107
atrial pace/sense competition, algorithms 251–5
atrial pacing
  atrioventricular pacing *vs.*, atrioventricular synchrony 107
  non-competitive 251–2, *254*
atrial pressures, atrioventricular synchrony 88–9, *90*
atrial protection interval (API) *252*, 254–5
atrial rate
  above maximum tracking rate, loss of biventricular pacing 267
  SVT–VT discrimination *346*, 350
  ventricular rate *vs.*, SVT–VT discrimination *346*, 350
atrial rate stabilization (ARS) *239*, 240
atrial-sensed atrioventricular interval, atrial-paced atrioventricular interval *vs.* 107
atrial sensing, accurate, importance in SVT–VT discrimination 350–2
atrial transport delay 100–1
atrio-biventricular pacing 116–18
atrioventricular (AV) block
  acquired *see* acquired atrioventricular block
  congenital complete AV block 23–4
  indications for permanent pacing, children and adolescents 24–5
  pacemaker mode selection 124, *126*, 127
atrioventricular building blocks, SVT–VT discrimination *346*, 350
atrioventricular conduction, intrinsic, algorithms to promote 255, 257–9, *260*
atrioventricular cross-talk *see* cross-talk
atrioventricular delay
  differential 225, 485
  rate-adaptive 107–8, 225–6, 485
atrioventricular interval (AVI)
  atrial-sensed *vs.* atrial-paced 107
  differential 225, 485
  dynamic 225–6
  dynamic, programming 77
  follow-up assessments 483–5
  hysteresis 226
  optimal, determination 104–8
  optimal timing, effects of 100–3
  pacemaker timing cycles 222–6
  programming, dynamic AVI 77
  programming considerations *479*, 483–5
  rate-adaptive 107–8, 225–6, 485
atrioventricular (AV) node, anatomy and physiology 2–3
atrioventricular (AV) optimization *77*
  CRT 406–7
  hemodynamics 104–7
atrioventricular pacing, atrial pacing *vs.*, atrioventricular synchrony 107
atrioventricular sequential, ventricular inhibited pacing (DVI) *213*, 215, *216*, 222
atrioventricular sequential asynchronous (DOO) pacing 212, *213*, 218
atrioventricular sequential pacing with dual chamber sensing and inhibition without P-synchronous (DDI) pacing *213*, 215, *216*, 222
atrioventricular synchrony
  advantages 88
  atrial pressures 88–9, *90*
  atrioventricular valvular regurgitation 90–1, 93, *94*
  autonomic neural/neurohormone level alterations 98
  blood pressure 93–4, *95*
  cardiac output 94–8
  cardiovascular outcomes 98–100
  determination of optimal atrioventricular interval 104–8
  effects of optimal atrioventricular interval timing 100–3
  hemodynamics 87–108
  loss of *see* pacemaker syndrome
  mortality 98–100
  pulmonary venous flow patterns 89–90, *91*, *92*
  see also dual chamber systems
atrioventricular valvular regurgitation, atrioventricular synchrony 90–1, 93, *94*
AutoCapture™ algorithm 45
automated capture 44–6
  algorithms 45–6
  pacing threshold 475, *476*
  post-procedure management 180
automated sensing 46
autonomic neural/neurohormone level alterations, atrioventricular synchrony 98
AVI *see* atrioventricular interval (AVI)
AV optimization *see* atrioventricular (AV) optimization

AV sequential, ventricular inhibited pacing (DVI) 212, *213*, *216*
AV sequential asynchronous (DOO) pacing 212, *213*, 218
AV sequential pacing with dual chamber sensing and inhibition without P-synchronous pacing (DDI) *213*, 215, *216*, 222
axillary vein approach, pacemaker implantation 161–4

bacteremia 190, 191
baseline data, troubleshooting 273
base rate, during mode switch/fallback 238–40, *241*
base-rate behavior 231–4
  atrial-based timing *see* atrial-based timing
  effect on rate-modulated pacing modes 232–3, *235*
  hybrid-based timing 234, *236*
  ventricular-based timing *see* ventricular-based timing
basic device data 315, *316*
batteries 67–9
  depletion 275–6, *277*, *278*, 470–1
  elective replacement indicator (ERI) 276, *278*, 465, 470–2
  end of life (EOL) 276, 470, *472*
  ICD 276, 329–30, *331*, 414
  life stages 470–2
  lithium–iodine 67–8, 470
  lithium–manganese dioxide 330, *332*
  lithium–silver vanadium oxide 68, 329–30, *331*, 470
  longevity, maximization 68–9
  status, indicators 470–2
Becker muscular dystrophy, permanent pacing 17
bifascicular block, chronic *see* chronic bifascicular block
Biotronik ICDs 431–2, *433*
bipolar leads 50–1
bipolar sensing, unipolar sensing *vs.* 36–7
bipolar stimulation, unipolar stimulation *vs.* 37–8
biventricular pacing 47–9, 263–9
  atrio-biventricular pacing 116–18
  complications 191
  loss of 266–9, 286, *289*
  maximizing 406, *407*
  recent advances 48, 49
  timing cycles *219*, 264–6
  see also cardiac resynchronization therapy (CRT)
biventricular trigger 267–8
blanked flutter search 251, *252*
blanking periods
  biventricular pacemakers *266*
  pacemaker timing cycles 217–18
  post-atrial ventricular blanking period (PAVB) 298, *300*
blended sensors 76
blood pressure, atrioventricular synchrony 93–4, *95*
Boston Scientific ICDs 429, *431*
bradycardia
  correction, hemodynamics 82–3
  drug-induced, temporary pacing 29–30
  during pacemaker implantation 183
  presentation, severe bradycardia 134, *135*
  reversible causes 134–5, *136*
  treatment algorithm, severe bradycardia *136*
bradycardia programming, ICD 420–1
bundle branch block (BBB)
  acute myocardial infarction 28
  chronic bifascicular block 11–12
bundle branch system, anatomy *2*, 3

Cabrera's sign 499
cannulation, coronary sinus 378–80, *381*
capacitors, ICD *329*, 330–4
capsule endoscopy, electromagnetic interference 440, 492
capture, automated *see* automated capture
Capture Control™ algorithm 45
capture problems *300*, *303*, 305–8
  biventricular pacing 266–9, 286, *289*
  temporary transvenous pacing 141, *143*
  troubleshooting/management 305–8, *309*
cardiac catheterization, indications for temporary pacing 29
cardiac myocyte, electrical excitability 34–5
cardiac output, atrioventricular synchrony 94–8
cardiac resynchronization defibrillation therapy (CRT-D)
  mild-to-moderate heart failure 393, 398
  severe heart failure 392–3
cardiac resynchronization pacing therapy (CRT-P), severe heart failure 392–3
cardiac resynchronization therapy (CRT) 20, 374–409
  algorithm to approach non-responders 407–9
  assessment of optimal left ventricular lead position 384–6, *387*, *388*
  AV optimization 406–7
  clinical outcomes 392–400
  complications related to left ventricular lead placement 390–2
  coronary sinus cannulation 378–80, *381*
  coronary vein navigation 380, 382–4
  factors affecting response 401–7
  hemodynamics 116–20
  implantation 376, 378–86
  indications 374–6, *377*
  left ventricular lead selection 380, 382–4
  left ventricular pacing 116–20
  management of left ventricular lead placement difficulties 386, 388–92
  mechanisms 374
  mild-to-moderate heart failure, outcomes 393, *398*, *399*
  non-responders, approach to 400–9
  patient selection 374–6, *378*
  QRS duration, outcomes 398–400
  QRS morphology, outcomes 400
  responders *vs.* non-responders 119–20, 401
  severe heart failure, outcomes 392–7
  suboptimal response, hemodynamics 119–20
  VV optimization 406–7
  see also biventricular pacing
cardiac signals, oversensing 298, 300, *301*
cardiac surgery
  permanent pacing after 25, 27
  temporary pacing after 29
cardioinhibitory neurogenic syncope, algorithms 244, *247*, *248*
cardiomyopathy
  etiology, impact on CRT response 401–3
  genetic, permanent pacing 18–20
  hypertrophic *see* hypertrophic cardiomyopathy
cardiopulmonary resuscitation, temporary pacing 134

