THE UNIPOLAR ELECTROCARDIOGRAM

A Clinical Interpretation

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JOSEPH M. BARKER, M.D., F.A.C.P.

Cardiologist, Yater Clinic; Associate Professor of Clinical Medicine and Special Lecturer in Physiology, Georgetown University School of Medicine; Director of the Heart Station and Visiting Physician, Georgetown University Hospital; Chief of Cardiology, Providence Hospital; Visiting Physician, Gallinger Municipal Hospital; Consulting Cardiologist, Arlington Hospital, Arlington, Virginia

Assisted by
JOSEPH J. WALLACE
M.D., F.A.C.P.

Advised by
WALLACE M. YATER
M.D., F.A.C.P.

Foreword by
FRANK N. WILSON, M.D., F.A.C.P.

PREFACE

The primary purpose of this book is to furnish guidance in unipolar electrocardiography for students and physicians.

Diseases of the heart are the most common cause of death. Cardiac disease is so widespread that it must be extremely rare that a physician, regardless of his type of practice, is not daily confronted with patients afflicted with ailments of this organ. There are numerous systemic diseases in which the heart is involved. A large segment of the cardiologist's practice consists of people who think they have or who may have a condition of the heart. It is obvious that the proper diagnosis should be made promptly and appropriate therapy be instituted without delay.

The modalities available for the diagnosis of the cardiac patient, in order of importance, are the history, the physical examination and the electrocardiogram. All of these must be correlated with one another and with other procedures, as indicated, in order to arrive at the correct conclusion. When the electrocardiogram is interpreted without regard to all obtainable data, it is just another test and, all too frequently, a useless one at that.

There is a great need for a comprehensive, yet simple, book dealing with the unipolar electrocardiogram. I have tried to attain simplicity by translating mathematical formulae and terminology into prose form and by the use of detailed descriptions. A serious attempt has been made to confine the latter to such length that they are not burdensome or soporific. Numerous original line drawings supplement the text. Although unipolar electrocardiography deals primarily with considerations of the ventricular complex, a section on the cardiac arrhythmias is included. This was done not merely to make the subject of electrocardiography complete but to show how often the correct diagnosis is disclosed by unipolar leads.

It is my belief that this volume contains all the data necessary for the student and physician with little or no background in electrocardiography to gain the necessary working knowledge through persistence. Those who are desirous of obtaining proficiency but are just beginning to learn will soon realize that there are no short cuts in acquiring the knowledge necessary for the intelligent interpretation of electrocardiograms. A great deal of study is required to master the basic principles and their applications to clinical electrocardiograms. This book has to be studied over a long period before its usefulness as a reference becomes apparent. When full responsibility for correct interpretation is placed upon a physician he then truly comprehends the necessity of a complete knowledge of the subject.

Frank N. Wilson and his group ushered in a new era by applying electric theory as the basis for interpreting the ventricular complex. This theory has supplanted the empirical approach, which consisted of memorizing patterns that represent changes within cardiac muscle. Their work has converted electrocardiography into a science.

For the year 1946 I had the great fortune of being appointed Research Fellow of the American College of Physicians. The entire period was spent in the Heart Station, University Hospital, Ann Arbor, Michigan. Under the tutelage of Drs. Frank N. Wilson, Franklin D. Johnston and Francis F. Rosenbaum, I acquired the basic knowledge of this subject. The fundamental writings of these researchers, their ideas, and unpublished observations communicated by close association later inspired me to write this book. Numerous other contributors to the field have been consulted. Of particular note are the works of Drs. Kenneth Cole, Robert Bayley, Richard Ashman, Gordon B. Myers and Sir Thomas Lewis. I am indebted to these and to many others. Grateful acknowledgement is hereby expressed. Any errors should be attributable to to no one but myself.

Original observations include demonstrations of diffuse intraventricular block and criteria for diagnosis; demonstrations that right, left, and diffuse intraventricular block can occur in anomalous atrioventricular conduction; more precise criteria for the diagnosis of right ventricular hypertrophy complicated by complete and incomplete right bundle branch block; the relationship between the transitional zone of the precordial electrocardiogram and cardiac position in left ventricular hypertrophy; a suggestion as to the cause of persistent displacement of the RS-T segment in ventricular aneurysm; that a Q wave in Lead III at times may be caused by myocardial infarction in the absence of a Q wave in Lead V_F; indications for the exercise test in the diagnosis of angina pectoris, and indications for leads from higher levels upon the precordium in high anterolateral infarction. The importance of the last two is stressed.

