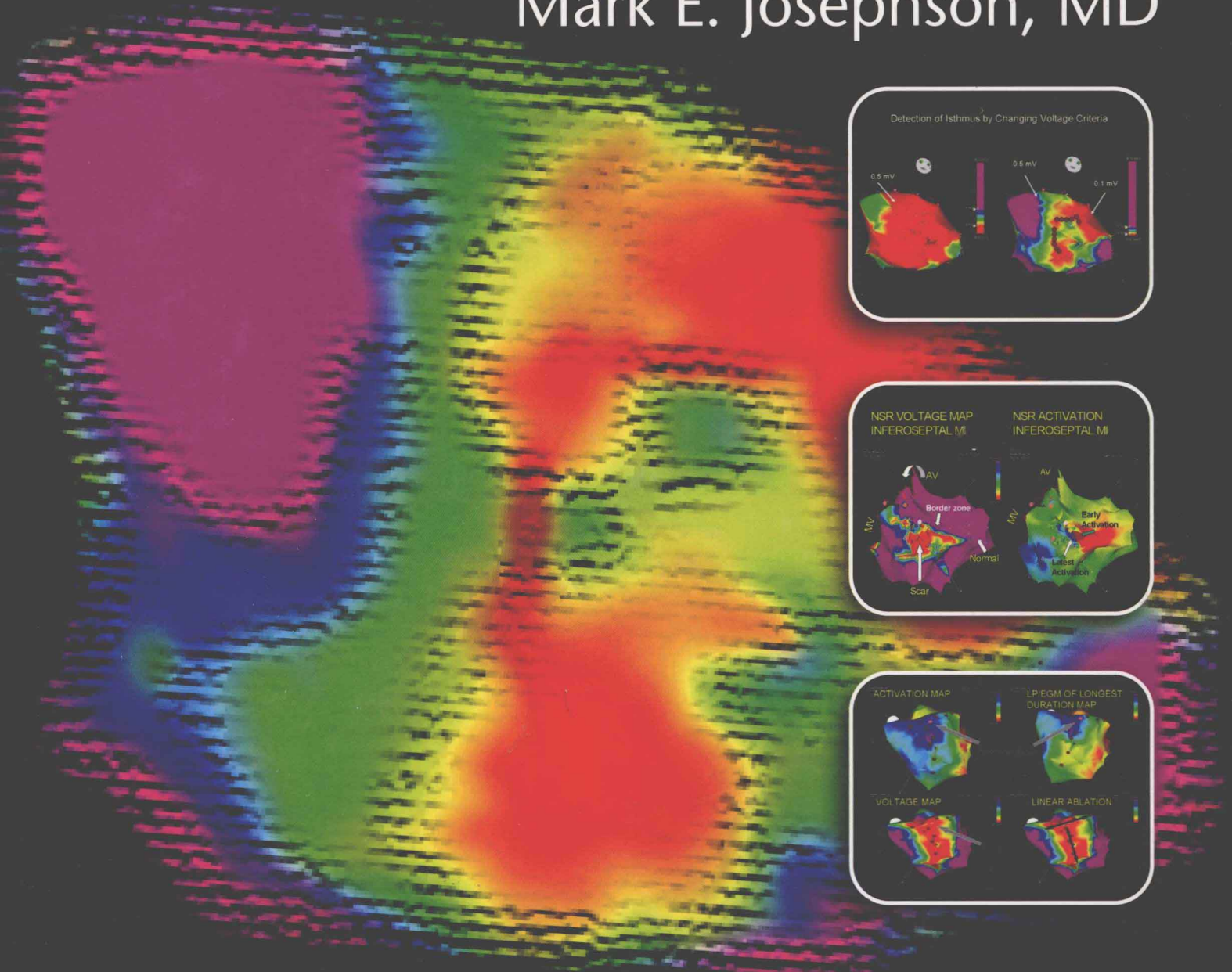
FOURTH EDITION

CLINICAL CARDIAC ELECTROPHYSIOLOGY

TECHNIQUES AND INTERPRETATIONS

Mark E. Josephson, MD



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SOLUTION

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Techniques and Interpretations

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Acquisitions Editor: Frances R. DeStefano
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Marketing Manager: Kim Schonberger
Project Manager: Cindy Oberle
Creative Director: Doug Smock
Cover Designer: Itzack Shelomi
Compositor: Aptara Corp

Printed in China

Library of Congress Cataloging-in-Publication Data

Josephson, Mark E.
Clinical cardiac electrophysiology : techniques and interpretations / Mark E. Josephson. — 4th ed.
p. ; cm.
Includes bibliographical references and index.
ISBN 978-0-7817-7739-1 (case : alk. paper)
1. Heart — Diseases — Diagnosis. 2. Electrocardiography. 3. Arrhythmia — Diagnosis. I. Title.
[DNLM: 1. Electrophysiologic Techniques, Cardiac — methods. 2. Arrhythmias, Cardiac — diagnosis. 3. Arrhythmias, Cardiac — therapy. 4. Heart Conduction System — physiopathology. WG 141.5.F9 J83c 2008]
RC683.5.E5J58 2008
616.1'2075 — dc22

2008001319

10 9 8 7 6 5 4 3 2

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This book is dedicated to my family—Sylvie Tessa, Elan Robert, Joan, Rachel, Todd, Stephanie, and Jesse—for their love and support, and to all current and future students of arrhythmias for whom this book was written.