cardiovascular outcomes, atrioventricular synchrony 98–100
cardioversion, electromagnetic interference 490–1, *492*, *497*
carotid sinus massage, follow-up assessments 461
carotid sinus syndrome, hypersensitive 15
  indications for pacing 15–16
"cast zone" 64, *65*
catheter-based therapy 438
catheterization (cardiac), indications for temporary pacing 29
catheters, temporary endocardial pacing 138–41
cathodal stimulation, anodal stimulation *vs.* 42
cautery, electromagnetic interference 439–40, 490–1, *497*
cell phones, electromagnetic interference 489, *491*
cephalic vein approach, pacemaker implantation 164–5
Chagas disease, permanent pacing 18
children, permanent pacing 23–5
chronic bifascicular block 11–13
  indications for permanent pacing 12–13
chronic heart failure *see* heart failure
chronic neuromuscular disorders, permanent pacing 16–17
chronotropic incompetence 84, 85–6
  diagnosis 85
  predictors 85
  rate-adaptive pacing 83, 85
  see also rate modulation
circadian variation, stimulation threshold 47
circuitry
  ICD 334–5
  pacemakers, schematic 67
circuits
  output, pulse generators 69–70
  sensing, pulse generators 70
  telemetry, pulse generators 70–1
  timing, pulse generators 70
clinical outcomes, CRT 392–400
clinical variables, impact on pacing threshold 47
clinics, follow-up 454–5
closed loop sensors 74
Closed Loop Stimulation (CLS) 76–7
co-axial lead designs 50, 61
collagen vascular diseases, permanent pacing 18
company-specific issues, ICDs 426, 428–32, *433*
complications, pacemaker implantation 180–91
  acute complications list 180
  air embolism 183
  arrhythmia 183–4
  biventricular pacing 191
  delayed complications list 181
  hemothorax 182
  infection *see* infections
  lead dislodgement *see* lead dislodgement
  lead placement *180*, *181*, 183–6
  leads 183–8
  perforation *see* perforation
  pneumothorax 182
  pulse generators *176*, *181*, 188–9
  related to left ventricular lead placement 390–2
  temporary pacing 145–7
  venous access 181–3
  venous thrombosis 187–8
  see also malfunctions
conduction system, anatomy and physiology 1–3
conductors
  fracture 64, *65*, 280, *281*, *282*
  lead materials 55–6
congenital heart block, permanent pacing 23–5
connector pins 59–60
consent, informed, pacemaker implantation 158
co-radial lead designs 50–1
coronary sinus (CS)
  cannulation, CRT 378–80, *381*
  dissection 191, 391
  lead extraction 206
  lead fixation 53–4
coronary vein anatomy, CRT implantation 376, 378, 386, *388*
  management of left ventricular lead placement difficulties 386, *389*, *390*
coronary vein dissection/perforation 191, 391–2
coronary vein navigation, CRT implantation 380, 382–4
coronary vein tortuosity, management of left ventricular lead placement difficulties 386, *389*
coronary venous leads, extraction 206
corticosteroid-eluting electrodes 59
cost effectiveness, pacemaker implantation 157–8
cross-talk 222–5, 298, *299*, *300*
  follow-up assessments 482
  sensing window 222–3, 482
CRT *see* cardiac resynchronization therapy (CRT)
current of injury 43, 52, 171
cut-off rates, ICD 421

dabigatran therapy 156
data *see* device data
DDD pacing mode *see* dual chamber pacing and sensing with inhibition and tracking (DDD)
DDDR (dual chamber rate-modulated) pacing 229–31, 240, *243*
DDI (dual chamber pacing and sensing with inhibition but without tracking) *213*, 215, *216*, 222
DDIR (dual chamber rate-modulated) pacing 229–31
deactivation *see* device deactivation, dying patients
deep vein thrombosis (DVT) 187–8
defibrillation 327–9
  electromagnetic interference 490–1, *492*, *497*
  strength–duration curve 338, *339*
  testing, at ICD implant 360–4
  waveforms, ICD *333*, 337–40
  see also implantable cardioverter–defibrillator (ICD)
defibrillation efficiency, testing at ICD implant 360–5
defibrillation threshold (DFT) 338, 339, 418
  causes of elevated DFT 366
  diagnosis of elevated DFT 366
  management of elevated DFT 365, *365*, *366*
  methods for calculating 360, *364*
  testing 360–4, 418
dependence, pacemaker 465–6
detection time/intervals, ICD 422, *424*
device advisories
  follow-up assessments 499–501
  see also advisories
device alerts 499–501
device behavior, features affecting 223
device data
  analysis *see* stored data analysis
  baseline, needed for troubleshooting 273
  basic 315, *316*
device deactivation, dying patients 496, 498
  ICDs 438–9
device identifiers, radiographic 274, 284, 463

device interrogation, follow-up assessments 466–85
approach 467–85
device advisories 499–501
diagnosis/treatment of arrhythmias 498
display of real-time electrograms, event markers, and ECG 468–9
evaluation of measured data, pacing thresholds, and sensing thresholds 469–78
ICDs 414
implantable loop recorders 485
programmers 466–7
programming considerations 483–5
review of patient diagnostics (stored data) 478, 480–1
review of programmed parameters 467–8
special considerations and maneuvers 482–3
telemetry 466–7
see also stored data analysis
device pro-arrhythmia, ICD 447–8
device programmers 466–7
follow-up assessments *see* device interrogation, follow-up assessments
device programming *see* programming
device recalls 455, *498*, 499–501
DFT *see* defibrillation threshold (DFT)
diaphragmatic stimulation, follow-up assessments 460–1
differential atrioventricular interval 225, 485
dilated cardiomyopathy 19
permanent pacing 19
dislodgement, lead *see* lead dislodgement
DOO (dual chamber sequential asynchronous) pacing 212, *213*, 218
DOOR (dual chamber rate-modulated asynchronous) pacing 229
double counting 298, *301*
driving guidelines, following ICD implantation 413–14
drug-induced bradycardia, temporary pacing 29–30
drugs, impact on pacing threshold 47
dual-antiplatelet therapy, patient assessment 156
dual chamber algorithms, SVT–VT discrimination
atrial *vs.* ventricular rate 350
discriminators that evaluate relative timing of atrial/ventricular events 350
operation 352
representative algorithms 352–4
single chamber atrial building blocks in 350
single chamber discriminators *vs.*, performance 354–5, *356*, *357*, *358*
ventricular building blocks *346*, 350
see also supraventricular tachycardia–ventricular tachycardia (SVT–VT) discrimination
Dual Chamber and VVI Implantable Defibrillator (DAVID) trial 112–13
dual chamber asynchronous pacing 212, *213*, 218
dual chamber pacing, temporary 142, *144*
dual chamber pacing and sensing with inhibition and tracking (DDD) *213*, 214–15, *216*, 218
timing cycles 218, *220*
dual chamber pacing and sensing with inhibition but without tracking (DDI) *213*, 215, *216*, 222
dual chamber rate-modulated asynchronous pacing 229
dual chamber rate-modulated pacing (DDDR, DDIR) 229–31, 240, *243*
dual chamber systems
atrial fibrillation management 480, *481*
cross-talk *see* cross-talk
electrical Wenckebach phenomenon 457–8
follow-up assessments 482–3
Holter transmission 458
ICDs 342, *343*, *346*, 350, 367
temporary pacing 142, *144*
see also atrioventricular synchrony; dual chamber algorithms, SVT–VT discrimination
Duchenne muscular dystrophy, permanent pacing 16–17
DVI (atrioventricular sequential, ventricular inhibited) pacing *213*, 215, *216*, 222
DVT (deep vein thrombosis) 187–8
dying patients
ICD 438–9, 496, 498
withdrawal of therapy 496, 498
dynamic atrioventricular interval 225–6
dynamic maneuvers, follow-up assessments 461, *462*, 483
dynamic post-ventricular atrial refractory period 227, *228*
dyspnea, follow-up assessment 457–8

