ELECTROCARDIOGRAPHIC ANALYSIS

VOLUME I

Biophysical Principles of Electrocardiography

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Preface

The development of electrocardiography has progressed through two major phases. Under the leadership of Willem Einthoven and Sir Thomas Lewis, a sound method of taking bipolar leads and the major diagnostic features of the arrhythmias were set forth during the period from 1905 to 1925. In the thirty years that have followed, even more remarkable developments have occurred under the masterful workmanship of Frank N. Wilson. These have centered upon the suitable application of the laws that define the flow of currents in volume conductors, an extensive interpretation of the normal and abnormal QRS complex in bipolar, semidirect, and direct leads, the first proper interpretation of the potential distribution that is produced by the field of injury, and the integrative method of analysis of the accession and the regression processes.

Out of the author's experience in teaching the subject at the undergraduate, graduate, and postgraduate levels developed the present text on *Electrocardiographic Analysis*, of which this book, *Biophysical Principles of Electrocardiography*, is Volume I. It will be followed by Volume II, *Clinical Applications of Electrocardiography*. Both volumes deal almost exclusively with the second general developmental phase mentioned above. This volume, *Biophysical Principles*, is intended to present a step-by-step account of specialized information from the fields of electricity and mathematics that has been reduced to several easily understandable methods useful in analysis of electrocardiographic wave form. The understanding of, and the practice with, these basic tools eliminates the hazardous and dubious task of pattern memorization of the multivaried wave forms that are displayed by modern electrocardiographic leads. With this knowledge deflections that are the least conspicuous may often be assigned a proper interpretation of first-order importance. Contrariwise, certain obvious pattern changes are not apt to receive empirical exaggeration in the light of coincidental clinical events.

Sufficient electrocardiograms have been selected, discussed, and supported with numerous bioelectrical and vector diagrams to offer the reader a reasonably sound working knowledge of all the most important types of wave-form changes that are assigned to intrinsic cardiac factors. The text should therefore serve as a valuable starting point for serious students of the subject and a valuable supportive treatment for the many current texts that devote comparatively little space to the more difficult basic aspects of the subject. It is hoped that this book and its forthcoming companion volume will be found useful by all interested in cardiovascular disease: clinicians and researchers, instructors and students.

It was considered advisable that only the more basic articles be indicated in the book by reference. An apology is offered to the many authors who are nameless here but who have kept the clinical aspects of the subject moving forward at a lively and exciting pace.

Volume II, *Clinical Applications*, will contain a comprehensive presentation of the principles of analysis of clinical problems under the various etiologic categories, including a section devoted to congenital heart disease. The book will be extensively cross-referenced with Volume I to indicate the analytical principles being utilized in the discussion. It will also include a section on extrinsic cardiac factors, a discussion of errors in recording techniques, and a chapter devoted to the desirable qualities of the differential amplifier that is required for accurate recording of the electrocardiogram.

There is a third and almost unexplored phase of electrocardiography in the vast basic field of ion activity in excitable tissues. Nature has adopted the bioelectric mechanism of excitation for the sensation and the initiation of movement of all kinds in most forms of life in both the plant and the animal kingdoms. Compare, for example, the action potential of a flower, the Venus's-flytrap, mounted over that of the canine electrocardiogram (direct lead from the left ventricle). The highest degree of specialization of the excitatory mechanism is undoubtedly exemplified by the human nervous system. At the moment, the ions involved appear to be those of potassium and sodium, but others may soon be implicated both in health and in disease. It appears likely that advances in knowledge at the cellular level will largely pace the advances of electrocardiography of the future.