The material from all sources has been inseparably integrated, including the latest significant information. There is still much to be learned by research in the field of electrocardiography.

Almost all the electrocardiograms were obtained from patients of the Yater Clinic and the Georgetown University Hospital. During the preparation of this volume the fellows and residents in medicine and cardiology and members of the staffs of both institutions have been most cooperative and helpful. I am grateful to each of them and, in particular, to Drs. H. Wolfe Paley, Hugh Stevens, Ralph Kilby, Laurence Kyle, Paul Doolan, W. Proctor Harvey, Lawrence Pack, and Mrs. Pack. In addition Drs. Nicolas Arcomano, John Maloney, John Stapleton, John Tuohy, Donald Edgren, Joao Tranchesi, Bruce Shnider, Clifton Gruver, Lawrence Lilienfield, Augustus C. P. Bakos, Arnaldo Elian, Norman Comeau and George Katter assisted in many ways.

I am greatly indebted to Dr. Joseph J. Wallace for his invaluable and generous help in preparing the manuscript and to Dr. Wallace M. Yater for his editorial guidance and assistance.

I want to thank Mrs. Wallace and my wife for their patience, encouragement and contribution to the preparation of this book. Mrs. Sarah Rice, Mrs. Rita Zarin and Miss Helen Wile were of great assistance in typing the manuscript.

Last, but far from least, I wish to thank my publisher, the Medical Editorial Staff, Mr. George A. McDermott and Mr. William Chapman Hall for their many courtesies and assistance.

JOSEPH M. BAKKER, M.D.

Washington, D. C.

FOREWORD

Selbstverständlich wird jeder denkende Geist versuchen,
die Erscheinungen, die er beobachtet, zu verstehen
und bis auf ihren Grund und Ursprung zu verfolgen.

Einthoven

During the last 25 years our knowledge of the interpretation of the electrocardiogram has advanced rapidly. A lively interest in this subject is now widespread among members of the medical profession and has extended to a wide circle outside it. When a prominent person is reported by the press or radio to have died suddenly of a "heart attack" a flock of middle-aged people rush to have a cardiogram taken on the following morning. I recall the days when these sudden catastrophes were attributed to "acute indigestion" and the string galvanometer with its camera and switchboard was a strange and somewhat frightening electrical machine. Many patients kindly told me that they felt much better after the treatment, but I remember one who looked with alarm at my electrocardiographic armchair with its cables and large immersion electrodes, became two shades lighter in color, and hurried to the nearest exit.

The outcome that this man feared was impossible, but now as then an electrocardiographic examination is not without its hazards. Many a person has become a semi-invalid and has given up his customary habits and occupations because of the discovery that his T wave is flat in the wrong places or his RS-T segment slightly depressed. He has "coronary disease" of electrocardiographic origin.

Such disastrous consequences of too little knowledge of the electrocardiogram can be avoided only by letting someone else make the mistakes or by learning more about the subject. What is the best way to acquire the information needed?

Graduate courses are now given annually in many medical centers. There are a great number of electrocardiographic books ranging in scope from the briefest introduction to the PQRST's of the subject to treatises in the "Handbuch" class. There is a vast and mostly indigestible periodical literature. All of these are of value. It is, however, the personal opinion of this writer that most men acquire sound and useful knowledge of an unfamiliar field most readily by working in it and studying at the same time. It is hard to obtain a working knowledge of mathematics, for example, by reading a mathematical textbook; it is necessary to work many of the problems at the end of each chapter and to try to make daily use of the principles you have mastered. In self-defense the mind will soon cast out any surplus facts and figures that render it no service.

A man who begins his study of the electrocardiogram by taking his own electrocardiograms on his own patients will acquire a great deal of knowledge that he cannot get in any other way. He will learn to associate the electrocardiographic findings with the patient's history, the results of his physical examination and other laboratory tests. He will acquire the habit of considering all of the data before making a definite diagnosis. He will remember patient, history, electrocardiogram and other findings as a single clinical experience. Reports of tests or interpretations made by someone else are not likely to have the same vital and lasting significance as the data collected and evaluated by the physician himself. A doctor who has personally taken a large number of tracings is not likely to mistake vibrations produced by a passing truck for the oscillations of a fibrillating auricle. It *has* happened here.

