The Cardiac Pacemaker

Function and Malfunction

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G&S

Grune & Stratton
A Subsidiary of Harcourt Brace Jovanovich, Publishers
New York London
Paris San Diego San Francisco São Paulo
Sydney Tokyo Toronto

Library of Congress Cataloging in Publication Data

Mond, Harry G.
The cardiac pacemaker, function and malfunction.

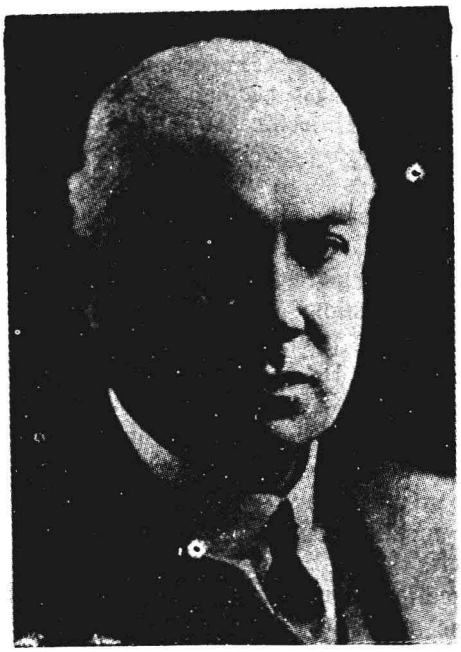
(Clinical cardiology monographs)
Bibliography
Includes index.
1. Pacemaker, Artificial (Heart)—Addresses, essays, lectures. I. Title. II. Series. [DNLM: 1. Pacemaker, Artificial. WG 26 M741c]
RC684.B3M66 1983 617'.4120645 83-8870
ISBN 0-8089-1578-9

Grune & Stratton, Inc.
111 Fifth Avenue
New York, New York 10003

Distributed in the United Kingdom by
Grune & Stratton, Inc. (London) Ltd.
24/28 Oval Road, London NW 1

Library of Congress Catalog Number 83-8870
International Standard Book Number 0-8089-1578-9

Printed in the United States of America



This book is dedicated to the memory of Mark C. Lidwill, M.D. (Melbourne), F.R.A.C.P., 1878–1968, an Australian physician and anesthesiologist who invented and successfully used the first artificial cardiac pacemaker.

Mark C. Lidwill, M.D., F.R.A.C.P., was born in 1878 in Cheltenham, England. When he was a boy his family emigrated to Australia, where he attended the Melbourne Grammar School and later studied medicine at the University of Melbourne, graduating in 1902. Lidwill became a specialist physician and anesthesiologist, moving his practice to Sydney, where he became Honorary Director of the Department of Anesthesia at The Royal Prince Alfred Hospital. In 1913 he designed the "Lidwill Machine," which was used for administrating anesthetic gases. Lidwill died in Nowra, NSW, Australia, in 1968 at 90 years of age. He was never known to the pacemaker fraternity but he will never be forgotten.

Although Dr. Albert Hyman is generally acknowledged as the originator of the artificial cardiac pacemaker, Hyman himself referred to an earlier Australian worker named "Gould" who developed, successfully used, and published information on a similar apparatus at least three years earlier. On pages 287–288 of his classic 1932 article, Hyman discussed the results of other workers who attempted to resuscitate the dead heart by using electrical currents: "More recently several authors have attempted to reanimate the asystolic heart by passing electric currents of different types through the chest. . . ."[1] Following the description of a number of these attempts in animals, Hyman went on to describe the Australian attempt in a human:

In 1929 at the Medical Congress held in Sydney, Australia, Gould demonstrated an electric device for stimulating the heart; this apparatus consisted of a neutral plate and a positive needle electrode which was inserted into the heart. Gould reported the case of a baby who was resuscitated by such electrical stimulations of this organ.[1]

The question thus remains as to why Gould has not been given the credit for the first pacemaker. Ironically, although Hyman acknowledged the contribution and inventiveness of Gould, it was probably Hyman who was responsible for the medical profession not giving credit to the Australian inventor. A careful search of the complete transactions and contemporary literature and records has failed to reveal that a "Gould" ever existed. Hyman probably confused Gould's name with the actual inventor, Dr. Mark C. Lidwill.[2]