PREFACE

The past 35 years have witnessed the birth, growth, and evolution of clinical electrophysiology, from a field whose initial goals were the understanding of arrhythmia mechanisms to one of significant therapeutic impact. The development and refinement of implantable devices and catheter ablation have made nonpharmacologic therapy a treatment of choice for most arrhythmias encountered in clinical practice. Unfortunately, these new therapeutic tools have captured the imagination of young electrophysiologists to such an extent that terms such as *ablationist*, *defibrillationist*, or *implanter* are used to describe their practice. Their zest for the application of such therapeutic modalities has been associated with a decrease in the emphasis of understanding the mechanisms, clinical implications, and limitations of the therapeutic interventions used to treat arrhythmias. Such behavior is often associated with a lack of, or limited, critical thought that is essential to the development of a new therapeutic concept. There should be the development of a hypothesis, the questioning the rationale of the hypothesis, and the testing the hypothesis prior to widespread application of the therapeutic strategy.

The purpose of this book is to provide the budding electrophysiologist with an *electrophysiologic* approach to arrhythmias, which is predicated on the hypothesis that a better understanding of the mechanisms of arrhythmias will lead to more successful and rationally chosen therapy. As such, this book will stress the methodology required to define the mechanism and site of origin of arrhythmias so that safe and effective therapy can be chosen. The techniques suggested to address these issues and specific therapeutic interventions employed represent a personal view, one that is based on experience and, not infrequently, on intuition.

Mark E. Josephson, M.D.

FOREWORD: HISTORICAL PERSPECTIVES

The study of the heart as an electrical organ has fascinated physiologists and physicians for nearly a century and a half. Matteucci (1) studied electrical current in pigeon hearts, and Kölliker and Müller (2) studied discrete electrical activity in association with each cardiac contraction in the frog. Study of the human electrocardiogram awaited the discoveries of Waller (3) and, most important, Einthoven (4), whose use and development of the string galvanometer permitted the standardization and widespread use of that instrument. Almost simultaneously, anatomists and pathologists were tracing the atrioventricular (A-V) conduction system. Many of the pathways, both normal and abnormal, still bear the names of the men who described them. This group of men included Wilhem His (5), who discovered the muscle bundle joining the atrial and ventricular septae that is known as the common A-V bundle or the bundle of His.

During the first half of the 20th century, clinical electrocardiography gained widespread acceptance; and, in feats of deductive reasoning, numerous electrocardiographers contributed to the understanding of how the cardiac impulse in man is generated and conducted. Those researchers were, however, limited to observations of atrial (P wave) and ventricular (QRS complex) depolarizations and their relationships to one another made at a relatively slow recording speed (25 mm/s) during spontaneous rhythms. Nevertheless, combining those carefully made observations of the anatomists and the concepts developed in the physiology laboratory, these researchers accurately described, or at least hypothesized, many of the important concepts of modern electrophysiology. These included such concepts as slow conduction, concealed conduction, A-V block, and the general area of arrhythmogenesis, including abnormal impulse formation and reentry. Some of this history was recently reviewed by the late Richard Langendorf (6). Even the mechanism of preexcitation and circus movement tachycardia were accurately described and diagrammed by Wolferth and Wood from the University of Pennsylvania in 1933 (7). The diagrams in that manuscript are as accurate today as they were hypothetical in 1933. Much of what has followed the innovative work of investigators in the first half of the century has confirmed the brilliance of their investigations.

In the 1940s and 1950s, when cardiac catheterization was emerging, it became increasingly apparent that luminal catheters could be placed intravascularly by a variety of routes and safely passed to almost any region of the heart, where they could remain for a substantial period of time. Alanis et al. recorded the His bundle potential in an isolated perfused animal heart (8), and Stuckey and Hoffman recorded the His bundle potential in man during open heart surgery (9). Giraud et al. were the first to record electrical activity from the His bundle by a catheter (10); however, it was the report of Scherlag et al. (11), detailing the electrode catheter technique in dogs and humans, to reproducibly record His bundle electrogram, which paved the way for the extraordinary investigations that have occurred over the past two and a half decades.

At about the time Scherlag et al. (11) were detailing the catheter technique of recording His bundle activity, Durrer et al. in Amsterdam and Coumel and his associates in Paris independently developed the technique of programmed electrical stimulation of the heart in 1967 (12,13). This began the first decade of clinical cardiac electrophysiology. Although the early years of intracardiac recording in man were dominated by descriptive work exploring the presence and timing of His bundle activation (and that of a few other intracardiac sites) in a variety of spontaneously occurring physiologic and pathologic states, a quantum leap occurred when the technique of programmed stimulation was combined with intracardiac recordings by Wellens (14). Use of these techniques subsequently furthered our understanding of the functional components of the A-V specialized conducting system, including the refractory periods of the atrium, A-V node, His bundle, Purkinje system, and ventricles, and enabled us to assess the effects of pharmacologic agents on these parameters, to induce and terminate a variety of tachyarrhythmias, and, in a major way, has led to a greater understanding of the electrophysiology of the human heart. Shortly thereafter, enthusiasm and inquisitiveness led to placement of an increasing number of catheters for recording and stimulation to different locations within the heart, first in the atria and thereafter in the ventricle. This led to development of endocardial catheter mapping techniques to define the location of bypass tracts and the mechanisms of supraventricular tachyarrhythmias (15).

