Advances in Electrocardiography

Volume 2

Edited by

ROBERT C. SCHLANT, M.D.

and

J. WILLIS HURST, M.D.

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Preface to Second Volume

One would think that there was little else to add to the field of electrocardiography. After all, many years have passed since Einthoven invented his machine. The years have not merely passed but have been filled with imaginative, investigative work and undoubtedly billions of electrocardiograms have been recorded. Despite the years, the investigative work, and the billions of recordings, there is continual effort to extract more information from the electrocardiogram. Perhaps this is a testimony to the true complexity of the heart coupled with the desire of physicians to know more about their patients by using simple, noninvasive methods.

This second volume of Advances in Electrocardiography continues the objective of the first volume to present authoritative reviews in selected areas of electrocardiography in which there have been recent and significant advances. It contains chapters on a number of new topics in addition to chapters from the first volume that have been updated by the authors to incorporate more recent material. Those chapters in the first volume that were on subjects in which there have not been enough new developments to justify an update at this time are omitted in this volume. Future volumes will include new subjects in addition to those subjects in which there have been additional recent advances.

We wish to thank Mrs. Kathy Tucker and Mrs. Vickie Reid, secretaries of the Division of Cardiology, Department of Medicine, Emory University School of Medicine as well as the secretaries of each author for their expert assistance in the preparation of the manuscripts. We would also like to thank the staff of Grune and Stratton for their assistance in the preparation of this book. Most of all, we wish to thank the authors of both volumes, to whom we would like to dedicate these books.

Robert C. Schlant, M. D.
J. Willis Hurst, M. D.

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PART I.

General Electrophysiology of the Heart

Allen M. Scher, Ph.D.

1.

Electrocardiographic Theory and Recording

Most of this volume is indirectly concerned with the electrocardiogram as a diagnostic tool and thus with the way in which electrocardiographic records are taken. Even the basic scientist who deals with isolated cells, with morphology, or with animal hearts may, if his work is successful, be responsible for a change in our understanding of the electrocardiogram, and such work may change the way we record body surface electrocardiographic potentials. If we understand a system, it is usually easy to monitor its performance.

The designer of a machine often equips it with monitoring devices to indicate its condition and furnish insight into the cause of failure. If the principles of design are clear, even an individual who has never designed a machine can often understand its principles, disassemble and reassemble it, and suggest ways in which performance may be monitored. Obviously, the most successful and expeditious monitoring of a system can be developed if we know how the system is put together. Digital computers, for example, can be furnished with hardware or software "de-bug" packages which can, or ideally should, indicate which card, module, integrated circuit chip, or program statement is causing a particular malfunction. Here the machine is its own diagnostician. In most biological and many physical fields, including electrocardiography, the functional components of "systems" are gradually being described, and we are moving slowly from empiricism to a more scientific stage based on solid observations and adequate theory.

We can consider the electrocardiographic "system" as one in which a muscular pump, incidentally but most importantly for clinical purposes, generates potentials over the body surface. Ideally, we should first understand the biophysical system that produces the body surface potentials and then use this understanding to design recording systems that will clearly disclose all the detec-

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table, significant clinical data. This ideal situation—first understand the system, then design the tools to monitor its performance—is a far cry from the first forty or more years of the clinical use of electrocardiographic recordings. Substantial progress was made in the clinical use of electrocardiographic signals during that period, while the mechanism of their generation was understood only in a fragmentary fashion. We might begin our examination of this problem by briefly reviewing the factors which are necessary for an understanding of the origin of electrocardiographic potentials.

BASIS FOR UNDERSTANDING THE ELECTROCARDIOGRAM

Understanding the origin of electrocardiographic potentials has three aspects: (1) We must understand the nature of the individual generators which are cardiac cells; (2) we must understand the pathway of activity within the heart; and (3) we must have an adequate physical theory to explain how potentials are produced at the body surface from activity within the heart. To restate the above, the potential at a recording site P in a three-dimensional conducting medium like the torso is determined by: (1) the nature of the generator (the cardiac cell); (2) the location of the area(s) which are depolarized or resting at a given time, and the location of the recording site; and (3) the physical laws regulating current flow in such conductors. A brief discussion of these factors follows.