ejection fraction, atrioventricular *vs.* ventricular pacing 98
elective replacement indicator (ERI) 276, *278*, 465, 470–2
electrical excitability, cardiac myocyte 34–5
electrical stimuli, propagation 35
electrical tools, electromagnetic interference 489, *491*
electrical Wenckebach phenomenon, dual chamber systems 457–8
electrocardiogram (ECG)
device interrogation, follow-up assessments 469
interpretation, pacer malfunction 284–8, *289*
electrocardiography
assessment of optimal left ventricular lead position, CRT 384, 386, *387*
follow-up assessments 463–4
manifestations of pacer malfunction 284–91
electroconvulsive therapy (ECT), electromagnetic interference 495–6, *497*
electrode–myocardial interface maturation 43
electrodes
corticosteroid-eluting 59
CRT 382–4
design and composition *51*, 58–9
temporary endocardial pacing 138–41
virtual 328
see also lead(s)
electrograms (EGMs)
bipolar *vs.* unipolar sensing 36–7
device interrogation, follow-up assessments 468
interpretation, pacer malfunction 288, 290–1
sensing circuit, pulse generators 70
stored, analysis *315*, 316, *320*
stored, ICD 341–2
truncation, limitations of SVT–VT morphology discriminators 345, 347
ventricular morphology, SVT–VT discrimination 345–8

width, SVT–VT discrimination *346*, 348
electromagnetic interference (EMI) 488–97
effects 276, 278, *279*, 301, 488–9
general management strategies *488*, 489
ICDs 439–40, 489
medical sources 439–40, 490–6, *497*
non-medical sources 489–90, *491*
perioperative (periprocedural) management 440, 496, *497*
electrophysiology 34–5
electrosurgery, electromagnetic interference 439–40, 490–1, *497*
Emery–Dreifuss muscular dystrophy, permanent pacing 17
EMI *see* electromagnetic interference (EMI)
endless-loop tachycardia *see* pacemaker-mediated tachycardia (PMT)
endocardial (transvenous) pacing
failure 141, *143*
indications, acute myocardial infarction 28–9
insertion of endovascular temporary pacemaker 144–5
left ventricular 119
temporary 138–41, *142*, *143*
see also temporary pacing
endocarditis
acute bacterial, temporary pacing 30
pacemaker-associated 190
end of life (patient)
ICD in dying patients 438–9
withdrawal of therapy 496, 498
end of life (EOL), batteries 276, 470, *472*
endoscopy, electromagnetic interference 440, 491–2
end stage renal disease (ESRD), patient assessment 154–5
epicardial lead placement 141, *143*, *144*, 174–5
epicardial pacing, temporary 141, *143*, *144*
epidemic, heart failure 374
epimyocardial leads 54
episodal counters, follow-up assessments 478, 479, *481*
ERI (elective replacement indicator) 276, *278*, 465, 470–2
erosion, pacemaker *see* pacemaker erosion
event counters
follow-up assessments 478, *480*
stored data analysis *293*, 315–6, *318–19*
event markers (marker channels) 291, *292*, 469
event recorders, outpatient monitoring 486
evidence, ICD implantation 323–7
excitability, cardiac myocyte 34–5
exercise physiology, rate modulation 84–5
exertional dyspnea, follow-up assessment 457–8
extraction, lead *see* lead extraction

fallback mode 238–40, *241*
familial cardiomyopathies, permanent pacing 18–20
far-field R-waves (FFRWs), oversensing 350, 352
femoral approach, lead extraction *199*, 202–5
fibrillation 327–9
see also atrial fibrillation
fist-based pacing 144
fixation mechanisms, leads 51–4, 166–7
flow charts for decision processes
device recalls/safety alerts 500
ICD implantation 326
pacemaker implantation 154
pacemaker revision 178
fluoroscopy
follow-up assessments 461–3
pacemaker implantation 152, 175–6
follow-up, ICD 413–20
follow-up assessments 453–501
atrioventricular interval (AVI) 483–5
clinics 454–5
device advisories (alerts and recalls) 499–501
device interrogation *see* device interrogation, follow-up assessments
dual chamber systems 482–3
dynamic maneuvers 461, *462*, 483
electrocardiography 463–4
electromagnetic interference 488–98
erosion, pacemaker 459–60
fluoroscopy 461–3
frequency, recommendations 487–8
goals 453
history 456–9
immediate post-transplantation period 453–4
implantable loop recorders 485
magnet application 464–5
mode of follow-up, recommendations 487–8
outpatient monitoring *see* outpatient monitoring
outpatient visit 455–64
pacemaker dependence 465–6
pacemaker erosion 459–60
pacemaker syndrome 456–7
physical examination 459–61, *462*
programming 478, *479*, 483–5
pulse generator pocket 459–60
radiography 284, 461–3
record keeping 454–5
special situations 488–99
symptoms, common 456–9
fracture, lead *see* lead fracture
functional pacemaker dependence 465–6

generators *see* pulse generators
genetic cardiomyopathies, permanent pacing 18–20
Guidant ICDs 429

head/neck tumor treatment, temporary pacing 30
headphones, electromagnetic interference 489, *491*
heart failure 374, *375*
mild-to-moderate, CRT outcomes 393, *398*, *399*
severe, CRT outcomes 392–7
systolic, permanent pacing 20–1
hematomas, pocket 189, 459
hemodynamics 82–127
atrioventricular synchrony 87–108
cardiac resynchronization therapy 116–20
correction of bradycardia 82–3
ejection fraction 98
hypertrophic obstructive cardiomyopathy 121–3
pacemaker mode selection 123–7
pacemaker syndrome 108–11
rate modulation 83–7
right ventricular pacing 111–16
hemothorax 182
heparin therapy, patient assessment 155–6
high-risk patients, who do not benefit from ICD therapy 325–7
high-voltage capacitor, ICD *329*, 330–4
His bundle 2, 3

His bundle pacing 115
His–Purkinje system, anatomy and physiology *2*, 3
histograms, stored data analysis 315, *318–19*
history, outpatient visits 455–9
HOCM (hypertrophic obstructive cardiomyopathy), pacing hemodynamics 121–3
Holter monitoring 486
Holter transmission, dual chamber systems 458
hospitalization, post-procedure management 179–80
hybrid-based timing 234, *236*
hyperkalemia
  capture problems 306, *308*
  temporary pacing 30
hypersensitive carotid sinus syndrome 15
  indications for pacing 15–16
hypertrophic cardiomyopathy 19–20
  permanent pacing 19–20
hypertrophic obstructive cardiomyopathy (HOCM), pacing hemodynamics 121–3
hyperventilation, sensor-driven pacing 314
hypotension, idiopathic orthostatic, permanent pacing 16
hypothyroidism, temporary pacing 30
hysteresis
  atrioventricular interval 226
  rate *see* rate hysteresis