In the mid-1970s, Josephson et al. (16) at the University of Pennsylvania were the first to use vigorous, systematic, multisite programmed stimulation in the study of sustained ventricular tachycardia resulting from myocardial infarction, which allowed induction of ventricular tachycardia in more than 90% of the patients in whom this rhythm occurred spontaneously. In addition, Josephson et al. (17) developed the technique of endocardial catheter mapping of ventricular tachycardia, which for the first time demonstrated the safety and significance of placing catheters in the left ventricle. This led to the recognition of

the subendocardial origin of the majority of ventricular tachyarrhythmias, associated with coronary artery disease and the development of subendocardial resection as a therapeutic cure for this arrhythmia (18). Subsequent investigators sought to establish a better understanding of the methodology used in the electrophysiology study to induce arrhythmias. Several studies validated the sensitivity and specificity of programmed stimulation for induction of uniform tachycardias, and the nonspecificity of polymorphic arrhythmias induced with vigorous programmed stimulation was recognized (19,20).

For the next decade, electrophysiologic studies continued to better understand the mechanisms of arrhythmias in man by comparing the response to programmed stimulation in man to the response to *in vitro* and *in vivo* studies of abnormal automaticity, triggered activity caused by delayed and early afterdepolarizations, and anatomical functional reentry. These studies, which used programmed stimulation, endocardial catheter mapping, and response of tachycardias to stimulation and drugs, have all suggested that most sustained paroxysmal tachycardias were due to reentry. The reentrant substrate could be functional or fixed or combinations of both. In particular, the use of entrainment and resetting during atrial flutter and ventricular tachycardia were important techniques used to confirm the reentrant nature of these arrhythmias (20–25). Resetting and entrainment with fusion became phenomena that were diagnostic of reentrant excitation. Cassidy et al. (26), using left ventricular endocardial mapping during sinus rhythm, for the first time described an electrophysiologic correlate of the pathophysiologic substrate of ventricular tachycardia in coronary artery disease—a fragmented electrogram (26,27). Fenoglio, Wit, Josephson, and their colleagues from the University of Pennsylvania documented for the first time that these arrhythmogenic areas were associated with viable muscle fibers separated by and imbedded in scar tissue from the infarction (28). They demonstrated that the quality and quantity of abnormal electrograms (and, hence, the pathophysiologic substrate) differed for sustained monomorphic ventricular tachycardia (VT), nonsustained VT, and ventricular fibrillation in patients with prior infarction and cardiomyopathy. Experimental studies by Wit et al. (29) demonstrated that these fractionated electrograms resulted from poorly coupled fibers that were viable and maintained normal action potential characteristics but that exhibited saltatory conduction caused by nonuniform anisotropy. Further exploration of contributing factors (triggers), such as the influence of the autonomic nervous system or ischemia, will be necessary to further enhance our understanding of the genesis of the arrhythmias. This initial decade or so of electrophysiology could be likened to an era of discovery.

Subsequently, and overlapping somewhat with the era of discovery, was the development and use of electrophysiology as a tool for therapy for arrhythmias. The ability to reproducibly initiate and terminate arrhythmias led to the development of serial drug testing to assess antiarrhythmic efficacy (30). The ability of an antiarrhythmic drug to prevent initiation of a tachycardia that was reliably initiated in the control state appeared to predict freedom from the arrhythmia in the 2- to 3-year follow-up. This was seen in many nonrandomized clinical trials from laboratories in the early 1980s.

The persistent inducibility of an arrhythmia universally predicted an outcome that was worse than that in patients in whom tachycardias were made noninducible. The natural history of recurrences of ventricular tachyarrhythmias (or other arrhythmias for that matter) and the changing substrate for arrhythmias were recognized potential imitations of drug testing. It was recognized very early that programmed stimulation may not be applicable to the management of ventricular tachyarrhythmias in patients without coronary artery disease (i.e., cardiomyopathy) (31). It was also recognized that the clinical characteristics of spontaneous ventricular arrhythmias dictated the type of recurrence on antiarrhythmic therapy. As such, patients who present with stable arrhythmias generally have recurrences that are stable; those presenting with cardiac arrest tend to recur as cardiac arrest. Thus, in patients presenting with a cardiac arrest, a 70–90% chance of no recurrence in 2 years based on serial drug testing still meant that 10–30% of the patients would have a recurrent cardiac arrest. This was not an acceptable recurrence rate and led to the subsequent abandonment of antiarrhythmic agents to treat patients with cardiac arrest with defibrillators (32). (See subsequent paragraphs.)

The ESVEM study (33), although plagued by limitations in protocol and patient selection, again showed the limitations of EP-guided drug testing to predict freedom of arrhythmias. Nevertheless, all studies to date have shown that patients with spontaneous sustained monomorphic ventricular tachycardia whose arrhythmias are rendered noninducible by antiarrhythmic agents fare better than those who have arrhythmias that are persistently inducible. Recent studies suggest that induction and EP-guided therapy of induced but never-before-seen ventricular arrhythmias is not accurate enough to make it a useful tool in isolation to predict malignant ventricular arrhythmias in patients with prior myocardial infarction (MUSTT, MADIT). Nevertheless, other investigators find EP-guided therapy useful in idiopathic ventricular fibrillation. Whether these data demonstrate the ability of EP testing to guide results, or the ability of EP testing to select patients at low and high risk, respectively, remains unknown.