But in addition to working and thinking and exploring one must study, and good books on the electrocardiogram are essential even for advanced students. It is also desirable to master the more simple physical principles necessary to the understanding of how the electrocardiograph operates and how the cardiac voltages which this instrument measures are produced and distributed throughout the body. Without this understanding electrocardiography becomes a mere collection of unrelated facts which burden the memory and stifle the intellectual interest without which learning is a chore instead of a pleasure.

I came to know the author of this book intimately during his sojourn in my laboratory. Soon after he arrived all of us who worked there became pleasantly aware of his friendly and jovial personality and the music of his laughter. We were impressed by the seriousness of his purpose, by his industry and by his all-round ability. Men of this kind were always welcome for in the informal give and take, discussion, and argument between the permanent staff and the visitors, it is hard to say whether the second group learned more from the first or the first from the second.

This is not the place to discuss in detail the book which Dr. Barker has written. It confirms the opinion of him that I have already expressed. In order to make it as easy as possible for his readers to become familiar with the essential and fundamental principles of his subject he has himself drawn a very large number of diagrammatic figures and he has discussed these in detail. He has presented and analyzed a great many tracings taken on his own patients. These depict not only the more common but also a great many unusual electrocardiographic patterns. He has made it evident that the interpretation of the electrocardiogram is not merely a matter of memorizing a few characteristic pictures; there are many unusual variations and combinations of electrocardiographic phenomena which must be studied, analyzed, and correlated one with another and with other available data before any definite conclusion is possible. These situations demand some acquaintance with the electrical and physiologic principles by which they are determined. He has presented electrocardiography as a compartment of scientific knowledge that is still expanding. We are beginning to understand some things about it, but there is a great deal still to learn. This is as it should be.

FRANK N. WILSON

Professor of Medicine
University of Michigan Medical School
Ann Arbor, Michigan

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GENERAL CONSIDERATIONS OF ELECTROCARDIOGRAPHY AND OF THE ELECTROCARDIOGRAM

INTRODUCTION

More than 20 years ago Wilson and his collaborators began the arduous task of converting electrocardiography into a science. During the following 10-year period they succeeded in presenting to the medical world all of the basic electrophysiologic facts and theory necessary to the understanding of the subject. These workers also made quick and most significant clinical applications of their knowledge, so that today nearly every use of the electrocardiogram that is made by the clinician, with the exception of the cardiac arrhythmias, is directly or indirectly attributable to them. The guiding light who led the way to the accomplishments which many of us consider today as commonplace fact in electrocardiography was Dr. Frank N. Wilson, of Ann Arbor, Michigan. The purpose of this book is to present the work of Wilson and his co-workers in as simple form as the author feels is possible. In doing this we are conscious of our own inadequacies. Over and above these, the reader's attention is drawn to the obvious facts that (1) simplification results in some deviation from fact, and that (2) when certain attitudes are taken by the author which appear to be unqualifiedly dogmatic, some of these may be erroneous. It is necessary to resort to these methods of presentation in order to have a concise comprehension of what at least approximates the truth. Having mastered the fundamental truths the student then should be able to make such modifications as are necessary.

Electrocardiography is the science which deals with the study of the electric forces produced by the heart muscle during the cardiac cycle. The electrocardiogram is the graphic record of the voltage fluctuations generated by the myocardium as picked up from the surfaces of the body. In order to obtain an electrocardiogram two electrodes are placed at two different points upon the body. Wires are attached to each of these and connected to a measuring instrument which is known as the **electrocardiograph.** The electrocardiograph is in reality a very sensitive voltmeter.

It is similar to the instrument used to measure the voltage of ordinary batteries. During any instant of the electric part of the cardiac cycle, electric activity of the myocardium causes a difference in voltage or potential between any two points upon the surface of the body. Because the difference in potential varies from moment to moment the record made by the electrocardiograph is a curve that continually alters its course with respect to time.

The term "electrocardiographic lead" has two closely related meanings:

1. It may refer to the two points on the body upon which the two electrodes are located and from which the two wires are connected to the electrocardiograph.