ICD *see* implantable cardioverter–defibrillator (ICD)
idiopathic orthostatic hypotension, permanent pacing 16
imaging, radiographic *see* radiography
imaging systems, pacemaker implantation 151–2
immediate post-transplantation period, follow-up assessments 453–4
impedance
  definition 38
  lead *see* lead impedance
  pacing *see* pacing impedance
  sensing 39
  time-dependent changes 44
impedance sensor, right ventricular 76–7
implantable cardioverter–defibrillator (ICD) 323–70
  advisories 420
  antitachycardia pacing (ATP) 309–10, 367, *368*, *369*, 432–5
  arrhythmia detection 342, *343*, *344*
  batteries 276, 329–30, *331*, 414
  Biotronik devices 431–2, *433*
  bradycardia programming 420–1
  capacitors *329*, 330–4
  circuitry 334–5
  company-specific issues 426, 428–32, *433*
  cut-off rates 421
  defibrillation waveforms *333*, 337–40
  detection of clinical events, follow-up 414
  detection time/intervals 422, *424*
  device interrogation 414
  device pro-arrhythmia 447–8
  DFT *see* defibrillation threshold (DFT)
  dual chamber systems 342, *343*, *346*, 350, 367
  dying patients 438–9, 496, 498
  electromagnetic interference (EMI) 439–40, 489
  failure to detect/treat sustained VT 445–7, *448*
  fibrillation and defibrillation 327–9
  follow-up 413–20
  Guidant/Boston Scientific devices 429, *431*
  high-risk patients who do not benefit from 325–7
  implantation *see* implantable cardioverter–defibrillator (ICD) implantation
  indications 323–7
  leads *see* implantable cardioverter–defibrillator (ICD) leads
  magnet application, follow-up assessments 465
  Medtronic devices 426, 428–9, *432*
  monitoring zones 421–2, *423*
  oversensing 297, *301*, *302*, 416–18, *419*, 489
  patient evaluation, inappropriate shocks 441–2
  perioperative management 440
  primary prevention 324–5, *327*, 422, 425, *427*
  programming *355*, *364*, 367–70, 420–6, *427*
  pulse generators 329–35
  rate sensing 340–2
  remote monitoring 418–20
  secondary prevention 324, 425, *427*
  sensing 340–2, 415–18
  sensitivity adjustments 292
  shocks *see* implantable cardioverter–defibrillator (ICD) shocks
  Sorin Group devices 429, *430*
  St. Jude Medical devices 429–31
  supporting evidence 323–7
  SVT–VT discrimination *see* supraventricular tachycardia–ventricular tachycardia (SVT–VT) discrimination
  tachycardia programming 421–6
  therapies 367–8, 432–8
  troubleshooting 440–8
  vulnerability testing 364–5
implantable cardioverter–defibrillator (ICD) implantation
  with assessment of defibrillation efficiency 360–5
  procedure 357–9
  warfarin therapy and 156
  without assessment of defibrillation efficacy 365–7
implantable cardioverter–defibrillator (ICD) leads 335–7
  advisories 420
  design 51, 61–2, 335–6
  failure 63–5, 280–1, 336–7
  infection 195–6
  insulation 57, 336
  integrity, follow-up assessment 414–15
  placement 359
implantable cardioverter–defibrillator (ICD) shocks 435, 459
  effects 327–8
  failure to deliver (VT underdetection) 445–7
  inappropriate, troubleshooting 441–8
  low- *vs.* high-energy shocks 435
  multiple shocks 442, 444, *445*, *446*
  patient evaluation 441–2, *443*
  pro-arrhythmia 447–8
  single shock 442, *444*
  unsuccessful 444–5
  vulnerable zone for shock-induced ventricular fibrillation 328
implantable loop recorders (ILRs) 485
implantation
  cardiac resynchronization therapy (CRT) 376, 378–86
  ICD *see* implantable cardioverter–defibrillator (ICD) implantation
  lead *see* lead implantation
  pacemaker *see* pacemaker implantation

indications
  cardiac resynchronization therapy 374–6, *377*
  ICD implantation 323–7
indications, cardiac pacing 1–31
  acquired atrioventricular block 10–11
  acute myocardial infarction 25, *26*, *27*, 28–9
  adolescents 24–5
  after cardiac surgery 25, 27, 29
  after transcatheter aortic valve implantation (TAVI) 27
  cardiac catheterization 29
  children 24–5
  chronic bifascicular block 12–13
  chronic neuromuscular disorders 16–17
  drug-induced bradycardia 29–30
  genetic cardiomyopathies 18–20
  hypertrophic cardiomyopathy 20
  infiltrative and inflammatory disorders 17–18
  permanent pacing 3–27
  prior to non-cardiac surgery 29
  procedural interventions 29
  reflex syncope 15–16
  sinus node dysfunction 6–7
  systolic heart failure 20–1
  tachycardia prevention/termination 22–3, 30
  temporary pacing 27–30, 134
infections
  follow-up assessments 459–60
  lead extraction *192*, 195–6
  leads *see* lead infection
  pacemaker implantation 158, 189–91, 195–6
  pacemaker pocket 189–90, 459
  patient assessment 153–4
infiltrative disorders, permanent pacing 17–18
inflammatory disorders, permanent pacing 17–18
informed consent, pacemaker implantation 158
injury, current of 43, 52, 171
insulated gate bipolar transistors (IGBTs) 335
insulation, lead *see* lead insulation
intercostal muscle stimulation, follow-up assessments 460
interval stability, SVT–VT discrimination 348
interventricular delay 266, *267*
intracardiac electrograms *see* electrograms (EGMs)

J-shaped leads 52
  Accufix wire fragment retrieval 205–6
  atrial lead implantation 172, *173*
  risks 196, 205, *206*

Kearns–Sayre syndrome, permanent pacing 17
kidney disease, patient assessment 154–5

lead(s) 49–67
  abandonment 206–7
  abrasion 64–5
  advisories 60–6
  complications 183–8
  components 49
  connectors 59–60
  design *see* lead designs
  epimyocardial 54
  extraction *see* lead extraction
  fixation mechanisms 51–4, 166–7
  follow-up assessments *470*, 472, *473*, 475, *477*
  ICD *see* implantable cardioverter–defibrillator (ICD) leads
  impedance 472, *473*
  implantation *see* lead implantation
  infected *see* lead infection
  left ventricular *see* left ventricular leads
  magnetic resonance compatible 71–3, 493
  malfunction *see* lead malfunction/failure
  novel intramyocardial lead 49
  performance trends 475, *477*, 478
  quadripolar 48
  status, indicators 472–5
lead designs 49–54
  bipolar leads 50–1
  epimyocardial leads 54
  fixation mechanisms 51–4, 166–7
  ICD leads 51, 61–2, 335–6
  lead failure and 60–6, 280
  unipolar leads 49–50
lead dislodgement *173*, *176*, 181, 186–7
  left ventricular leads 392
  macro-dislodgement 281
  micro-dislodgement 281, 283–4
  twiddler's syndrome *176*, 186
lead endocarditis 190–1
lead extraction 191–207
  Accufix wire fragment retrieval 205–6
  approaches 194, 199–205
  coronary venous leads 206
  femoral approach *199*, 202–5
  indications *192–4*, 195–6
  infection as indication *192*, 195–6
  kits 198
  lead abandonment as alternative 206–7
  locking stylets 199, *200*
  needle's eye technique *203*, 204–5
  pre-explant information 197
  principles 191–5
  recommended personnel 198
  risks 196–7
  sheaths 199–205
  superior approach 199–202, *203*
  techniques 197–207
  thoracotomy 206
  tools 199–207
  tying sutures to "cables" 199, *201*
lead fracture 64, *65*, 280, *281*, *282*
  pacemaker implantation 161, 186
lead impedance 472, *473*
  abnormalities 280, *281*, *282*, *283*
lead implantation 166–75
  atrial 172–4
  revision *174*, 176–9
  single lead VDD pacing 175
  ventricular lead positioning 167–72
  see also lead placement
lead infection 190–1
  indications for extraction *192*, 195–6
lead insulation
  abnormalities 280, *282*
  ICD leads 57, 336
  materials 56–8
  polyurethane 57–8, 336–7
  silicone 57, *58*, 337
lead-integrity algorithm (LIA) 64
lead malfunction/failure 280–4
  dislodgement *see* lead dislodgement
  fracture *see* lead fracture
  ICD leads 63–5, 280–1, 336–7
  impact 60
  insulation failure 280, *282*
  lead design and 60–6, 280
  management 63, 65
  manifestations 62
  monitoring, detecting, and reporting 66–7
  perforation *see* perforation
  returned products analysis 64, 65, 66, 67
  sites of failure 63
  time since implant relationship 305, *306*
  see also malfunctions
lead materials 54–66
  anchoring sleeve 60
  conductors 55–6