With the known limitations of EP-guided therapy to predict outcomes uniformly and correctly, as well as the potentially lethal proarrhythmic effect of antiarrhythmic agents demonstrated in the CAST study (34), the desire for nonpharmacologic approaches to therapy grew. Surgery had already become a gold standard therapy for Wolff-Parkinson-White syndrome, and innovative surgical procedures for ventricular tachycardia had grown from our

understanding of the pathophysiologic substrate of VT and coronary disease and the mapping of ventricular tachycardia from the Pennsylvania group. However, surgery was considered a rather drastic procedure for patients with a relatively benign disorder (supraventricular tachycardia and the Wolff-Parkinson-White syndrome), and although successful for ventricular tachycardia for coronary artery disease, was associated with a high operative mortality. These limitations have led to two major areas of nonpharmacologic therapy that have dominated the last decade: implantable antitachycardia/defibrillator devices and catheter ablation. These techniques were the natural evolution of our knowledge of arrhythmia mechanisms (e.g., the ability to initiate and terminate the reentrant arrhythmias by pacing and electrical conversion) and the refinement of catheter mapping techniques and the success of surgery used with these techniques.

It was Michel Mirowski who initially demonstrated that an implantable defibrillator could convert ventricular tachycardia or ventricular fibrillation to sinus rhythm regardless of underlying pathophysiologic substrate and prevent sudden cardiac death (32). The initial devices that were implanted epicardially via thoracotomy have been reduced in size so that they can be implanted pectorally using active cans as a pacemaker of two decades ago. Dual-chambered implantable defibrillators with a full range of antitachycardia pacing modalities are in widespread use for the treatment of patients with ventricular tachycardia that is either stable or producing cardiac arrest. The antitachycardia pacing modalities are very effective in terminating monomorphic reentrant VTs and can terminate nearly 50% of VTs with cycle lengths less than 300 ms, terminate them by synchronized cardioversion with great efficacy and speed, which has allowed patients not only freedom from sudden death, but freedom from syncope. Whether implantable defibrillators prolong survival in patients presenting with hemodynamically stable VT remains unknown. Atrial defibrillation is also possible, and a brief flurry of interest took place in developing atrial defibrillators as a therapeutic option for paroxysmal atrial fibrillation. Pain was a major limitation and made this therapy short-lived. Perhaps in the future, "painless defibrillation" can be achieved and dual-chambered atrial and ventricular defibrillators will be available to treat patients who have both atrial fibrillation and malignant ventricular arrhythmias (35).

The other major thrust of the last two decades has been the use of catheter ablation techniques to manage cardiac arrhythmias. Focal ablation using radiofrequency energy is now the treatment of choice for patients with a variety of supraventricular tachycardias, including AV nodal tachycardia, circus movement tachycardia using concealed or manifested accessory pathways, incessant atrial automatic tachycardia, atrial flutter that is isthmus-dependent as well as other scar-related atrial tachycardias, ventricular tachycardias in both normal hearts and those associated with prior coronary artery disease, and, most exciting and recent, in the management of atrial fibrillation (36–55).

Although isolation of the pulmonary veins should successfully treat "focal" atrial fibrillation arising in the pulmonary veins, it is not easily accomplished. Reconnection is common, suggesting better electrophysiologic endpoints are necessary to achieve isolation. Anatomic procedures without demonstration of electrophysiologic endpoints should, in my opinion, be discouraged. The use of additional linear lesions to manage other forms of atrial fibrillation has been suggested, but achieving permanent block is difficult resulting in a high incidence of procedure related left atrial flutters. These lesion sets are attempts to more closely mimic the surgical procedure developed by Dr. James Cox (the MAZE procedure) to manage multiple wavelet atrial fibrillation (56,57). Use of cool-tip radiofrequency catheters and the development of new energy sources and catheter configurations (e.g., cryothermal energy) may improve our success rate.

New minimally invasive surgical procedures are being developed to isolate the pulmonary veins and simultaneously remove or clip the left-atrial appendage. These procedures may become the procedure of choice in patients who cannot be highly heparinized as is required during catheter-based procedures or in patients with recent strokes who have experienced serious bleeding. Finally, indirect methods to treat arrhythmias, such as creation of AV nodal block to manage rates in atrial fibrillation associated with pacemaker implantation, are also now a commonly used therapeutic intervention in patients with permanent atrial fibrillation or in patients with brady-tachy syndrome who are intolerant of or unwilling to take multiple drugs required for rate control (58). Certainly, catheter ablative techniques have largely replaced surgical approaches to the management of most supraventricular and ventricular tachyarrhythmias.

Finally, there has been a recognition that electrical therapies may help heart failure. Many trials have demonstrated that resynchronization therapy can benefit a significant number of patients with severe heart failure. Although there has been an explosion in the use of resynchronization therapy, we need to be able to better predict who will and who won't benefit from these devices. Mapping and stimulation techniques may be useful in determining the answer to this question as well as defining optimal sites of pacing.