2. It often refers to the record made by any set of such connections. An electrode is a piece of metal (usually German silver) of suitable surface area that acts as a "pick-up" for the voltages generated by the heart and which are conducted to the body's surface.

The dog has been the principal experimental animal used for the study of the electric forces generated by the myocardium. Under experimental conditions one has the advantage of exploring the cardiac surfaces, both epicardial and endocardial, by placing electrodes directly upon cardiac muscle. The potential variations originating from specific points in the normal heart and from the heart in abnormal conditions can be determined with a high degree of accuracy. This advantage is lost in clinical electrocardiography because one must depend on indirect leads which are subject to distortions resulting from their distant location from the myocardium. The problem is further complicated by the fact that certain parts of the heart are almost entirely inaccessible to any type of lead, e. g., parts of the posterior surface.

Since electrocardiography is by its very nature primarily an electric problem, this science cannot be mastered without a sound fundamental knowledge based upon the full application of electric theory. This theory leans heavily upon mathematics for the solution of problems and the establishment of basic principles. Until recently most electrocardiographers have been content to use only the empirical approach to the electrocardiogram. By the method of noting the constant relationship between anatomic changes to abnormalities found in the electrocardiogram, certain electrocardiographic diagnoses have become well established. This procedure is a most necessary and valid one, and many great contributions have resulted from it. However, in the study of electrocardiography there is a vast gap between anatomic specimens and clinical electrocardiograms, and all of the armamentaria comparable to those employed in the other medical sciences must be freely used in order to close it. This approach must be made because many electrocardiographic phenomena have no demonstrable anatomic counterparts and a great number of the methods to be mentioned have to be utilized to analyze and explain them. These include especially a detailed study of the electrophysiologic phenomena of heart muscle. The theoretical approach which is based on well-founded facts rather than the purely empirical one would, therefore, seem preferable a priori.

The tremendous value of the application of electric theory and mathematics to the study of the electrocardiogram has become more and more recognized in the past few years. Most of the criticisms have come from those who have little or no knowledge of theoretical physics. Their main complaint is that it makes the subject too complicated or that only approximations can be reached. There is no doubt that electrocardiography is inherently complicated, but so are many other sciences. By disregarding basic principles obtained by painstaking study all that remains are superficial and at times actually erroneous concepts. To deny that approximations are not valid is also to deny that mathematics or theoretical physics can be applied to any specific problem.

Some of the reasons why the average physician has not become more interested in the theoretical considerations of the electric phenomena of electrocardiography are (1) unfamiliarity with electric and mathematic terminology, (2) failure to see, offhand, the practical aspects as applied to the patient, and (3) the fact that the papers which have described the development of the subject are spread widely through numerous different publications and over many years. Although these are well integrated, many of them, when taken singly, require knowledge of previous researches for understanding. It is difficult to assemble all these data and moreover quite time-consuming to read them. Most of us are scared off by even the simplest of mathematic formulae, and even more so by the conclusions obtained by mathematic processes.

In emphasizing the above points it should be understood that every physician does not have to be a mathematician and a theoretical physicist in order to read electrocardiograms. Fortunately the groundwork and nearly all of the practical applications have been already laid by the brilliant work of Wilson and his associates. The significance of the basic principles and of their conclusions cannot be disregarded if one is desirous of obtaining a sound fundamental knowledge of electrocardiography.

SUBDIVISIONS OF ELECTROCARDIOGRAPHY

There are two great natural subdivisions of electrocardiography: (1) the cardiac arrhythmias and **(2) the study of the form of the ventricular complex (QRS, RS-T and T group of deflections)**. In the first, the sequence of auricular and ventricular activity and the site of origin of the impulse are studied. Although the electric phenomena do not take place at the same time as the mechanical events of the cardiac cycle, the relationship is constant, and clinically, by a review of the electrocardiogram, the time that these mechanical events occur can be inferred. Because of this fact, the electrocardiographic diagnosis of the arrhythmias also represents the clinical diagnosis. No special knowledge of electric phenomena of cardiac muscle is needed to have a thorough understanding of the cardiac arrhythmias. This is not true with regard to the interpretation of the form of the series of deflections produced by ventricular muscle which is termed the "ventricular complex" of the electrocardiogram. This represents a record of the electric activity of the ventricular myocardium. A complete understanding of it must include a knowledge of the origin and distribution of the electric forces in the heart as well as their transmission to the body's surface. Etiologic diagnoses made on the basis of alterations in the form of the ventricular complex are impossible because identical changes in the electric activity of cardiac muscle can be produced by more than one cause.