At the Third Session of the Australasian Medical Congress (British Medical Association) held in Sydney, Australia, September 2–7, 1929, Dr. Lidwill presented a paper that was published in the transactions of this session, with the relevant data on the invention given in an appendix to that paper.[3] Almost certainly this was the meeting referred to in Hyman's article. Lidwill, in conjunction with a physicist, Major Edgar Booth, originally planned to present this work during the Medical Session of the Congress but was unable to do so and instead gave an outline of it in the appendix to his anesthesia paper. From the published "question and answer" session at the end of the meeting there is no doubt that the contents of the appendix were actually presented at the Congress. The complete text of his appendix follows:

Appendix*

I find that there will not be time at the Section of Medicine of the congress to read my paper on certain forms of cardiac failure and its treatment, so I will give you an outline of my ideas and also of the means by which a body may be brought back to life in certain forms of cardiac failure.

As I said in my paper, there are three forms of cardiac failure: Failure of the neuro-muscular mechanism, failure of the musculature and *ante mortem* clotting of the heart's blood. In the last two nothing can be done whatsoever. My attention was drawn to the failure of the neuro-muscular mechanism when watching a patient die and at the same time taking electrocardiographic tracings. The sino-auricular node first ceased to act. Then Tawarra's node ceased and the heart kept on beating by means of extra systoles. I also noticed that in certain toxaemias one of the signs of cardiac failure was impairment of the conductivity or functioning of portions of the neuro-muscular mechanism, namely, the bundle of His. When sudden death takes place, during diphtheria, it is reasonable to assume that what ceases to act is the neuro-muscular mechanism, because, on careful microscopical examination, the muscle itself seems quite able to carry on the circulation. Then one considers the causation of the cessation of ordinary muscle to reaction from nerve impulses and, as you know, it is found that the nerve endings become fatigued and cease to act long before the muscle itself ceases to act. The muscle can still be stimulated by electrical means and will contract long after the nerve endings have ceased to act. I then thought that if I designed some means of stimulating the heart after the sino-auricular

* Complete Text of the Appendix of Dr. Lidwill's article describing the first pacemaker. Reprinted with permission of PACE from Lidwill MC: Cardiac disease in relation to anaesthesia, in Transactions of the Third Session, Australasian Medical Congress (British Medical Association). Sydney, Australia, September 2–7, 1929. p. 160.

node and other portions of the system had ceased to act, life might be carried on and it might be possible to revive patients from time to time. Of course, as you know, adrenalin injected into a heart will occasionally cause it to beat again, as pointed out by me in 1909 and 1910. The adrenalin apparently acts on the sino-auricular node or possibly on some other portion of the neuro-muscular mechanism; but, if this fails to respond, one can supply an artificial impulse. With this in view, I designed some time ago a machine by means of which direct stimulation to the heart's muscle may be applied. It was unknown, at first, what voltage was required. Dr. Briggs, who was at the Crown-Street Women's Hospital, carried out experiments for me in stillborn infants. Voltage was used from 1.5 up to 120 and it was found that somewhere about 16 volts was the pressure required. The method was tried in two or three cases and was completely successful in the case of a stillborn infant, when everything else had been done to revive the child, artificial respiration, injections of "Pituitrin" and adrenalin injected into the heart itself. After this had failed, the needle of the machine was plunged into the auricle and various voltages were tried with no result. The needle was then plunged into the ventricle, and the heart responded to each impulse. At the end of ten minutes the current was stopped and it was found that the heart would beat of its own accord. The child recovered completely and is now living and quite healthy. After Dr. Briggs left the Women's Hospital the work was not carried on, as the machine was so complicated that it was very difficult to understand. I now demonstrate to you a portable and simplified form of this machine. The rate of impulses can be varied from about 80 to 120. This method of cardiac revival is applicable to the following types of cases: (i) Cardiac failure during anesthesia, (ii) cases of drowning, if combined with intratracheal insufflation, (iii) certain types of gas poisoning, (iv) sudden death during the incidence of acute disease, for example diphtheria, (v) possible, sudden death during cardiac disease.

The machine, as shown, requires only to be plugged into a lighting point and its use does not require very much intelligence. One pole is applied to a pad on the skin, say the left arm, and is saturated with strong salt solution. The other pole which consists of a needle insulated except at its point, is plunged into the ventricle and the machine is started. It may be necessary to alter the polarity of the poles and there is a switch for doing this. When the current is applied to the apparently dead body, the whole thorax and arm contract. I think if this machine were used, it would often save lives. There may be many failures, but one life in fifty or even a hundred, is a big advancement where there is no hope at all.