Although much has been accomplished, much still remains. We certainly must not let technology lead the way. We electrophysiologists must maintain our interest in understanding the mechanisms of arrhythmias so that we can devise nonpharmacologic approaches that would be more effective and safe to manage these arrhythmias. New molecular approaches may be comparable in the near future because we have entered the world of molecular biology and have seen the recognition of ion channelopathies

such as long-QT syndrome (59,60), Brugada syndrome, and catecholaminergic polymorphic ventricular tachycardia (61,62). Cardiovascular genomics will play an important role in risk stratification of arrhythmias in the future, and the new fields of proteomics and metabolomics will be essential if we are to develop specifically targeted molecules.

The past has seen a rapid evolution of electrophysiology, from one of understanding mechanisms to one of developing therapeutic interventions. Hopefully, the future will be a combination of both.

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ACKNOWLEDGMENTS

I would like to thank the current and recently graduated electrophysiology fellows and faculty at the Beth Israel Deaconess Medical Center, without whose help in the performance and interpretation of electrophysiologic studies this book could not have been written. Additional thanks to the technical staff of the electrophysiology laboratory, whose skills and constant supervision made our laboratory function efficiently and safely for our patients. Special thanks are owed to Jack Wylie, who made major contributions in updating Chapter 14; to David Callans, who reviewed, updated, and edited many chapters; and to Duane Pinto, who has the unenviable task of trying to make me computer literate. I am eternally grateful to Eileen Eckstein for her superb photographic skills and guardianship of my original graphics, and to Angelika Boyce and Susan Haviland, my administrative assistants during the writing of each addition, for protecting me from distractions. Finally, this book could never have been completed without the encouragement, support, and tolerance of my wife, Joan.

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CHAPTER 1

Electrophysiologic Investigation: Technical Aspects

Personnel

The most important aspects for the performance of safe and valuable electrophysiologic studies are the presence and participation of dedicated personnel. The minimum personnel requirements for such studies include at least one physician, one or two nurse-technicians, an anesthesiologist on standby, and an engineer on the premises to repair equipment. With the widespread use of catheter ablation, appropriate facilities and technical support are even more critical (1,2). The most important person involved in such studies is the physician responsible for the performance and interpretation of these studies. This person should have been fully trained in clinical cardiac electrophysiology in an approved electrophysiology training program. The guidelines for training in clinical cardiac electrophysiology have undergone remarkable changes as interventional electrophysiology has assumed a more important role. The current training guidelines for competency in cardiac electrophysiology have been developed by the American College of Cardiology, the American Heart Association, and the American College of Physicians–American Society of Internal Medicine in collaboration with the North American Society for Pacing and Electrophysiology (3,4). Based on these recommendations, criteria for certification in the subspecialty of clinical cardiac electrophysiology have been established by the American Board of Internal Medicine. Certifying exams are given every other year. Clinical electrophysiologists should have electrophysiology in general and arrhythmias in particular as their primary commitment. As such, they should have spent a minimum of 1 year—preferably 2 years—training in an active electrophysiology laboratory and should have met the criteria for certification. The widespread practice of device implantation by electrophysiologists will certainly make a combined pacing and electrophysiology program mandatory for implanters. This should be a 2-year program. Recently, with the development of resynchronization therapy for heart failure, there is interest in developing a program to train heart failure physicians to implant devices in their patients. At the least, this should be a 1-year program and, in my opinion, should include training in basic electrophysiology. Such programs are currently available at a few centers. Sufficient training is necessary for credentialing, which will be extremely important for practice and reimbursement in the future.

One, or preferably, two nurse-technicians are critical to the performance of electrophysiologic studies that both are safe and yield interpretable data. These nurse-technicians must be familiar with all the equipment used in the laboratory and must be well trained and experienced in the area of cardiopulmonary resuscitation. We use two or three dedicated nurse-technicians in each of our electrophysiology laboratories. Their responsibilities range from monitoring hemodynamics and rhythms, using the cardioverter-defibrillator when necessary, and delivering antiarrhythmic medications and conscious sedation (nurses), to collecting and measuring data online during the study. They are also trained to treat any complications that could possibly arise during the study. An important but often unstressed role is the relationship of the nurse and the patient. The nurse is the main liaison between the patient and the physician during the study—both verbally, communicating symptoms, and physically, obtaining physiologic data about the patient's clinical status. The nurse-technician may also play an invaluable role in carrying out laboratory-based research. It is essential that the electrophysiologist and nurse-technician function as a team, with full knowledge of the purpose and potential complications of each study being ensured at the outset of the study. A radiation technologist should also be available to assure proper equipment function and monitor radiation doses received by patients and laboratory personnel.

An anesthesiologist and probably a cardiac surgeon should be available on-call in the event that life-threatening arrhythmias or complications requiring intubation, ventilation, thoracotomy, or potential surgery should arise. This is important in patients undergoing stimulation and mapping studies for malignant ventricular arrhythmias and, in particular, catheter ablation techniques (see Chap. 14). In addition, an anesthesiologist or nurse-anesthetist usually provides anesthesia support for implantable cardioverter-defibrillator (ICD) implantation and/or testing. We use anesthesia for all our atrial fibrillation ablations and for ablative procedures in patients with fragile

hemodynamics to enable us to maintain smooth hemodynamic control during the procedure. Anesthesia is also extremely useful in elderly patients because of the frequent paradoxical response to standard sedation. Although conscious sedation is usually given by laboratory staff, in the substantial minority of laboratories, anesthesia (e.g., Propafol) is given by the laboratory staff (nurse or physician) and not by an anesthesiologist.