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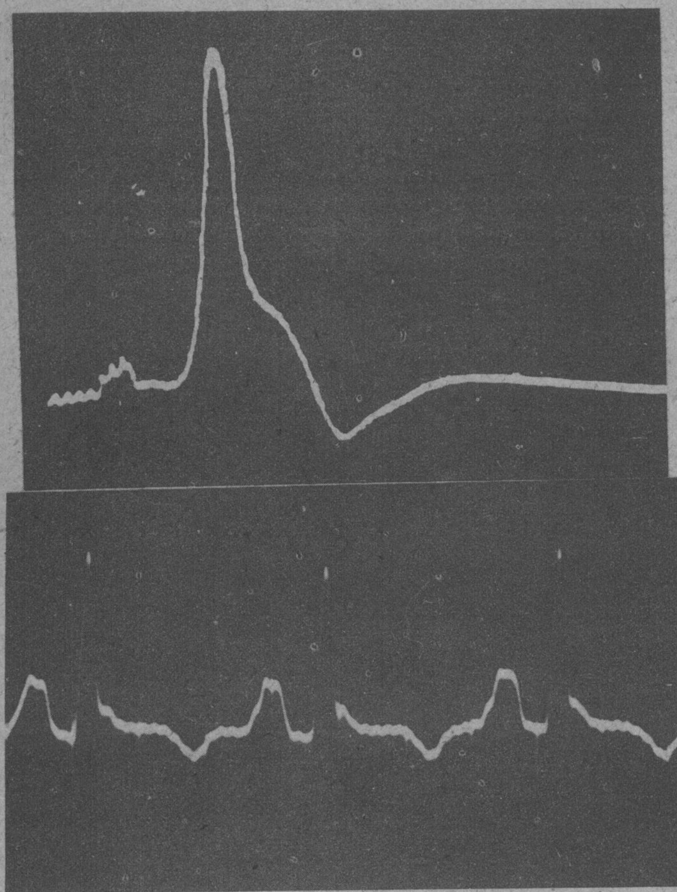
reviewed the files for the illustrative electrocardiograms and helped in countless other ways to make the task possible. Her support has been generously contributed by the Oklahoma State Heart Association.



Illustrating the general similarity of wave form of the action potential (0.13 volt peak) of the Venus's-flytrap (top curve, courtesy V. A. Greulach, *Scientific American*, Feb., 1955, p. 100) and that of the unipolar direct lead from the surface of the canine left ventricle.

Thanks are given to Miss Ruth Doelling and to Mrs. Juanita Baughman for their painstaking task of typing the prepublication drafts of the manuscript.

Finally, appreciation is expressed for the courtesy, help, and generous cooperation of Paul B. Hoeber.

R. H. B.

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Introduction

The electrocardiogram is first of all a laboratory procedure and in accordance with other laboratory procedures should receive interpretation by the physician in direct charge of the patient. Interpretation should not be attempted without a knowledge of the essential clinical findings, pertinent laboratory data, and the purpose for which the electrocardiogram has been taken.

Like most laboratory procedures much helpful information may be obtained that falls into the category of corroborative data. Unlike most laboratory procedures, a vast amount of additional information may be obtained that cannot be anticipated by any other means.

Heart muscle belongs to a class of living structure known as *excitable tissue*. In the animal body smooth and striated muscle and nerve also belong to this class. Excitable tissues are characterized by their ability to generate an electric field throughout the conducting medium in which they are naturally imbedded and of which they form an integral part. The electric field consists of a flow of current along paths that leave the surface element of the excitable cell, enter the surrounding medium, and re-enter the same cell through an adjacent surface element by virtue of an alteration of the electrical properties of the latter. The electrical behavior, is, therefore, dependent upon the conducting properties of the medium, both exterior and interior to the surface elements of the fiber, as well as upon the conducting properties of the surfaee elements themselves [9, 23].

A failure to appreciate these facts has led to a great deal of confusion in the past. Moreover, a great many experiments have been and continue to be performed in physiologic laboratories (wherein the conducting medium exterior to the excitable tissue is replaced in part or in whole by moist air, a non-conducting medium). Experiments of this kind impose a very complicated boundary condition upon the electrical behavior and alter the temperature gradient throughout the tissue under study. Under the circumstances the electrical behavior cannot be interpreted in terms of that which would occur had the external environment and the internal temperature gradient remained unaltered. The so-called monophasic action potential recorded under these conditions as a potential difference between an injured and uninjured region can have little bearing upon the problem of analysis of the heart's field in situ.

BIOPHYSICAL PRINCIPLES OF ELECTROCARDIOGRAPHY

Contents

CHAPTER 1

Idealized Volume Conductor and Clinical Electrocardiographic Leads

[1:1] Conductors

The electrocardiologist is primarily interested in the flow paths of current throughout the conducting medium exterior to the cardiac fibers for it is these flow paths that determine his measured pattern of potential differences. Factors that determine these flow paths in health and in disease are situated both outside and inside myocardial fibers. A major electrocardiographic problem is posed in the differentiation of extrinsic from intrinsic factors, which operate both singly and in combination to determine the distribution of currents throughout the body.