For his help in the design of this new machine, I should like to thank Major Booth, of the Physics Department, University of Sydney.

This appendix highlights the logical approach and the reasoning that Lidwill used in developing the equipment. As a physician and anesthesiologist, Lidwill was interested in the cardiac causes of death. Using an ECG he recorded tracings at the time of death and noted failure of the normal pacemakers and the emergence of an idioventricular rhythm. Similarly, he noted that in certain toxemias failure of the conducting system was a possible cause of death. Lidwill also knew that cardiac muscle could be made to contract by using either intracardiac adrenalin or electrical stimulation. Using this logic, Lidwill set about to design an electrical device with the objective of resuscitating patients in whom the conducting system had failed.

Working with Major Booth at the University of Sydney Physics Department, Lidwill designed a number of machines, one of which was portable and was the machine demonstrated at the Third Session of the Australasian Medical Congress in 1929. It is unfortunate that photographs, drawings, or models of this or any of

the previous pacemaker designs have never been found despite very careful and thorough searching.

Although Lidwill recognized that as a means of resuscitation the pacemaker would yield a success rate of only 1–2%, he regarded this as a significant improvement over any techniques available at the time. With Dr. Briggs at the Crown Street Women's Hospital, Lidwill conducted his only documented experiments. Little is known of Briggs although it is assumed that he was Dr. Webster Briggs who graduated with a degree in medicine from Sydney University in 1924 and subsequently went to England where he died in 1927. If this was the same Dr. Briggs, then one can assume that the experiments were performed in either 1925 or 1926.

The experimental work carried out on a number of stillborn infants showed that about 16 V was required. In the case of the stillborn infant described in Lidwill's appendix, the infant recovered and was reported in 1929 to be alive and healthy. Follow-up search for details of the patient and procedure at the Crown Street Women's Hospital has proved unrewarding since the medical records of patients were removed from the hospital. However, it seems more than possible that the first pacemaker-resuscitation patient may still be alive as a result of this experimental work done before 1929.

For the reasons described, the apparatus built and used by Lidwill before 1929 must be regarded as the first pacemaker. Although photographic or diagrammatic evidence of this machine has not been found, contemporaries of Lidwill remember the existence of such a machine. It is important to remember that Hyman did not publish data on the use of his pacemaker in humans because of adverse publicity.[4] Lidwill may have been aware of this and therefore did not continue with his experiments in humans. It is even possible that Hyman deliberately changed Lidwill's name to "Gould," hoping to protect his fellow clinical scientist from the same adverse publicity that he had received from his animal experiments.

Thus it would appear that Dr. Lidwill built and used the first pacemaker. Although his equipment was clinically described, its long-term success was never documented. Yet it is to Dr. Lidwill that I would like to dedicate this book.

Preface

Cardiac pacing is a rapidly advancing and ever-changing specialty. The value of pacing in the treatment of a variety of brady- and tachyarrhythmias cannot be challenged. Consequently, a highly competitive and lucrative industry has developed to satisfy the demands of the physician and the patient. Within that industry highly specialized engineers have been responsible for the development of a complex sophisticated product with a quality control unparalleled in any industry.

This book was written to satisfy the continuously growing demands of physicians, medical students, nurses, technicians, and engineers eager to learn of the new advances in the pacing industry. Of the many books written on cardiac pacing, almost all have been devoted to clinical aspects of pacing, such as indications for pacing, electrophysiological investigations, pathology of the conducting system, electrocardiographic syndromes, and temporary pacing. Very little has been written on the hardware or pacing systems. Other areas that generally have been ignored in other texts include pacemaker electrocardiography and the investigation, identification, classification, and treatment of pacemaker malfunction. It is hoped that this book fills these gaps in the literature. The areas adequately covered in other texts listed above have been avoided.

This book, as its title suggests, is divided into two sections: normal pacemaker function and malfunction. An attempt has been made to thoroughly review each aspect of cardiac pacing to cater not only to the beginner, but also to the advanced practitioner requiring a reference manual. Illustrations and references thus are in abundance.