The resting cardiac cell is electrically polarized and undergoes a relatively constant (from cell type to cell type) electrical change called depolarization, which is a necessary antecedent to cardiac contraction. It then repolarizes. The action potential of the cardiac cell is shown in Figure 1. The physicochemical basis for these electrical changes is gradually being elucidated, but it is not necessary to understand the physical chemistry in order to understand the shape of the ECG. We can consider this type of potential change standard for cardiac

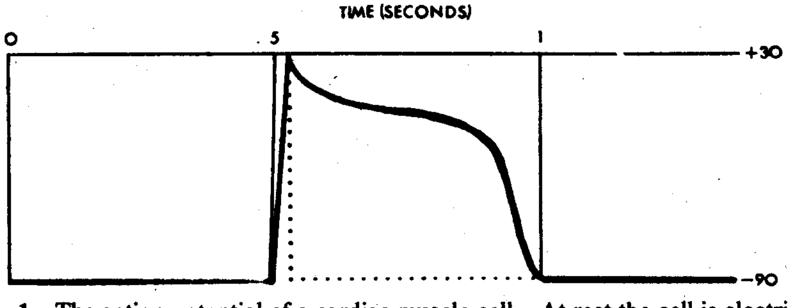

Figure 1. The action potential of a cardiac muscle cell. At rest the cell is electrically polarized, the inside of the cell showing a negative potential of 90 mV. With depolarization, this potential reverses polarity so that the inside becomes positive with respect to the outside. The action potential of cardiac cells has a duration of up to 1/2 sec. Action potentials in nerve and muscle cells have a duration of about 1 msec (as shown by the dotted line).

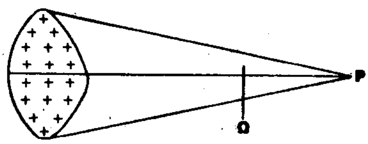

Figure 2. The potential at recording point P, due to the polarized surface shown, is determined by the conductivity of the medium, the charge density per unit area of the polarized surface, and the solid (three-dimensional) angle subtended at the recording point by the surface.

cells (while realizing that changes in action potential shapes, as in infarction, produce ST segment shifts).

The second factor, location of the areas depolarized and repolarized at a given time, is also being studied. It is imperfectly known, but there is some information we can use, including the recent plots of activation of the human heart (see chapter 3).

Most relevant to this discussion is the physics of current flow in three-dimensional conductors and its relationship to the pathway of electrical activity in the heart. The potential (Ep) produced at a recording rate (P) by a dipole sheet in a three-dimensional, infinite, homogeneous medium is simply described (Fig. 2): $E_P = K_1 \Omega \Phi$, where K_1 corrects for the conductivity, Ω is the solid angle subtended at the recording point by the sheet, and Φ is the charge density per unit area of the dipole sheet. If we knew the locations of the dipole sheets that develop in the heart during depolarization and if the torso were infinite and homogeneous, we could predict the voltages which would develop.

The above formulation is inadequate because the torso is neither homogeneous nor infinite. Although the computation for the infinite case is trivial, the computation for the real case with an inhomogeneous, bounded torso was impossible until 1964 when Gelernter and Swihart [11], and later Barr et al. [5] and Barnard et al. [3,4] proposed techniques to handle this problem. Gelernter and Swihart realized that the limiting or boundary condition imposed by the body–air contact is that no current can flow into the air. They proposed to solve this problem in the same way that it is naturally "solved" by the torso. The procedure is equivalent to making an infinite medium calculation with accurate geometry, and then allowing no current to flow beyond a fictitious boundary equivalent to the air boundary. The current flow through the torso into the air is eliminated by placing charges at each point on the body surface to equal and cancel the perpendicular current flow. Unfortunately, charges so added have effects on flow through the boundary at other areas so that the final solution is arrived at only after many iterations of the basic calculation. This solution would not be possible without the capabilities of high-speed digital computers. Even with computers, the solution is extremely costly.

The availability of a solution to the volume conductor problem means that we have the capability to understand the generation of the electrocardiogram since we have adequate information about the generator, good information about the pathway of activity, and the capability to use these, plus the geometry in a digital computer simulation to generate electrocardiograms. This process, constructing electrocardiograms from known depolarization pathways and geometry, is referred to as a "forward problem." Unfortunately, the clinician faces the inverse problem, which is far more difficult. The information available to him consists of body surface potentials, and from these he tries to decide what the generator (the heart) is like. In viewing the attempts to set up electrocardiographic systems to do this, we must realize that the inverse problem is one for which there is, in truth, no solution. In the general case, it is an insoluble problem. In the parallel field of electrostatics, the impossibility can be clearly stated: If one knows only the potential distribution on the surface of a body, one can postulate an infinite number of internal generators. This impossibility of a physicomathematical solution is not absolute if one has other information about the system. This physical limitation thus does not prevent clinicians from making accurate diagnoses. One way in which these are made is that the clinician compares a particular set of electrocardiographic recordings in an individual with what he would expect from a given clinical state. Such comparisons can be made statistically or they can be made on the basis of intuitive guesses or other information about the state of the heart. However, some researchers are going further. There are those who feel that, given a set of electrocardiograms, they can, by an inverse solution (usually employing a digital computer), determine the state of the heart, including the presence or absence of healed infarction, even when complicated by block or hypertrophy. In so doing they must make assumptions, for instance deciding that the left wall is depolarized from inside-out. If these assumptions are sufficiently rigid, the inverse problem can be solved. Unfortunately, a solution will always be found, even if the assumptions are incorrect. There is thus the possibility of a tautology in which an answer specified in the assumptions turns out, not surprisingly, to be true.