connector pins 59–60
electrodes 58–9
insulation 56–8
lead placement
acceptable electrical parameters 171
complications *180*, *181*, 183–6
epicardial 141, *143*, *144*, 174–5
ICD leads 359
see also lead implantation
lead-to-lead interactions 63, 280, 284
left ventricular assist devices (LVADs), electromagnetic interference 493–4, *497*
left ventricular leads
assessment of optimal position 384–6, *387*, *388*
complications related to placement 191, 390–2
placement difficulties, management 386, 388–92
positioning, impact on CRT response 403–6
selection 380, 382–4
left ventricular offset 266, *267*
left ventricular outflow tract (LVOT) obstruction, pacing hemodynamics 121–3
left ventricular pacing
cardiac resynchronization therapy 116–20
endocardial 119
hemodynamics 116–20
univentricular 118–19
left ventricular protection period (LVPP) 265–6
left ventricular refractory period (LVRP) 265
left ventricular scar burden, impact on CRT response 403
left ventricular structure, impact on CRT response 403
left ventricular systolic function, impaired, indications for pacing 20–1
limb girdle muscular dystrophy, permanent pacing 17
lithium–iodine battery 67–8, 470
lithium–manganese dioxide battery 330, *332*
lithium–silver vanadium oxide battery 68, 329–30, *331*, 470
lithotripsy, electromagnetic interference 440, 495, *497*
LMWH (low-molecular-weight heparin), patient assessment 155–6
locking stylets, lead extraction 199, *200*
2:1 lock-in protection algorithm 251, *252*, *253*
logistical considerations, pacemaker implantation 151–3
long-QT syndrome, permanent pacing 21–3
low-molecular-weight heparin (LMWH), patient assessment 155–6
Lyme disease, temporary pacing 30

magnet application
follow-up assessments 464–5
pacemaker response 269–70, 276, 464–5
magnetic resonance imaging (MRI)
compatible pacemakers and leads 71–3, 493
electromagnetic interference 439, 492–3, *497*
magnet mode, pulse generators 71
malfunctions 272–321
analysis of stored device data *see* stored data analysis
battery depletion 275–6, *277*, *278*, 470–1
capture problems *see* capture problems
cross-talk *see* cross-talk
differential diagnosis 274–5
electrocardiographic manifestations 284–91
EMI *see* electromagnetic interference (EMI)
general considerations 272–4
leads *see* lead malfunction/failure
mechanical components 275–84
pacing at unexpected rate or sudden change in pacing rate 308–14, *315*
pseudo-malfunctions 310
pulse generators 62, 275–9
radiographic imaging *275*, 284, *285*, *286*, *287*
sensing problems *see* sensing abnormalities
software abnormalities 279
symptoms suggestive of pacemaker abnormality 273
see also complications, pacemaker implantation; troubleshooting
Manufacturer and User Facility Device Experience (MAUDE) database 66, 500
marker channels 291, *292*, 469
mastectomy, prior, patient assessment 157
maximum tracking rate (MTR), rapid sinus/atrial rates above MTR, loss of biventricular pacing 267
medicolegal aspects, pacemaker implantation 207
Medtronic ICDs 426, 428–9, *432*
Medtronic Sensing Assurance™ algorithm 46
metabolic effects, stimulation threshold 47
metal detectors, airport, electromagnetic interference 489, *491*
microprocessors, pulse generators 69
micropuncture technique, pacemaker implantation 161–4
mild-to-moderate heart failure, CRT outcomes 393, *398*, *399*
minute-ventilation sensors 75–6, 314
mitral regurgitation (MR), atrioventricular synchrony 91, 93
mobile phones, electromagnetic interference 489, *491*
modes, pacing *see* pacing modes
Mode Selection Trial (MOST) 87, 109, 110, 111, 112
mode switch 244, 249–51
episodes, follow-up assessments 478, 480, *481*
inappropriate/false 250–1
rate enhancements 238–40, *241*
monitoring
lead malfunction 66–7
outpatient *see* outpatient monitoring
pacemaker implantation 152
monitoring zones, ICD 421–2, *423*
mortality, atrioventricular synchrony 98–100
MR (mitral regurgitation), atrioventricular synchrony 91, 93
MRI *see* magnetic resonance imaging (MRI)
multipolar pacing leads 51
muscle stimulation, follow-up assessments 460–1
muscular dystrophies, permanent pacing 16–17
myocardial infarction, acute *see* acute myocardial infarction
myocardial ischemia/infarction, diagnosis in pacemaker patients 498–9
myocyte, electrical excitability 34–5
myopotential sensing, follow-up assessments 461, *462*

myotonic muscular dystrophy, permanent pacing 16

NCAP (non-competitive atrial pacing) 251–2, *254*
Needle's Eye Snare *203*, 204
needle's eye technique, lead extraction *203*, 204–5
neural alterations, atrioventricular synchrony 98
neurally-mediated syncope 13–16
  indications for pacing 15–16
  types 13
neurogenic syncope, cardioinhibitory, algorithms 244, *247*, *248*
neurohormone level alterations, atrioventricular synchrony 98
neuromuscular disorders, chronic, permanent pacing 16–17
noise, oversensing 301, *304*
noise reversion 70, 269, 439
nomenclature, pacing 211–12
non-apical right ventricular pacing 115–16
non-competitive atrial pacing (NCAP) 251–2, *254*

open loop sensors 74
outcomes, cardiovascular, atrioventricular synchrony 98–100
outcomes, clinical, CRT 392–400
outpatient monitoring 485–8
  frequency 487–8
  Holter and event recorders 486
  remote monitoring 486–7, 488
  trans-telephonic monitoring 485–6, 488
  see also follow-up assessments
outpatient visits 455–64
  electrocardiography 463–4
  history 456–9
  physical examination 459–61, *462*
  radiography/fluoroscopy 461–3
  see also follow-up assessments
output circuit, pulse generators 69–70
oversensing 296–7, *298*
  cardiac signals 298, 300, *301*
  electromagnetic interference 301, 488, 489
  far-field R-waves (FFRWs) 350, 352
  follow-up assessments 474
  ICD 298, *301*, *302*, 416–18, *419*, 489
  non-cardiac signals 300–5

pacemaker dependence 465–6
pacemaker erosion 188–9
  follow-up assessment 459–60
pacemaker function, evaluation
  general considerations 272–4
  see also device interrogation, follow-up assessments
pacemaker hardware 49–71
  leads *see* lead(s)
  magnetic resonance compatible 71–3, 493
  pulse generators *see* pulse generators
pacemaker implantation 151–91
  air embolism 183
  antibiotic prophylaxis 158–9
  arrhythmia 183–4
  axillary vein approach 161–4
  cephalic vein approach 164–5
  complications *see* complications, pacemaker implantation
  cost effectiveness 157–8
  decision process, flow chart 154
  generator insertion 175–9
  imaging systems 151–2
  infection 158, 189–91, 195–6
  informed consent 158
  lead implantation *see* lead implantation
  logistical requirements 151–3
  medicolegal aspects 207
  micropuncture technique 161–4
  pacemaker pocket 166, 175–6
  patient assessment 153–7
  patient monitoring 152
  patient preparation 159
  perforation *see* perforation
  physician qualifications 150–1
  physicians' responsibilities 207
  pneumothorax 182
  post-procedure management 179–80
  pre-implantation orders 158–9
  procedure 159–66
  revision *174*, 176–9
  sedation 159
  single lead VDD pacing 175
  site 159–60
  subclavian vein approach 165–6
  techniques 150–91
  temporary endovascular pacemakers 144–5
  venous access 160–6
  venous access, complications *180*, 181–3
  venous thrombosis 187–8
  see also implantable cardioverter–defibrillator (ICD) implantation
Pacemaker in the Elderly (PASE) trial 109, 110, 111