At the end of many of the chapters there are a number of illustrated cases useful for testing the reader. In the appendix, there are also a number of illustrated cases that cover both normal and abnormal pacemaker function. The material is presented in a sequential manner that assumes that the reader has little knowledge of cardiac pacing. Chapter 1 introduces the terminology used in this book and has been written in summary form and is thus valuable for the novice. The remainder of normal pacemaker function is discussed under separate headings in

an order that does not presume knowledge from a future chapter. Where necessary, the reader is referred to the relevant chapter for further discussion.

The investigation of pacemaker malfunction has been my particular interest for a number of years. The classification developed uses the ECG and follows a set investigative protocol. Aspects of this classification were published in PACE during 1981.

Contents

Acknowledgments

This book was written mainly during my six months of sabbatical leave from The Royal Melbourne Hospital in 1981 and early 1982. The granting of sabbatical leave for this purpose is almost unique in Australia, and for this I owe a debt of thanks to the hospital.

There were many people responsible for the compilation of this text. In particular, I must give thanks to Graeme Sloman, David Hunt, Jitu Vohra, and Annette Cole for their guidance during my formative years and for their inspiration to complete this text. A number of pacemaker companies have assisted me with illustrations and references, in particular Medtronic and Telectronics. Many technicians have been responsible for preparing the illustrations for publication, and Arthur Wigley and his staff in medical photography have provided an outstanding service over the 10 years that most of these illustrations were collected. Paul Kelly and Paul Kertes have led the gallant band of proofreaders, and Rosa Librandi and Di Lang had the unenviable job of typing the manuscript from my messy notes and garbled dictating.

Lastly, sincere thanks are due to Evelynne, Jonathan, Dean, and Natalie for the lost year. Their devotion, patience, and understanding made this book possible.

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111 Fifth Avenue
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Distributed in the United Kingdom by
Grune & Stratton, Inc. (London) Ltd.
24/28 Oval Road, London NW 1

Library of Congress Catalog Number 83-8870
International Standard Book Number 0-8089-1578-9

Printed in the United States of America

PART I

Normal Pacemaker Function

1

The Pacemaker System: An Introduction to Basic Terminology and Concepts

The objective of this chapter is to present to the pacing novice an overall perspective of cardiac pacing. Basic principles, terminology, and concepts are introduced and briefly discussed. As this chapter is only an introduction, the principles are discussed again in greater detail under individual chapters. No references are given, and only normal pacing function is discussed. In this book a simple diagram of the heart is used to explain pacing systems (Fig. 1.1).

The artificial pacemaker is an integrated, sophisticated system dependent on an intact electrical circuit for adequate function. Electrical energy is fed from a power source to an electronic substation where it is stored in preparation for discharge to the heart. The power source and electronic circuitry are housed within a pulse generator that must be protected from the hostile environment of body tissues. For this reason, modern pulse generators are hermetically sealed in a metal capsule or can (Fig. 1.2).

A number of power sources have been used for implantable pulse generators. The objective has been to create a safe, reliable, long-life, and compact battery. The original power source, the zinc mercury battery, served the industry for over 15 years. Its major disadvantage, however, was a liquid corrosive, electrolyte sodium hydroxide. The battery was inadequately sealed because it produced hydrogen gas that needed to be vented. Unfortunately, the electrolyte also frequently leaked, destroying the battery and the surrounding components. Although zinc mercury power cells had a predicted life of up to 5 years, only a very small percentage of pulse generators lasted this long; premature power source failure usually occurred at about 3 years.

During the early 1970s, three new power sources were incorporated into pulse generators. The nuclear power source originally was very large and the resultant pulse generator was cumbersome. Because of the size of this generator, erosion through the skin was not infrequent. Smaller nuclear power cells were then developed, and these proved to be very reliable and to have a long life.

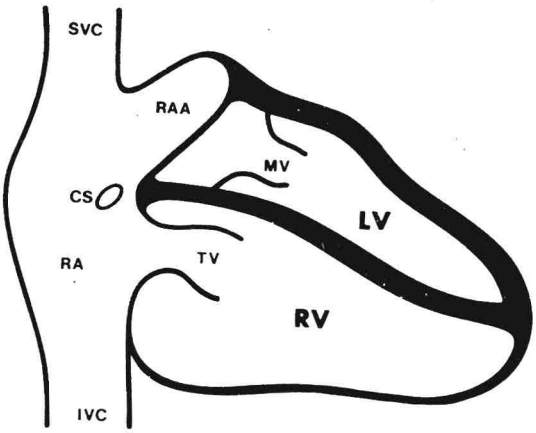

Figure 1.1: Simple line diagram of heart showing the right ventricle (RV), the left ventricle (LV), the right atrium (RA), the right atrial appendage (RAA), the coronary sinus (CS), the venae cavae (SVC and IVC), and the tricuspid and mitral valves (TV and MV).