INDICATIONS FOR ELECTROCARDIOGRAPHY

An electrocardiogram is absolutely necessary for the complete evaluation of every cardiac patient. The correct diagnosis and prognosis may often be rendered without recourse to this method. In the great majority of cases the electrocardiogram is essential to diagnosis, prognosis and treatment.

If the electrocardiographer is not the physician who is attending the patient, certain pertinent data should be supplied to him in order that the utmost value may be obtained from the interpretation of the electrocardiogram. These should include the clinical diagnosis or, when this is impossible, the conditions to be differentiated; the drugs the patient has received, especially the amounts of digitalis and quinidine; and whether or not previous electrocardiograms have been made. In addition to the above, the physician requesting the electrocardiogram should indicate any question which he feels may possibly be answered by this method. Some electrocardiographic findings may be caused by one or more of several agents, e.g., in differentiating between digitalis effect and myocardial changes, it is of paramount importance for the electrocardiographer to know which one is suspected. With the proper information it is often possible to make the diagnosis or to indicate whether further serial tracings and/or additional leads might be helpful in defining equivocal findings or in lending support to those which are not definitely diagnostic.

The electrocardiogram is most useful in the following conditions:

1. **Coronary Artery Disease.** a. The electrocardiogram is the most accurate means of diagnosing **myocardial infarction.** It is useful in determining the extent of the infarct and detecting extensions of an already existing infarct. These facts, together with others to be pointed out later, are most helpful in prognosis.

b. **Transient myocardial ischemia and injury** are often detectable by the electrocardiogram. This may be of great value in establishing the diagnosis of **angina pectoris.** In this condition, positive findings in the electrocardiogram, either in the routine tracing or in one after exercise, may be the deciding factor. Negative tracings do not rule out this disease.

c. **Nonspecific changes due to coronary artery disease which result in myocardial degeneration** may not be found by any other method.

Whether the cause is due to coronary artery sclerosis, to syphilitic aortitis with narrowing of the coronary ostia, to rheumatic coronary arteritis, or to other types of arteritis, to pericarditis, myocarditis, or to trauma cannot be differentiated by the electrocardiogram, and the etiologic diagnosis must be established from the clinical evaluation of the patient as a whole.

2. **Ventricular Hypertrophy.** The electrocardiogram is useful in confirming the presence of significant degrees of right and especially of left ventricular hypertrophy. Those tracings which display the typical picture of either right or left ventricular hypertrophy usually indicate that the etiologic agent has been active for a longer time and/or to a more intense degree than if such changes are not present. However, this information is not of value in all cases from a prognostic standpoint. For example, some patients who show striking signs of left ventricular hypertrophy as a result of hypertension may live comfortably for many years after the initial discovery, whereas in others the course may be rapid and death occur from congestive heart failure with little or no accompanying electrocardiographic phenomena until near the end. Before characteristic changes indicative of right ventricular hypertrophy appear, the thickness of the right free wall must be very great.

Indirectly, assistance may be afforded the clinician in differentiating the site of certain valvular lesions in cases in which there is doubt. For example, pulmonary regurgitation causes right ventricular hypertrophy, whereas aortic regurgitation produces left ventricular hypertrophy.

3. **Myocarditis.** This method is useful in establishing the presence of and in following the course of certain inflammatory processes or deficiency states in which the

myocardium is affected. Examples of such conditions are **acute rheumatic myocarditis, acute nonspecific myocarditis** or **myocarditis secondary to other diseases** such as diphtheria, trichinosis, Chagas' disease, yellow fever, **pericarditis** due to any cause, and others. In general, **a changing form in serial tracings indicates that there is activity, whereas a stable electrocardiogram usually means quiescence.**

The findings ascribed to acute pericarditis are due to involvement of the subepicardial myocardium.