This appears to be sufficient or more than sufficient background material to embark on a historical discussion of the past and present techniques in electrocardiographic recording.

EINTHOVEN LEADS AND THE MEAN VECTOR

Early use of the extremities as recording points by Einthoven and others, which defined leads I, II, and III, was probably occasioned in part by the fact that it was very easy to put the hands and feet in buckets of salt water and use these as electrodes. The connections which Einthoven used at the limbs were determined by the fact that he liked potentials in which the ventricular complex was upright. Early days were devoted in part to identifying the relationship between the various waves and cardiac chambers, relationships of the P wave to the atrium, of the ventricle to the QRS complex and T wave, etc. In 1913, Einthoven et al. [9] indicated the relationship between heart position and mean electrical axis, and described the procedure for determining the axis from the standard limb leads. This was essentially a vectorial analysis.

UNIPOLAR LEADS

Wilson and co-workers' description of the unipolar leads [24] is nearly coincident with investigations in which he and his collaborators recorded potentials from the exposed heart in both the animal and human [22]. The concept on which these leads were based was as follows: An electrode touching or closely overlying a portion of the heart preferentially records activity of the underlying myocardium. With the addition of Wilson's six unipolar leads to Einthoven's frontal plane leads, the present-day system of electrocardiographic recording and interpretation had been established, based on a variety of qualitative assumptions but obviously very useful.

THE VECTORCARDIOGRAM

Shortly thereafter, and without concern for the contradiction, Wilson and Johnston [23], following the earlier work of Mann [17], suggested the use of the vectorcardiogram. The use of the vectorcardiogram is based on the assumption that the heart as a generator can be considered equivalent to a single, fixed-location dipolar source (a positive and a negative pole with fixed center varying in strength and direction). Therefore, a sizable amount of useful information (and, in the eyes of some, virtually all the useful information) is contained in three voltage differences (X, Y, and Z) which analyze potentials from four or more body surface points. At times more than four body surface points are used, but the potentials are summed to make the three "orthogonal" leads. The purpose of multiple body surface input points to these leads is to compensate for "distortions" introduced, for example, by the conductivity of the thorax or the position of the heart, or both.

If we jump ahead to 1957 and look at the symposium organized by Hecht [12] on the electrical activity of the heart, we find that a discussion of cellular potentials and excitation is followed by a discussion of electrocardiographic recording procedures which revolves around the vectorcardiogram.

At this time, there were several questions about the unipolar leads and the vectorcardiogram. The major question concerning the unipolar leads involved the accuracy of the Wilson central terminal, which in theory was considered to be at "zero" potential. This concern was resolved [6] in favor of the central terminal.

There were several problems about the vectorcardiogram. The most important concerned the accuracy of the dipole hypothesis: Can the potentials on the body surface be regarded as originating from a single, fixed, center dipole? Affirmative but not universally accepted arguments were presented by Schmitt et al. [20] and by Frank [10].

A second question concerned the procedures for recording the vectorcardiogram. Here the aim was to devise techniques to record the X, Y, and Z components of the cardiac vector in such a fashion as to minimize effects due to the heart's eccentricity and the inhomogeneity of the torso. Several vectorcardiographic lead systems were proposed, some of which are still in use. A major determinant of the survival of these systems has been the ease of making the requisite electrode connections to the torso.