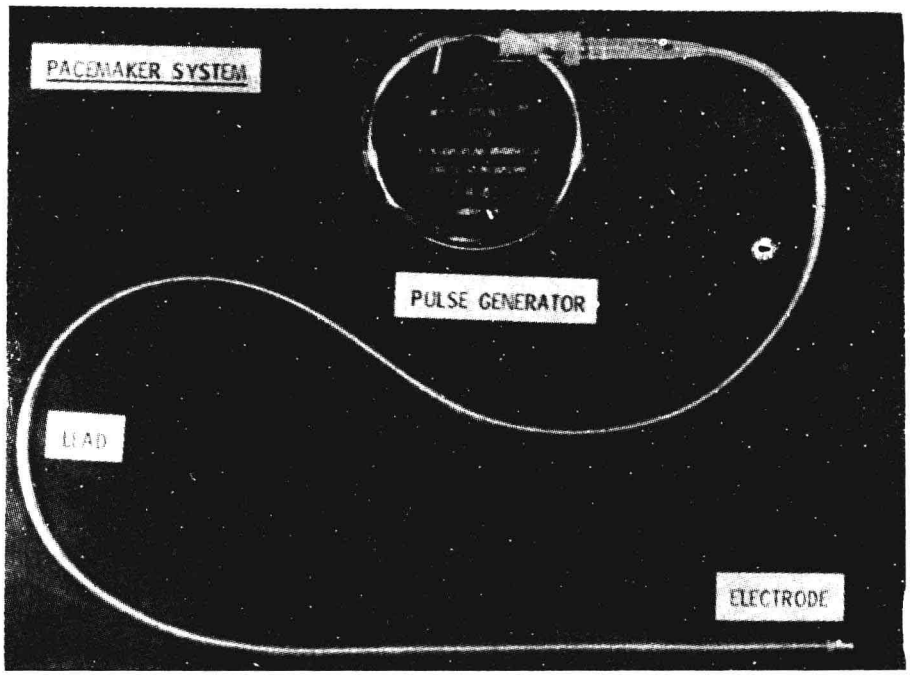

Figure 1.2: A pacemaker comprises a pulse generator and lead. The lead has at its proximal end a connector that is inserted into a receiving port within the pulse generator. At the distal end is an area of bare metal—the electrode, which is used for stimulating the heart. In order to create a pacemaker system, an electrical circuit must be present. In this illustration the lead is unipolar and thus current flows from the pulse generator through the lead to the electrode and back to the metal casing of the pulse generator through body tissues.

They were very expensive, however, and nuclear irradiation to patient and spouse remained a theoretical if not a practical problem.

A second power source used was the rechargeable nickel cadmium battery. The power source was reliable although large and cumbersome. Weekly recharging was necessary. Despite this, many physicians felt that the rechargeable nickel cadmium battery was preferable to zinc mercury as it was probably more reliable and longer-lasting. Work was continuing on the development of a smaller battery, which required less frequent charging, when the initial results on a third power source utilizing a lithium anode were released. First used clinically in 1972, this battery completely revolutionized the pacemaker industry, and today a lithium anode power source is used in more than 90% of pulse generators. By far the most common cathode has been iodine. This combination is a "dry" battery that does not produce gas and thus can be hermetically sealed to protect the battery from body tissues. Further development of the lithium iodine cell has produced a small, compact, very reliable, thin, long-life battery ideally suited for cardiac pulse generators. Other cathode materials have been used, and the most popular is silver chromate.

Marked developments have also occurred with electronic circuitry. Discrete components originally were hand-mounted on circuit boards. The electronic circuits were thus large and prone to sudden failure because of faulty components or inadequate hand soldering. With the use of discrete components, electronic functions were also severely limited because of circuit size. The development of reliable hybrid and integrated circuits resolved the problems that electronic engineers faced when trying to design functions and compact electronics. Today, highly sophisticated hybrid and integrated circuits are used in pulse generators. These now allow for memory, logic, programmability, and telemetry functions.