4. **Control of Medication.** It is useful in controlling medication, particularly digitalis and quinidine. The effect of digitalis is not specific, and the magnitude of the changes affecting the **RS-T** segments and the **T** waves is highly variable from one individual to another. Toxic manifestations in a patient known to have received digitalis in adequate amounts result in rather definite electrocardiographic alterations.

Electrocardiographic control of patients receiving quinidine therapy for arrhythmias is a necessity in order for one to evaluate with certainty when an adequate therapeutic result has been reached or when early signs of dangerous toxic effects upon the myocardium become manifest.

In cardiac patients overmedication may cause a perplexing picture, and the electrocardiogram is necessary to clarify the diagnosis.

5. **Acute and Chronic Cardiac Disease.** The electrocardiogram may indicate the presence of acute and chronic cardiac disease or conditions even though there are no detectable clinical symptoms or signs. For example, the Wolff-Parkinson-White syndrome is usually revealed by a routine electrocardiogram obtained from a young person or in the course of an examination for some coincidental condition.

6. **Other Conditions.** Other conditions which display more or less characteristic although nonspecific signs in the electrocardiogram are:

a. Pericarditis with effusion
b. Chronic constrictive pericarditis
c. Hypocalcemia
d. Hyperkalemia
e. Myxedema
f. Beriberi

7. **Pulmonary Embolism.** This may be distinguished from myocardial infarction with a high degree of accuracy, especially if serial curves are taken. Very many cases show no changes.

8. **Cardiac Arrhythmias.** Although it is possible to diagnose many of the cardiac arrhythmias on clinical grounds, the mechanism in others can be established only by means of the electrocardiogram. In any event this method is the "last court of appeal" in the diagnosis of all of the arrhythmias. An electrocardiogram is indicated whenever there is a change in the cardiac rhythm.

9. **Auricular Hypertrophy.** This is indicated by abnormally tall, broad, often notched **P** waves. This suggests that right ventricular hypertrophy is also present.

LIMITATIONS OF ELECTROCARDIOGRAPHY

There are certain very definite limitations imposed by electrocardiography. This method records only the electric activity produced by the auricular and the ventricular musculature and the course of the "impulse" through them. No element of the electrocardiogram results from the mechanical activity of muscle nor of the valves, nor directly from the state of the coronary arteries. It tells nothing of the cardiac reserve nor of the presence or absence of congestive heart failure. Certain conditions, such as bundle branch block, inversion of the T wave, evidence of right or of left ventricular hypertrophy, when discovered by the electrocardiogram do not, in themselves, warrant a serious prognosis, but must be interpreted in the light of the clinical findings in the individual case. It would be difficult to prescribe the correct therapy for an inverted T wave found in a routine electrocardiogram in a patient without clinical evidence of heart disease.

2

FUNDAMENTAL ELECTRIC PHENOMENA AND THE ELECTROCARDIOGRAM

Definitions
Potential of a Simple Battery
Bipolar Leads
The Electric Field
Electrocardiographic Instruments

There are certain important basic electric phenomena and definitions of electric terms with which the reader should be familiar.

All of the electric forces which are produced within the heart have their origin within the cardiac muscle. The unit source of these electromotive forces (E.M.F.) or voltages is essentially a battery. The conduction and distribution of these electric forces through the conducting media of the body to its surface constitute the electric field of the heart.

DEFINITIONS

Potential (potential difference) refers to the difference in electric charge between two points. It is comparable to the gravitational potential of water located at a height in relation to a low point.

Electromotive force (E.M.F.) or voltage refers to the potential difference or electric "pressure" which is set up by batteries, generators, etc. The E.M.F. of a circuit is defined as the work done in moving a unit charge completely around the circuit. The unit of measurement is called the volt. Since the potentials produced by the heart are changing from instant to instant, they are referred to as **potential variations** in the completed record.

Electric current, or **current,** for short, refers to the flow of electrons through a conductor and can be compared to the flow of water in a river or a pipe. The direction of the current flow by common usage is opposite to that of the electron stream.

A **circuit** is a pathway through which it is possible for current (stream of electrons) to flow from the point of origin and back again. In the case of a battery, the circuit is divided into two parts (Fig. 1): (1) **external circuit,** in which current flows from the positive to the negative pole, and (2) **internal circuit,** in which current flows from the negative to the positive pole. The latter is analogous to the action of a pump lifting water from a well which creates a high pressure, whereas the former is similar to the flow of water outside from a high to a lower pressure.