A biomedical engineer and/or technician should be available to the laboratory to maintain equipment so that it is properly functioning and electrically safe. It cannot be stated too strongly that electrophysiologic studies must be done by personnel who are properly trained in and who are dedicated to the diagnosis and management of arrhythmias. This opinion is shared by the appropriate associations of internal medicine and cardiology (1–4). Finally, a radiation technologist should be available to assure that excessive radiation is not delivered to the patient or the electrophysiology team.

Equipment

The appropriate selection of tools is of major importance to the clinical electrophysiologist. Although expensive and elaborate equipment cannot substitute for an experienced and careful operator, the use of inadequate equipment may prevent the maximal number of data from being collected, and it may be hazardous to the patient. To some degree, the type of data collected determines what equipment is required. If the only data to be collected involve atrioventricular (A-V) conduction intervals (an extremely rare situation), these can be determined with a single catheter and a simple ECG-type amplifier and recorder, which are available at most cardiology units. However, a complete evaluation of most supraventricular arrhythmias, which may require activation mapping, necessarily involves the use of multiple catheters and several recording channels as well as a programmable stimulator. Thus, an appropriately equipped laboratory should provide all the equipment necessary for the most detailed study. In the most optimal of situations, a room should be dedicated for electrophysiologic studies. This is not always possible, and at many institutions, electrophysiologic studies are carried out in the cardiac hemodynamic-angiographic catheterization laboratory. A volume of more than 100 cases per year probably requires a dedicated laboratory. The room should have air filtering equivalent to that in a surgical operating room, if it is used for ICD and pacemaker implantation. This is the current practice at more than 90% of centers and is likely to be the universal practice in the future. It is important that the electrophysiology laboratory have appropriate radiographic equipment. The laboratory must have an image intensifier that at least is equipped for fluoroscopy and, in certain instances, is capable of cinefluoroscopy if the laboratory is also used for coronary angiography. To reduce radiation exposure, pulsed fluoroscopy or other radiation reduction adaptations are required. This has become critical in the ablation era, when radiation exposure can be prolonged and the risk of malignancy increased. Currently the best systems are pulsed and digitally based, which reduces the radiation risk and allows for easy storage of acquired data. The equipment must be capable of obtaining views in multiple planes. Newer systems that markedly reduce radiation exposure enable the electrophysiologist to move catheters at a distance or in the absence of the fluoroscopic system. Examples of such systems are the Stereotaxis magnetic guided catheter positioning system and Hanson robotic system. The Stereotaxis system is available at this time; it is expensive and requires special catheters, which add to the expense. The Hanson system is currently not approved in the United States but is likely to be within the year. It is less expensive, but all catheters can be used. These systems are of most value for complex ablations (e.g., atrial fibrillation and untolerated ventricular tachycardia) but seem excessive for most procedures. Other navigation systems are also being developed with the goal of reproducible three-dimensional navigation and reduction of fluoroscopy time and exposure. Currently, state-of-the-art equipment for the gamut of electrophysiologic studies includes permanent radiographic equipment of the C-arm, U-arm, and biplane varieties. It is critical that dosimetry to the patient is monitored. Guidelines for total dosage delivered during a single procedure should be mandated to prevent radiation-induced injury.

Electrode Catheters

A variety of catheters is currently available, with at least two ring electrodes that can be used for bipolar stimulation and/or recording. The catheter construction may be of the woven Dacron variety or of the newer extruded synthetic materials such as polyurethane. As a general all-purpose catheter, we prefer the woven Dacron catheters (Bard Electrophysiology, Billerica, MA) because of their greater durability and physical properties. These catheters come with variable numbers of electrodes, electrode spacing, and curves to provide a range of options for different purposes (Fig. 1-1). Although they have superior torque characteristics, their greatest advantage is that they are stiff enough to maintain a shape and yet they soften at body temperature so that they are not too stiff for forming loops and bends in the vascular system to adapt to a variety of uses. The catheters made of synthetic materials cannot be manipulated and change shapes within the body, so they are less desirable. Many companies make catheters for specific uses such as coronary sinus cannulation and His bundle recording, but in most cases I believe this is both costly and unnecessary. The advantages of the synthetic catheters are that they are cheaper and can be made smaller (2 to 3 French) than the woven Dacron types. Currently, most electrode catheters are size

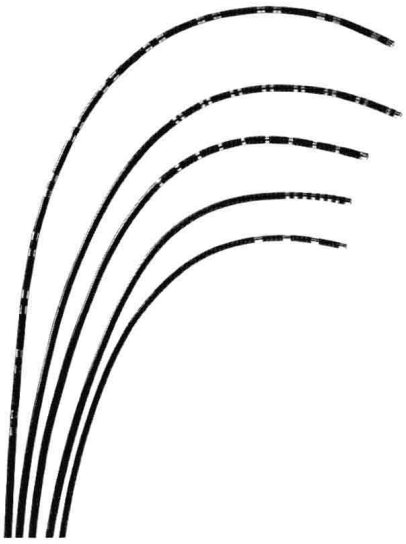

FIG. 1-1. *Electrode catheters routinely used.* Woven Dacron catheters with varying numbers of electrodes and interelectrode distances.