The arbitrary notion must be rejected as untenable that, because an injured region does not support an electric double layer and an excitation process, this region cannot bear a potential distribution in a manner similar to that borne by other nongenerating regions of the volume conductor. Moreover, the interpretation of the potential distribution that is produced by excitable tissues in situ on the basis of experiments conducted upon these tissues isolated in moist air has been clearly shown *(23)* to be in serious conflict with the well-known physical laws that determine the flow of currents in volume conductors. It is through a conservative application of these laws that clinical electrocardiography now enjoys a reasonably firm foundation. Inasmuch as the medium is three-dimensional, it is referred to as a volume conductor in contrast to a copper wire, which potential-wise is a linear conductor. Unlike the wire, the body tissues make up a relatively poor conducting medium. Living tissues are said to possess a finite conductivity and thus are able to maintain a potential difference (difference in electrical pressure) between various points within their substance or upon their surface. In good conductors the conductivity is "infinite" and potential differences are often too small for convenient measurement. The nonconducting class of materials (dielectrics) creates large potential differences and permits extremely small currents to flow. Engineering science, with its primary aim at generation and control of electricity (movement of electrons) has naturally developed with the study and use of good conductors and good insulators. Consequently, information on poor conductors is limited and receives no mention in most of the introductory texts on electricity.

[1 : 2] Dipole Field

When an electromotive force (potential difference) is applied to a volume conductor of finite conductivity, current enters the volume conductor through

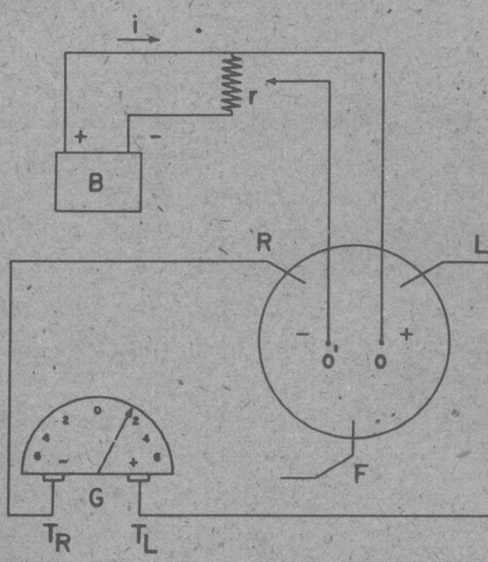

FIG. 1:1.1. B is a battery and i is the current through the circuit BOO′B. R, L, F are electrodes. G is a galvanometer or detector. T_r is the right-arm terminal of G. T_l is the left-arm terminal of G. r is a variable (potentiometer) shunt that controls the electromotive force applied to electrodes o and o′. The experiment is oversimplified (see Figure 1:1.2 and legend).

a region called the *source* and leaves the volume conductor through a region called the *sink*. After leaving the source and before entering the sink currents flow throughout the whole interior of the volume conductor. The various paths along which the currents flow are determined by a pattern of potential differences or differences in electromotive pressure. The applied electromotive force is obtained from a *generator* of some kind. In the laboratory a dry cell battery will suffice (Figures 1:1.1 and 1:1.2). Wires connected from its positive and negative poles serve to apply the electromotive force at two points (source and sink) of the volume conductor. A large bath of normal saline solution may be utilized as the volume conductor. The battery, its wires, and the electrodes o and o′ (which are insulated except at their tips) are referred to collectively as the generator circuit. The current flow from the generator circuit enters the saline at the source, flows throughout all parts of the volume conductor, and leaves the saline at the sink.

This flow constitutes the electric field of the volume conductor. All currents leaving the source enter the sink, for the saline is surrounded by a dielectric. Consequently the *strength* of the source is *equal* to the strength of the sink. The current that moves through the high resistance of the galvanometer is too small to be considered.

Insofar as the volume conductor is concerned the region of highest potential (=pressure) is the source and the region of lowest potential is the sink. The maximum potential difference is across the source and sink. If we measure this potential difference at 100 millivolts, we know that the generator circuit applies an electromotive force of 100 mv. to the volume conductor. Moreover the potential V_o at the source is 50 mv. and the potential V_o' at the sink is −50 mv. Consequently, the applied electromotive force (emf) is given by

$$\begin{aligned} \text{emf} &= (V_o - V_o') = 50 - (-50) \qquad (1:1) \\ &= 100 \text{ mv.} \end{aligned}$$

[1 : 3] Generator

When the source and sink are close to each other the electric field of the volume conductor is said to be produced by a current *dipole* or *doublet*. If we add more salt to the solution we increase the conductivity of the medium and more current will flow (Figure 1:1.1) if the applied emf is held constant by adjusting the potentiometer r. If the applied emf decreases, the current i will decrease, and potential differences at various points in the volume conductor will decrease. Consequently, the magnitude of the potential difference across any two points in a volume conductor is proportional to the current strength of the dipole and varies inversely with the conductivity.

[1 : 4] Field Determinants

Given a current dipole of constant strength in a volume conductor, the factors that determine the flow paths throughout the conductor are the