Conductors are those materials which offer the least resistance to the flow of current. **Dielectrics** or **insulators** do not have this property. They tend to obstruct the flow of current.

Resistance, in a general way, is that property of some materials which tend to oppose the flow of current. It depends upon the length of the conductor, its area of cross section, and the material from which it is made. The unit of measurement is called the **ohm**.

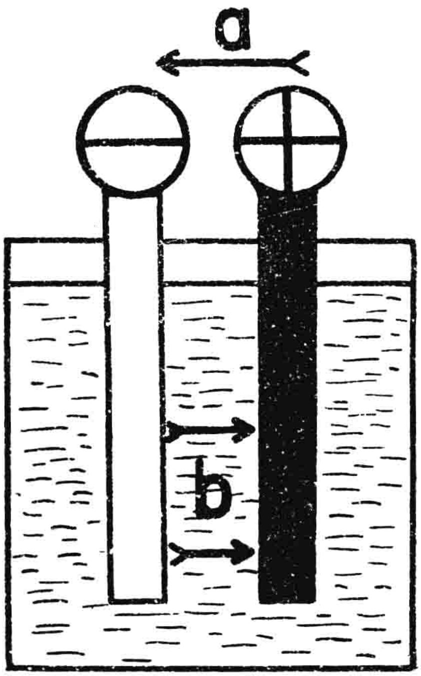

Fig. 1. Simple battery.

a, external circuit. *b*, internal circuit. The black bar represents the positive pole and the white bar the negative pole. The arrows indicate the direction of current flow when the positive pole is connected to the negative pole by a conductor.

POTENTIAL OF A SIMPLE BATTERY

Any battery (dry cell or storage) has a positive and a negative pole (Fig. 1). For instance, a 6-volt battery has a positive pole at a potential of plus 3 volts and a negative pole at a potential of minus 3 volts. No current flows unless the two poles are connected to each other by a conductor, e.g., a length of copper wire. The direction of current flow is from the positive to the negative pole. The connection between the two poles constitutes a completed circuit. Since this circuit is entirely outside of the battery it is referred to as the external circuit.

The internal circuit of the battery is from the negative pole through the internal medium to the positive pole. It is not necessary to be concerned with the chemical substances or reactions which are responsible for the production of these electric forces.

When a **voltmeter** is connected to the poles of the battery according to the established standard, it registers a difference in potential of 6 volts (Fig. 2 *A*). The instrument registers under these conditions the voltage of the positive pole minus that of the negative pole:

$$+3 - (-3) = +6 \text{ volts}$$

It must be explained that, for reference purposes, the two poles of all electric measuring instruments, which in this case is a voltmeter, have been arbitrarily standardized and designated as positive and negative. The arrangement is such that, when the positive pole of a battery is connected to the positive pole of a

voltmeter and the negative to the negative respectively, the registration is to the positive side. Similarly if a hypothetical 6-millivolt battery is connected to an electrocardiograph, the record would show an upward shift of the baseline. The degree of movement would depend upon the standardization of the instrument.

If the battery connections are reversed (Fig. 2 *B*), **the registration will be exactly opposite.** When the polarity is reversed with respect to the voltmeter in the case of the 6-volt battery referred to above, the equation becomes:

$$-3 - (+3) = -6 \text{ volts}$$

This means that the voltmeter indicator is pointing to minus 6 volts (Fig. 2 *B*). If the connections from the hypothetical 6-millivolt battery to the electrocardiograph are reversed, a downward movement of the baseline will be shown (Fig. 2 *B*).

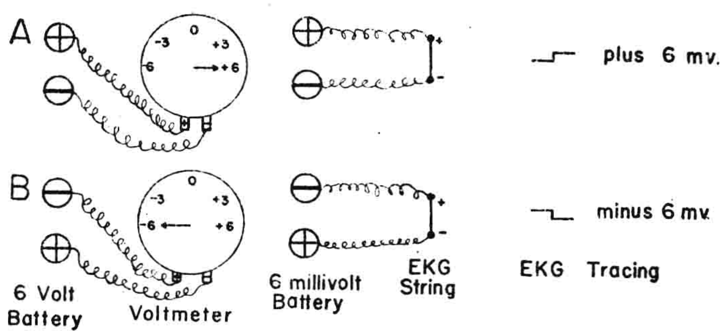

Fig. 2. Measurement of the potentials produced by a 6-volt and a 6-millivolt battery by means of bipolar leads.