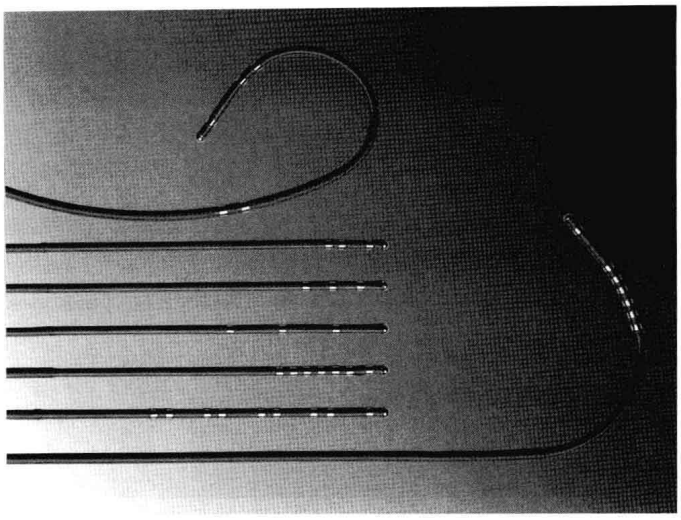

FIG. 1-2. *Different types of electrode catheters with deflectable tips.* These are primarily made of extruded plastic.

3 to size 8 French. The smaller sizes are used in children. In adult patients, 5- to 7-French catheters are routinely used. Other diagnostic catheters have a deflectable tip (Fig. 1-2). These are useful to reach and record from specific sites (e.g., coronary sinus, crista terminalis, and tricuspid valve). In most instances the standard woven Dacron catheters suffice, and they are significantly cheaper. Although special catheters are useful for specific indications described below, standard catheters can be used for most standard pacing and stimulation protocols. We save our hospital thousands of dollars by using standard woven Dacron catheters for all but the ablation catheter. Skilled catheterizers rarely require steerable catheters for positioning, the cost of which is often >$500 more than that of standard catheters.

Electrode catheters have been designed for special uses. Catheters with an end hole and a lumen for pressure measurements may be useful in (a) electrophysiologic hemodynamic diagnostic studies for Ebstein's anomaly; (b) validation of a His bundle potential by recording that potential and the right atrial pressure simultaneously (see Chap. 2); (c) the occasional instance when it may be desirable to pass the catheter over a long guide wire or transseptal needle; and (d) electrophysiologic studies that are part of a more general diagnostic study and/or for which blood sampling from a specific site (e.g., the coronary sinus) or angiography in addition to pacing is desirable. Special catheters have also been designed to record a sinus node electrogram, although we believe that such electrograms can be obtained using standard catheters (see Chap. 3). Other catheters have been specially designed to facilitate recording of the His bundle potential using the antecubital approach, which occasionally may be useful when the standard femoral route is contraindicated. This catheter has a deflectable tip that permits it to be formed into a pronounced J-shape once it has been passed into the right atrium.

In the last decade the evolution of ablation techniques for a variety of arrhythmias necessitated the development of catheters that enhance the ability to map as well as to safely deliver radiofrequency energy. Mapping catheters fall into two general categories: (a) deflectable catheters to facilitate positioning for mapping and delivering ablative energy and (b) catheters with multiple poles (8 to 64) that allow for simultaneous acquisition of multiple activation points. The former category includes a variety of ablation catheters as well as catheters to record and pace from specific regions (e.g., coronary sinus, tricuspid annulus, slow pathway [see Chap. 8], crista terminalis [see Chap. 9]). Some ablation catheters have a cooled tip, one through which saline is infused to allow for enhanced tissue heating without superficial charring. Ablation catheters deliver radiofrequency energy through tips that are typically 4 to 5 mm in length but may be as long as 10 mm (Fig. 1-3). Catheters that are capable of producing linear radiofrequency lesions are being developed to treat atrial fibrillation by compartmentalizing the atria, but currently the ability of these catheters to produce transmural linear lesions that have clinical benefit and are safe is not proven. Catheters that deliver microwave, laser, cryothermal, or pulsed-ultrasound energy to destroy tissue are currently under active investigation. The cryothermal catheters have recently been approved by the U.S. Food and Drug Administration (FDA) for A-V nodal modification for A-V nodal tachycardia (see Chap. 14) but are also being evaluated for other uses, such as atrial fibrillation. The second category

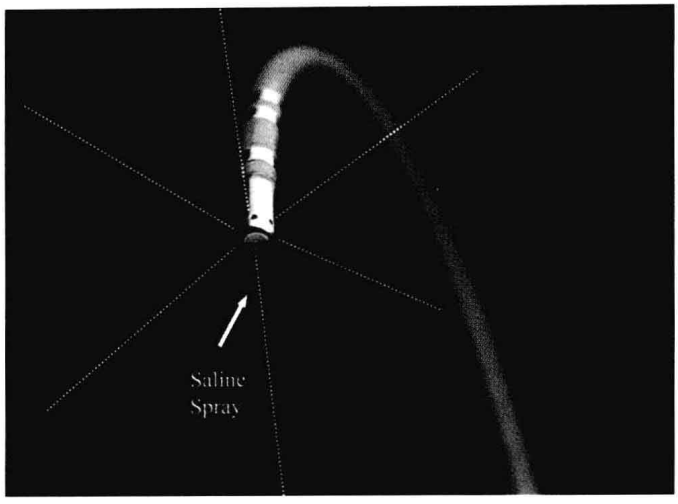

FIG. 1-3. *Cool-tip ablation catheter.* Saline spray through the catheter tip is used to maintain a "low" tip temperature, which prevents charring and, at the same time, increases the lesion size. See text for discussion.