A number of basic circuits are required for a pulse generator to function. Energy is delivered from the power source to a capacitor where it is stored until delivery through the output circuit. The interval between pulse generator discharges is the pulse repetition rate, and this is controlled by a timing circuit. A third basic circuit, the sensing circuit, controls demand function.

The other major component of a pacemaker is the lead connecting the pulse generator to the heart (Fig. 1.2). The lead is joined to the pulse generator by a connector. This connector has a bulbous plastic male end that fits snugly into the entry port on the pulse generator. Although not hermetically sealed from body tissues, the connector must be as fluidtight as possible to prevent short-circuiting. At the tip of the lead connector is a bare metal pin that is in contact with the lead conductor. This rod is the lead pin (sometimes referred to as *connector* or *terminal pin*) and is responsible for electrical contact with the pulse generator. The connector must be positioned in the pulse generator receiving port so that the lead pin traverses a pulse generator connector block. The lead pin is secured to this connector block by a set screw. The set screw must be insulated from body tissues; otherwise, a short circuit is created. The electrical contact between the pulse generator and the lead is now completed.

The remainder of the lead is composed of a metal conductor covered with a plastic insulator. At the distal end of the lead there is another area of bare metal that makes contact with the heart and is the electrode. Leads may be attached by using the transvenous route or placed directly onto the surface of the heart

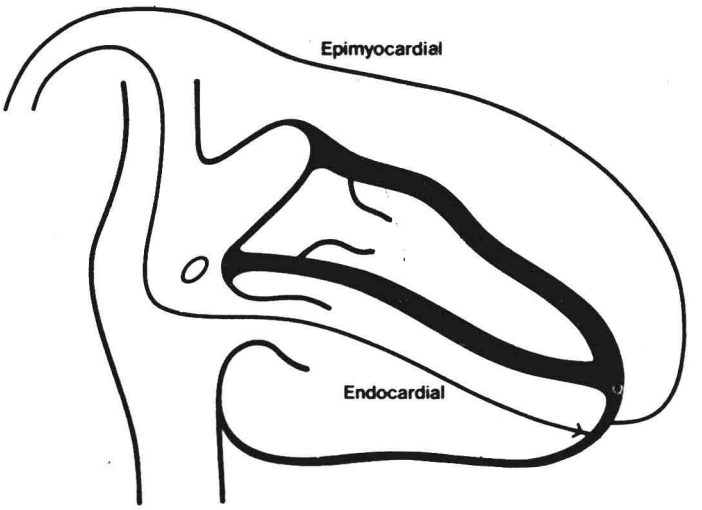

Figure 1.3: The two major types of lead system are endocardial (transvenous) and epimyocardial.

(Fig. 1.3). With a transvenous lead, the electrode makes contact with the endocardium. With the epimyocardial route, the electrode is usually placed within the myocardium as direct epicardial pacing is generally not satisfactory in the long term. With endocardial pacing, the electrode is placed against the endocardial wall, and unless there is some fixation device, dislodgement frequently occurs. There are two types of lead fixation device: passive and active. Passive fixation devices are simple end pieces constructed from or behind the electrode that allow a loose form of fixation to the trabeculae of the right atrium or ventricle. These include wedges, tines, helifix coils, balloons, or cages. Active fixation devices are more sophisticated. They compromise endomyocardial screws and metal or nylon barbs, and a common feature is myocardial penetration.

In order to create an electrical circuit, there must be two poles. Current flows from the cathode—the negative or active pole, to the anode—the positive or indifferent pole. With temporary pacing systems the negative is black-colored and the positive, red. A useful mnemonic to use with a temporary pacing system is "RIP"—red, indifferent, positive.

The pacing lead may be unipolar or bipolar. With unipolar leads, the electrode is the cathode terminal. The anode that completes the circuit lies on the surface of the pulse generator and thus is in contact with body tissues. This is called the "indifferent plate." With bipolar leads, both poles are in the single lead. The distal tip electrode is the cathode, and behind it lying proximally is a ring electrode, which is the anode. Current flows from the pulse generator to the cathode and back into the lead at the anode. Only a small distance separates the two poles, and this is composed of cardiac tissue and blood. With both bipolar and unipolar systems, body tissues and especially the heart are required to conduct current. These tissues contain a high proportion of water and electrolytes and are thus excellent conductors of electricity. The skin, however, is a poor conductor, having a high resistance or impedance. Consequently, the indifferent