pacemaker-mediated tachycardia (PMT) 259, 261–3, 313–14
  algorithms to prevent, identify, and terminate 262–3, *264*, 313
  follow-up assessments 482–3
  runaway pacing *vs.* 314
pacemaker mode selection
  atrioventricular block 124, *126*, 127
  hemodynamics 123–7
  sinus node dysfunction 124, *125*, 127
pacemaker pad placement, transcutaneous pacing 135, 137
pacemaker pocket
  follow-up assessments 459–60
  hematoma 189, 459
  infections 189–90, 459
  pacemaker implantation 166, 175–6
pacemaker programmers, follow-up assessments 466–7
pacemaker removal *see* lead extraction
pacemaker syndrome 108–11, 456–7, *458*
  diagnosis 109
  etiology 108, 109–10, *111*
  follow-up assessment 456–7
  hemodynamics 108–11
  incidence 109
  management 111
  predicting 109–110
  symptoms 109
pacemaker timing cycles 211–70
  abbreviations 211
  atrioventricular interval 222–6
  base-rate behavior *see* base-rate behavior
  biventricular pacing *219*, 264–6
  blanking periods *see* blanking periods
  features affecting device behavior 223
  pacing modes 212–17, 218–22
  pacing nomenclature 211–12
  portions 217–27
  rate enhancements *see* rate enhancements
  refractory periods *see* refractory periods
  upper rate behavior 234, 237, *238*
  ventriculoatrial interval 226, 232
  see also atrioventricular interval; rate-modulated pacing
pacing, basic concepts 35–49
pacing impedance 38–9
  time-dependent changes 44

pacing modes 212–17
atrial asynchronous (AOO) pacing 212, *213*, 218
atrial inhibited (AAI) pacing 213, *214*, 218, *220*, *221*
atrioventricular sequential, ventricular inhibited pacing (DVI) *213*, 215, *216*, 222
dual chamber asynchronous pacing 212, *213*, 218
dual chamber pacing and sensing with inhibition and tracking *see* dual chamber pacing and sensing with inhibition and tracking (DDD)
dual chamber pacing and sensing with inhibition but without tracking (DDI) *213*, 215, *216*, 222
rate-modulated pacing *see* rate-modulated pacing
single chamber asynchronous pacing 212, *213*, *214*, 218
single chamber inhibited pacing 213, *214*, 218, *220*, *221*
single chamber triggered mode pacing (AAT and VVT) 213–14
timing cycles 218–22
ventricular asynchronous (VOO) pacing 212, *213*, *214*, 218
ventricular inhibited (VVI) pacing 213, *214*, 218, *220*, *221*
ventricular pacing, dual chamber sensing with P-synchronous ventricular pacing and inhibition *see* VDD (ventricular pacing, dual chamber sensing with P-synchronous ventricular pacing and inhibition) pacing
ventricular pacing with inhibition and dual chamber sensing (VDI) *213*, 215
pacing nomenclature 211–12
pacing rate, unexpected/sudden changes 308–14, *315*
pacing system analyzers (PSAs) 153
pacing thresholds
automated capture 475, *476*
follow-up assessments 474–8
impact of clinical variables 47
see also stimulation threshold
passive fixation leads 51–4, 166–7
patient assessment
anticoagulants 155–6
antiplatelet agents 155–6
asystole risk 157
follow-up *see* follow-up assessments
infection 153–4
kidney disease 154–5
mastectomy, prior 157
pacemaker implantation 153–7
subclavian vein anomalies 156–7
tricuspid valve disease 157
venography 152
patient diagnostics, follow-up assessments 478, 480–1
patient evaluation, ICD shocks 441–2, *443*
patient preparation
pacemaker implantation 159
pre-implantation orders 158–9
patient selection, CRT 374–6, *378*
PAVB (post-atrial ventricular blanking period) 298, *300*
PCW (pulmonary capillary wedge) pressure, atrioventricular synchrony 88–9, *90*
peak endocardial acceleration sensor 76
pectoral muscle stimulation, follow-up assessments 460
percussion-based pacing 144
perforation 184–6, 284, *285*
coronary vein, CRT implantation 191, 391–2
temporary transvenous cardiac pacing 146, *147*
pericardial tamponade, pacemaker implantation 184
perioperative management, electromagnetic interference 440, 496, *497*
peripheral vascular resistance, in pacemaker syndrome 109, *111*
permanent pacing
acquired atrioventricular block 10–11
acute myocardial infarction 25, *26*, *27*
adolescents 23–5
after cardiac surgery 25, 27
after transcatheter aortic valve implantation 27
amyloidosis 18
Becker muscular dystrophy 17
Chagas disease 18
children 23–5
chronic bifascicular block 12–13
chronic neuromuscular disorders 16–17
classes of guideline recommendations 4
collagen vascular diseases 18
dilated cardiomyopathy 19
Duchenne muscular dystrophy 16–17
Emery–Dreifuss muscular dystrophy 17
genetic cardiomyopathies 18–20
hypertrophic cardiomyopathy 19–20
idiopathic orthostatic hypotension 16
indications 3–27
infiltrative and inflammatory disorders 17–18
Kearns–Sayre syndrome 17
limb girdle muscular dystrophy 17
myotonic muscular dystrophy 16
neuromuscular disorders, chronic 16–17
reflex syncope 15–16
sarcoidosis 17–18
sinus node dysfunction 6–7
systolic heart failure 20–1
tachycardia prevention/termination 21–3
personnel
follow-up clinics 454
lead extraction 198
pharmacological effects, stimulation threshold 47
pharmacological therapy, arrhythmias 438
phrenic nerve stimulation, management of left ventricular lead placement difficulties 388–90
physical examination
evaluation of pacemaker malfunction 273–4
follow-up assessments 459–61, *462*
general aspects 461
physician qualifications, pacemaker implantation 150–1
physician responsibility, pacemaker implantation 207
physiology, conduction system 1–3
piezoelectric crystals (vibration sensors) 74
PMT *see* pacemaker-mediated tachycardia (PMT)
pneumothorax, pacemaker implantation 182
pocket, pacemaker *see* pacemaker pocket
polarization 41–2
polyurethane, lead insulation 57–8, 336–7
post-atrial ventricular blanking period (PAVB) 298, *300*
post-procedure management
electromagnetic interference 496
pacemaker implantation 179–80

post-transplantation period, immediate, follow-up assessments 453–4
post-ventricular atrial refractory period (PVARP) 226–7, 294
  dynamic 227, *228*
power-on reset (POR) mode 471–2
power source, pulse generators 67–9
pre-implantation orders, pacemaker implantation 158–9
premature atrial contractions, loss of biventricular pacing 268
premature ventricular contractions, loss of biventricular pacing 268
preoperative pacing, temporary 29
primary prevention, ICD therapy 324–5, *327*, 422, 425, *427*
PR intervals, short and dynamic, loss of biventricular pacing 267–8
procedural interventions, temporary pacing 29
procedure, pacemaker implantation 159–66
programmed parameters, review of, follow-up assessments 467–8
programmers
  follow-up assessments 466–7
  see also device interrogation, follow-up assessments
programming
  consideration of time-dependent changes 46–7
  dynamic AV and VV interval programming 77
  features affecting device behavior 223
  follow-up assessments 478, *479*, 483–5
  general guidelines for common bradycardia parameters 479
  ICD *355*, *364*, 367–70, 420–6
  post-procedure management 179–80
  sensor algorithms 77–8
  spurious 467
propagation, electrical stimuli 35
protection period, left ventricular 265–6
pseudofusion 305, 464
pseudo-malfunctions 310
pulmonary capillary wedge (PCW) pressure, atrioventricular synchrony 88–9, *90*
pulmonary venous flow patterns, atrioventricular synchrony 89–90, *91*, *92*
pulse, follow-up assessment 461
pulsed digital fluoroscopy, pacemaker implantation 152
pulse generators 67–71
  batteries *see* batteries
  complications *176*, *180*, *181*, 188–9
  ICD 329–35
  insertion 175–9
  insertion, revision 176–9
  magnetic resonance compatible 73, 493
  magnet mode 71
  malfunction 62, 275–9
  microprocessors 69
  output circuit 69–70
  power source 67–9
  sensing circuit 70
  telemetry circuit 70–1
  timing circuit 70
Purkinje fibers 3
PVARP *see* post-ventricular atrial refractory period (PVARP)