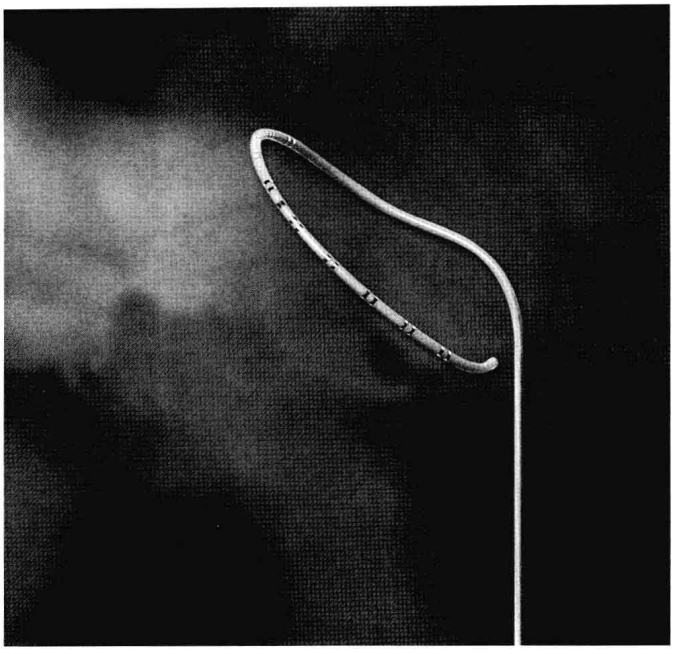

FIG. 1-5. *Multipolar deflectable catheter for recording around the tricuspid annulus.* While standard 10- to 20-pole woven Dacron or deflectable catheters can be used to record along the anterolateral tricuspid annulus, the "halo" catheter has been specifically designed to record around the tricuspid annulus.

includes standard catheters with up to 24 poles that can be deflected to map large and/or specific areas of the atrium (e.g., coronary sinus, tricuspid annulus) (Fig. 1-4). Of particular note are catheters shaped in the form of a "halo" to record from around the tricuspid ring (Fig. 1-5) and basket catheters (Fig. 1-6), which have up to 64 poles or prongs that spring open and are used to acquire simultaneous data from within a given cardiac chamber.

Another catheter with the characteristics and appearance of a standard ablation catheter that has a magnetic sensor in the shaft near the tip is made by Biosense Webster (Diamond Bar, CA). Together with a reference sensor, it can be used to precisely map the position of the catheter in three dimensions. This Biosense Webster and anatomic mapping system is composed of the reference and catheter sensor, an external, ultralow magnetic field emitter, and the processing unit (5). The amplitude, frequency, and phase of the sensed magnetic fields contain information required to solve the algebraic equations yielding the precise location in three dimensions (x, y, and z axes) and orientation (roll, yaw, and pitch) of the catheter tip sensor. A unipolar or bipolar electrogram can be recorded simultaneously with the position in space. An electrical anatomic map can, therefore, be generated. This provides precise (approximately 1 mm) accuracy and allows one to move the catheter back to any desirable position, a particularly important feature in mapping. In addition, the catheter may be moved in the absence of fluoroscopy, thereby saving unnecessary radiation exposure. The catheter, because of its ability to map the virtual anatomy, can display the cardiac dimensions, volume, and ejection fraction.

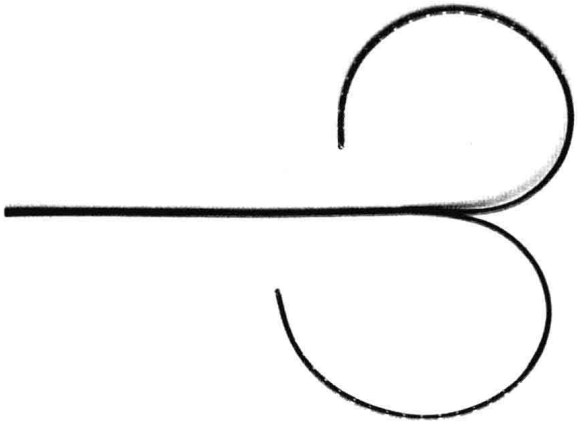

FIG. 1-4. *Multipolar, bidirectional deflectable catheter.* Deflectable catheters with 10 to 24 poles that have bidirectional curves are useful for recording from the entire coronary sinus or the anterolateral right atrium along the tricuspid annulus.

Another new mapping methodology, with its own catheter, is so-called noncontact endocardial mapping. An intracavitary multielectrode probe (Fig. 1-7) is introduced retrogradely, transseptally, or pervenously into the desired chamber, and endocardial electrograms are reconstructed using inverse solution methods (6). Endocardial potentials and activation sequences are reconstructed from intracavitary probe signals by a mathematical process called the "inverse solution." Beat-to-beat