A, when the positive pole of the 6-volt battery is connected to the positive pole of a voltmeter and the negative pole is connected to the negative pole of the voltmeter, the instrument will register plus 6 volts. Similarly, a hypothetical 6-millivolt battery, when connected in the same way to an electrocardiograph, produces an upward movement of the baseline, when the instrument is properly standardized, of 6 cm. which is the equivalent of 6 millivolts.

B, when the same batteries are connected to these instruments in a reverse manner so that the negative pole of the respective battery is connected to the positive pole of the recording instrument, and the positive pole of the battery is connected to the negative pole of the voltmeter in one case and to the negative pole of the electrocardiograph in the other, then the former will register minus 6 volts and the latter will record minus 6 millivolts.

BIPOLAR LEADS

The method of leading from the poles of the battery to the poles of the voltmeter (galvanometer) constitutes a bipolar lead. Any lead that measures the difference in potential between two points, one of which is positive and the other negative, or both of which are positive but one more positive than the other, or both of which are negative but one more negative than the other, is a bipolar lead. It is evident that the connections to the battery reveal only the difference in potential between its two poles and yield no information regarding the potential of either pole alone.

As has been indicated, for purposes of reference in electrocardiography, the polarity with respect to the galvanometer is always such that an upward deflection represents positivity of the positive pole and/or negativity of the negative pole.

THE ELECTRIC FIELD

One of the great difficulties presented by electrocardiography is that the source of all of the electric forces, the cardiac musculature, is embedded deeply in the body and, therefore, is some distance from the electrodes which lead to the electrocardiograph. The voltages which are produced by the heart are conducted to the external surface of the body by means of the conducting media which it contains. Except experimentally, all of the cardiac potentials recorded in clinical electrocardiograms are obtained by means of electrodes placed upon the surface of the body, including the mucous membrane of the esophagus and other parts of the gastrointestinal tract.

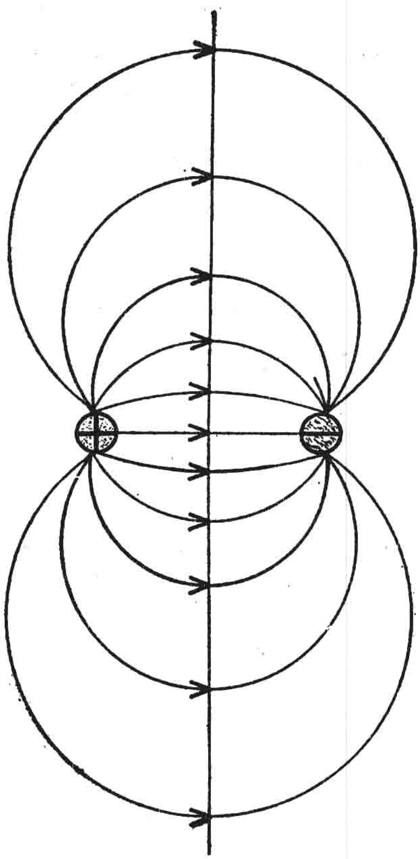

Fig. 3. Electric field of a 6-millivolt battery submerged in a homogeneous volume conductor of infinite extent.

The positive pole, which is plus 3 volts, is indicated by the plus sign, and the negative pole, which is minus 3 volts, is indicated by the negative sign. Concentric lines indicate some of the pathways of current flow, and arrows indicate the direction of the current. The vertical line which is located midway between the two poles and is perpendicular to a line drawn from the positive to the negative pole is everywhere at a zero potential.

The conditions imposed by clinical electrocardiography may be simulated in greatly simplified form by submerging a hypothetical 6-millivolt battery in a solution of normal saline of very large extent. **Such a medium is known as a homogeneous volume conductor because it is capable of conducting electricity equally well in three dimensions.** This is in contrast to a linear conductor, such as a wire, which can conduct in only one direction.

The medium is said to be of infinite extent if it is extremely large in all three dimensions (1) as compared with the distance between the two poles of the battery, and (2) when there are points within it so far away from the poles of the battery