QRS complex, pacing artifacts 305, *306*
QRS duration, CRT outcomes 398–400
QRS morphology
  CRT outcomes 400
  paced, from various electrode positions 140–1
QT interval sensors 77
quadripolar lead 48
qualifications, physician, pacemaker implantation 150–1
quality assurance, pacemaker implantation 151

radiation exposure, device malfunction 278–9
radiation therapy, electromagnetic interference 494–5, *497*
radiofrequency ablation, electromagnetic interference 494, *497*
radiographic device identifiers 274, 284, 463
radiography
  follow-up assessments 284, 461–3
  malfunction evaluation *275*, 284, *285*, *286*, *287*
random access memory (RAM)-based pulse generators 69
rate-adaptive atrioventricular delay 107–8, 225–6, 485
rate-adaptive sensors 73–9, 83–4, 87, 314
rate drop response (RDR) 244, *247*, *248*, *311*
rate enhancements 238–44
  algorithms for cardioinhibitory neurogenic syncope 244, *247*, *248*
  algorithms to allow intrinsic sinus rate 244, *245*, *246*
  base rate during mode switch/fallback 238–40, *241*
  rate smoothing/stabilization *239*, 240, *242*, *243*
  see also rate-modulated pacing
rate hysteresis 244, *245*, *246*
  advanced 244, *247*
rate-modulated pacing 227–31, 240, *243*, 314
  dual chamber rate-modulated pacing 229–31, 240, *243*
  effects of base-rate behavior 232–3, *235*
  sensors 73–9, 83–4, 87
  single chamber/dual chamber rate-modulated asynchronous pacing 229
  single chamber inhibited and rate-modulated pacing 228–9
rate modulation
  advantages and clinical benefits 86–7
  chronotropic incompetence 83, 85
  exercise physiology 84–5
  hemodynamics 83–7
rate-related aberrancy, limitations of SVT–VT morphology discriminators 347
rate sensing
  ICD 340–2
  see also sensing
rate smoothing *239*, 240, *242*
rate stabilization *239*, 240, *243*
read-only memory (ROM)-based pulse generators 69
real-time data, follow-up assessments 468–9
recalls, device 455, *498*, 499–501
record keeping, follow-up assessment 454–5
reed switch, pulse generators 71
reflex syncope 13–16
  indications for permanent pacing 15–16
  types 13
refractory periods 217–18
  biventricular pacemakers 265, *266*
  left ventricular refractory period 265
  post-ventricular atrial refractory period *see* post-ventricular atrial refractory period (PVARP)
  total atrial refractory period 227

regurgitation, mitral, atrioventricular synchrony 91, 93
remote monitoring
ICD 418–20
outpatient monitoring 486–7, 488
removal, pacemaker *see* lead extraction
repetitive non-re-entrant ventriculoatrial synchrony 313–14, *315*
reporting, lead malfunction/failure 66–7
responders *vs.* non-responders, CRT 401
response to pacing, SVT–VT discrimination *346*, 352
rest rate 244, *245*
resuscitation, cardiopulmonary, temporary pacing 134
retrograde conduction, pulmonary venous flow patterns 90, *91*
returned products analysis (RPA), lead failure 64, 65, 66, 67
reversible causes, bradycardia 134–5, *136*
right ventricular impedance sensor 76–7
right ventricular outflow tract (RVOT) pacing 115
right ventricular pacing
algorithms to minimize 255, 257–9, *260*
alternative site 114–16
detrimental effects 111–13
hemodynamics 111–16
minimizing strategies 113–14
rivaroxaban therapy 156
runaway pacemaker 315

safety margin strategy, ICD implant testing 360
safety pacing 222–5
sarcoidosis, permanent pacing 17–18
scan hysteresis 244, *245*, *246*
scar burden, CRT non-response and 403
SCD (sudden cardiac death) prevention, ICD indications 323–7
schedules, follow-up assessments 487–8
search hysteresis 244, *245*
secondary prevention, ICD therapy 324, 425, *427*
sedation, pacemaker implantation 159
Seldinger technique, venous access 160–1
sensing
automated 46
bipolar *vs.* unipolar 36–7
EMI *see* electromagnetic interference (EMI)
follow-up assessments 472–4
ICD 340–2, 415–18
impedance 39
problems *see* sensing abnormalities
time-dependent changes 43–4
unipolar *vs.* bipolar 36–7
see also sensors
sensing abnormalities 291–305
causes and management 307
oversensing *see* oversensing
undersensing *see* undersensing
see also malfunctions
sensing circuit, pulse generators 70
sensing thresholds, follow-up assessments 472–4
sensitivity adjustments, implantable cardioverter–defibrillator (ICD) 292
sensor algorithms, programming 77–8
sensor-driven pacing 314
see also rate-modulated pacing
sensors 73–9, 314
accelerometers 74–5, 314
blended minute-ventilation and activity sensors 76
choosing 78–9
minute-ventilation sensors 75–6, 314
peak endocardial acceleration sensor 76
right ventricular impedance sensor 76–7
types 73–7
see also sensing
severe heart failure, CRT outcomes 392–7
shocks, ICD *see* implantable cardioverter–defibrillator (ICD) shocks
silicone, lead insulation 57, *58*, 337
single chamber algorithms, SVT–VT discrimination
dual chamber discriminators *vs.* , performance 354–5, *356*, *357*, *358*
operation 352
ventricular building blocks 345–50
see also supraventricular tachycardia–ventricular tachycardia (SVT–VT) discrimination
single chamber asynchronous pacing 212, *213*, *214*, 218
single chamber inhibited and rate-modulated pacing 228–9
single chamber inhibited pacing 213, *214*, 218, *220*, *221*
single chamber rate-modulated asynchronous pacing 229
single chamber triggered mode pacing 213–14
single lead VDD pacing, lead implantation 175
sinoatrial (SA) node, anatomy and physiology 1–2
sinus node, anatomy and physiology 1–2
sinus node dysfunction 4–7, 73
acute myocardial infarction 28
diagnosis *5*, 6
indications for permanent pacing 6–7
manifestations 4–6
pacemaker mode selection 124, *125*, 127
sinus preference 244, *245*, *246*
sinus rate (SR)
above maximum tracking rate, loss of biventricular pacing 267
intrinsic, algorithms to allow 244, *245*, *246*
sites
alternative, right ventricular pacing 114–16
pacemaker implantation 159–60
sleep rate 244, *245*
software abnormalities 279
Sorin Group ICDs 429, *430*
spurious programming 467
St. Jude Medical ICDs 429–31
Steinert disease, permanent pacing 16
steroid-eluting electrodes 59
stimulation
anodal 42
bipolar *vs.* unipolar 37–8
stimulation threshold 39–41
bipolar *vs.* unipolar stimulation 37–8
definition 35
high left ventricular, management of left ventricular lead placement difficulties 386, 388
impact of clinical variables 47
metabolic effects 47
pharmacological effects 47
strength–duration relationship 39–41
strength–interval relationship 41
time-dependent changes 44
stored data analysis 314–20
arrhythmia logbook and stored electrograms *315*, 316, *320*

basic device data 315, *316*
event counters and histograms *293*, 315, *318–19*
follow-up assessments 478, 480–1
strength–duration curve
defibrillation 338, *339*
stimulation threshold 39–41
strength–interval relationship, stimulation threshold 41
subclavian vein anomalies, patient assessment 156–7
subclavian vein approach, pacemaker implantation 165–6
subclavian vein thrombosis 187–8
sudden bradycardia response (SBR) 244, *247*, *248*
sudden cardiac death (SCD) prevention, ICD indications 323–7
sudden onset, SVT–VT discrimination 348, 350
sudden rate changes 308–14, *315*
superior approach, lead extraction 199–202, *203*
supraventricular tachycardia (SVT) discriminators 422, 425–6
antiarrhythmic drug therapy 425
common discriminators 426
overriding timers 354, 425–6
primary prevention ICDs 422, 425
secondary prevention ICDs 425
see also supraventricular tachycardia–ventricular tachycardia (SVT–VT) discrimination
supraventricular tachycardia–ventricular tachycardia (SVT–VT) discrimination 342, 345–57
active discrimination *346*, 352
atrial building blocks *346*, 350–2
atrioventricular building blocks *346*, 350
clinical role 355, 357
dual chamber algorithms *see* dual chamber algorithms, SVT–VT discrimination
duration-based "safety-net" features to override discriminators 354, 425–6
interval stability 348
morphology discriminators 345–8
morphology discriminators, limitations/failure modes 345, 347, *349*
older discriminators 348, 350
operation of algorithms 352–4
performance of algorithms 354–5, *356*, *357*, *358*
single chamber algorithms *see* single chamber algorithms, SVT–VT discrimination
sudden onset 348, 350
supplementary use of electrogram width *346*, 348
ventricular building blocks 345–50
see also supraventricular tachycardia (SVT) discriminators
surgery
cardiac *see* cardiac surgery
electrosurgery, electromagnetic interference 439–40, 490–1, *497*
non-cardiac, temporary pacing prior to 29
symptoms, follow-up assessments 456–9
syncope
follow-up assessments 459
ICD therapy 433
in pacemaker syndrome 109
reflex *see* reflex syncope
systolic heart failure, permanent pacing 20–1