MULTIPOLAR LEAD SYSTEMS

Following the 1957 conference on electrical activity of the heart, the most coherent movement in research electrocardiographic theory was toward the view that the heart could not be considered a single dipole insofar as body surface potentials were concerned. This idea was and is favored by groups in Memphis, Philadelphia, and by others represented here, and who should certainly speak for themselves. The feeling that the heart could not be treated as a dipole stemmed from two different types of information. First, the plots of excitation of the heart [8,18] indicated that it is a heart rather than a dipole and that there could, at times, be several separate waves of excitation moving in different directions in the heart. Second, the plots of body surface potential distribution, as seen in Taccardi's laboratory particularly [21], indicated that at times one could have isolated areas of positivity or negativity and fields which, at least insofar as the surface appearance, seemed to arise from something more complicated than a dipolar generator. A dipole is an idealized source consisting of a single pair of poles. More complicated idealized sources are the quadripole and the octapole. The latter two are called multipolar sources. The aim of studies in this area was to devise lead systems which would (separately) show dipolar, quadripolar, and octapolar sources underlying the ECG. There were some surprises in this area. Our own study, which involved a factor analysis of body surface potentials [19], indicated that body surface potentials could be explained to a very high degree by the effects of three fixed, internal generators. More recent studies by Kornreich [15] seem to indicate that we may have underestimated the amount of useful information in the electrocardiogram. The dipole is a special case of the three-fixed-generator situation. In the more general case, the generators need not be mutually perpendicular with a shared center. This was not, however, an era of unanimity since work continued on the vectorcardiogram, on the conventional 12-lead electrocardiogram, and even the "multipolists" were not agreed on ways to find the multipole (just as vectorcardiographers were not agreed on ways of finding the dipole).

COMPUTER ANALYSIS OF THE ELECTROCARDIOGRAM

The late 1960s saw the birth and growth of numerous computer systems for analyzing the electrocardiogram. The confusion about electrocardiographic recording is reflected in computer usage. The most commonly used systems employ either conventional recording leads or the vectorial approach. The approach in electrocardiographic diagnosis with computers is either to duplicate the commonly accepted criteria for electrocardiographic disease or, at times, to establish new criteria through statistical procedures. There is a certain limitation in either approach. In the first case, an individual may cause a machine to give exactly the diagnosis he himself would give faced with a particular ECG, and the diagnosis will thus be strong or weak, depending on the criteria built into the program. In the second case, the diagnostic criteria may be initially unfamiliar and divorced from any known physiological significance. In both cases, perhaps more easily for the second case, diagnostic criteria should be anatomically verified. This has been done in Pipberger's studies [7]. Research with computers has also concentrated on both the total body surface map and the multipolar approaches. The practical success of any particular novel approach remains to be demonstrated. Unbiased tests of computer programs have recently appeared [2]. Some programs show surprising weaknesses in pattern recognition (recognizing the onset of QRS) [1]. Recently, Kornreich [15,16] has used total body surface maps collected by Holt et al. [13] to devise a new set of leads for computer analysis which may lead to improved computer diagnosis of the ECG.

TOTAL BODY SURFACE MAPS

Much interest in electrocardiographic lead systems, as indicated previously, has been directed at recording the maximal amount of diagnostic information available from the body surface electrocardiogram. As indicated, there does not seem to be a clear answer to the question of how much useful information there is on the body surface electrocardiogram. There is a way of getting around this problem if one does not fear to record too much. We can record potentials over the entire body surface, as has been done in Taccardi's laboratory [21]. One is sure one has not lost any information, but the possibility exists that one has recorded information that is diagnostically insignificant and/or redundant. Potentials recorded in this fashion are converted to a number of instantaneous total body surface maps for every millisecond or every two milliseconds during QRS. Forty, or even 80 such maps show a QRS complex. Taccardi's original recording and reading of records were made the hard way, i.e., they were done by hand. Taccardi later utilized a multichannel digital recording system which made it possible to record maps rather quickly. Since there is other discussion of these maps in Chapters 3 and 4 of the first volume of *Advances in Electrocardiography*, there seems no need to present examples. Recording data and making maps of this sort are a heroic procedure. It is many times as complicated as taking a standard electrocardiogram (even when leads are recorded simultaneously). Although it is the hope of some body surface mappers that the digital computer will make the *analysis* of such maps simpler, this has not yet occurred. Some individuals regard maps as a research tool (and some feel that they will always be a research tool), while others are hopeful that they can be converted into a clinically useful diagnostic tool. One problem with these maps is that they are not at present useful for mass screening. They seem rather more applicable to difficult diagnoses than to screening. For instance, Horan and coworkers believe they have detected infarctions of the right ventricle which would not have been detected with other techniques.

THE MAGNETOCARDIOGRAM

When electrical currents flow in the torso, a magnetic field is also induced in the surrounding air. These constitute the magnetocardiogram. The detection of magnetic currents around the human torso during the cardiac cycle is not easy. Magnetic field strength is far weaker than the magnetic field of the earth, and in cities or other magnetically "active" environments, changes in the magnetic field near a patient may be much larger than that patient's magnetocardiogram. It has been proposed that the magnetocardiogram has a unique advantage in that the magnetic permeability of the torso and of the air are the same. One might,