tachy–brady syndrome 4, *5*
tachycardia
interfering signals, limitations of SVT–VT morphology discriminators 347
during pacemaker implantation 183–4
pacemaker-mediated *see* pacemaker-mediated tachycardia (PMT)
permanent pacing 21–3
prevention/termination 21–3, 30
temporary pacing 30
see also ventricular tachycardia (VT)
tachycardia programming, ICD 421–6
tantalum capacitors, ICD *332*, 333–4
TAVI (transcatheter aortic valve implantation), permanent pacing after 27
telemetry
follow-up assessments 466–7
see also device interrogation, follow-up assessments
telemetry circuit, pulse generators 70–1
temporal trends
follow-up assessments 480–1
see also time-dependent changes
temporary pacing 134–48
acidosis and hyperkalemia 30
acute bacterial endocarditis 30
acute myocardial infarction 25, 28–9
cardiac catheterization 29
cardiopulmonary resuscitation 134
clinical application 147
comparison of technologies 147, *148*
complications 145–7
drug-induced bradycardia 29–30
dual chamber pacing 142, *144*
epicardial pacing 141, *143*, *144*
following cardiac surgery 29
head/neck tumor treatment 30
hypothyroidism 30
indications 27–30, 134
insertion of endovascular pacemaker 144–5
Lyme disease 30
options 135, 137–44
percussion-/fist-based pacing 144
tachycardias 30
transcutaneous *see* transcutaneous pacing
transesophageal pacing 141–2
transvenous endocardial pacing 138–41, *142*, *143*
TENS (transcutaneous electrical nerve stimulation), electromagnetic interference 439, 495, *497*
therapeutic radiation, electromagnetic interference 494–5, *497*
thoracotomy, lead extraction 206
threshold, stimulation *see* stimulation threshold
thrombosis, venous 187–8
time-dependent changes
consideration of, device programming 46–7
impedance 44
sensing 43–4
stimulation threshold 44
timing circuit, pulse generators 70
timing cycles, pacemakers *see* pacemaker timing cycles
torsades de pointes 21, *22*
permanent pacing 10
temporary pacing 30
total atrial refractory period (TARP) 227
transcatheter aortic valve implantation (TAVI), permanent pacing after 27
transcutaneous electrical nerve stimulation (TENS), electromagnetic interference 439, 495, *497*

UPLOADED BY [STORMRG]

transcutaneous pacing 135, 137–8
  complications 137–8
  failure 137, *138*
  pad placement 135, 137
transesophageal pacing, temporary 141–2
trans-telephonic monitoring 485–6, 488
transvenous pacing *see* endocardial (transvenous) pacing
treadmill testing, follow-up assessment 458–9
tricuspid valve, lead complications 186
tricuspid valve disease, patient assessment 157
trifascicular block 11–12
triggered pacing 310, 312–13
troubleshooting 305–6, *307*, *308*
  baseline data needed 273
  ICD 440–8
  see also malfunctions
twiddler's syndrome *176*, 186
2:1 lock-in protection algorithm 251, *252*, *253*

undersensing *288*, 291–6
  apparent 310
  causes 293
  follow-up assessment 472, *473*
  functional 294
unexpected rate changes 308–14, *315*
unipolar leads 49–50
unipolar sensing, bipolar sensing *vs.* 36–7
unipolar stimulation, bipolar stimulation *vs.* 37–8
univentricular left ventricular pacing 118–19
upper limit of vulnerability (ULV) 328
upper rate behavior 234, 237, *238*

vacuum-assisted wound closure 190
VAI (ventriculoatrial interval) 226, 232
valvular regurgitation, atrioventricular, atrioventricular synchrony 90–1, 93, *94*
VDD (ventricular pacing, dual chamber sensing with P-synchronous ventricular pacing and inhibition) pacing *213*, 215–17, 222
  single lead, implantation 175
VDI (ventricular pacing with inhibition and dual chamber sensing) *213*, 215
venography
  deep vein thrombosis 187
  pacemaker implantation 152
venoplasty, management of left ventricular lead placement difficulties 386, *390*
venous access
  complications *180*, 181–3
  pacemaker implantation 160–6
  Seldinger technique 160–1
venous thrombosis, pacemaker implantation 187–8
ventricular arrhythmia, during pacemaker implantation 184
ventricular asynchronous (VOO) pacing 212, *213*, *214*, 218
ventricular-based timing 231
  atrial-based timing *vs.* 231–2, *233*, *234*
  effect on rate-modulated pacing modes 232–3, *235*
ventricular building blocks, SVT–VT discrimination 345–50
ventricular capture, transcutaneous pacing 137, *138*
Ventricular Capture Management™ 46
ventricular contractions, premature, loss of biventricular pacing 268
ventricular electrogram morphology, SVT–VT discrimination 345–8
ventricular fibrillation 327–9
ventricular inhibited (VVI) pacing 213, *214*, 218, *220*, *221*
ventricular lead positioning 167–72
ventricular pacing
  atrioventricular pacing *vs.* 87–108
  left *see* left ventricular pacing
  pacemaker syndrome *see* pacemaker syndrome
  right *see* right ventricular pacing
ventricular pacing, dual chamber sensing with P-synchronous ventricular pacing and inhibition *see* VDD (ventricular pacing, dual chamber sensing with P-synchronous ventricular pacing and inhibition) pacing
ventricular pacing with inhibition and dual chamber sensing (VDI) *213*, 215
ventricular rate, atrial rate *vs.*, SVT–VT discrimination *346*, 350
ventricular rate regularization (VRR) *239*, 240
ventricular rate stabilization (VRS) *239*, 240, *243*
ventricular-sensed response 267–8
ventricular tachycardia (VT)
  failure to detect/treat sustained VT, ICD troubleshooting 445–7
  fast, antitachycardia pacing (ATP) 432–4
  permanent pacing 21–3
  prevention/termination, cardiac pacing 21–3, 30
  programming, ICD 421–6
  sensing, ICD 340–2, 415–18, *419*
  slow, antitachycardia pacing (ATP) 435
  supraventricular tachycardia *vs. see* supraventricular tachycardia–ventricular tachycardia (SVT–VT) discrimination
  temporary pacing 30
  see also tachycardia
ventriculoatrial (retrograde) conduction, pulmonary venous flow patterns 90, *91*
ventriculoatrial interval (VAI) 226, 232
vibration sensors 74
virtual electrodes 328
vital signs, follow-up assessments 461
VOO (ventricular asynchronous) pacing 212, *213*, *214*, 218
VT *see* ventricular tachycardia (VT)
vulnerability testing, ICD 364–5
vulnerable period 328
vulnerable zone, shock-induced ventricular fibrillation 328
VV (left ventricular–right ventricular) interval, dynamic programming 77
VVI (ventricular inhibited) pacing 213, *214*, 218, *220*, *221*
VV (left ventricular–right ventricular) optimization 77
  CRT 406–7
VVT (single chamber triggered mode pacing) 213–14

warfarin, patient assessment 156
Wedensky effect 41
Wenckebach-like behavior, upper rate behavior 237, *238*
Wenckebach phenomenon, dual chamber systems 457–8
Wilkoff chronotropic assessment exercise protocol 85
withdrawal of therapy, dying patients 496, 498
wound closure, vacuum-assisted 190

Zener diode 70