Advances in Electrocardiography

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By

J. A. ABILDSKOV, M.D.
ABDUL S. AGHA, M.D.
ROGER C. BARR, Ph.D.
MARY JO BURGESS, M.D.
AGUSTIN CASTELLANOS, JR., M.D.
CESAR A. CASTILLO, M.D.
HÉCTOR DA RUOS, M.D.
C. J. DE SANDO, M.D.
MARCELO V. ELIZARI, M.D.
GUNGOR ERTEM, M.D.
NANCY C. FLOWERS, M.D.
HENRY GELBAND, M.D.
M. SUSANA HALPERN, M.D.
BRIAN F. HOFFMAN, M.D.
LEO G. HORAN, M.D.
THOMAS N. JAMES, M.D.
ANDRÉS KRETZ, M.D.
JULIO O. LÁZZARI, M.D.
DANILO LEE, M.D.
EUGENE LEPESCHKIN, M.D.
RAÚL J. LEVI, M.D.
ALVARO MARTINEZ, M.D.
RASHID A. MASSUMI, M.D.
ROBERT J. MYERBURG, M.D.
GERARDO J. NAU, M.D.
MAURICIO B. ROSENBAUM, M.D.
ALLEN M. SCHER, Ph.D.
LIBI SHERF, M.D.
MADISON S. SPACH, M.D.
BORYS SURAWICZ, M.D.
ZAKAUDDIN VERA, M.D.
A. CALHOUN WITHAM, M.D.

Edited by

ROBERT C. SCHLANT, M.D.
Professor of Medicine and Director, Division of Cardiology, Department of Medicine, Emory University School of Medicine, Atlanta, Georgia

and

J. WILLIS HURST, M.D.
Professor and Chairman, Department of Medicine, Emory University School of Medicine, Atlanta, Georgia

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Contributors

J. A. ABILDSKOV, M.D., Professor of Medicine, University of Utah Medical Center, Salt Lake City, Utah 84112

ABDUL S. AGHA, M.D., Cardiology Fellow, Veterans Administration Hospital, Miami, Florida 33125

ROGER C. BARR, Ph.D., Department of Pediatrics, Department of Biomedical Engineering, Duke University, Durham, North Carolina 27710

MARY JO BURGESS, M.D., Assistant Professor of Medicine, University of Utah Medical Center, Salt Lake City, Utah 84112

AGUSTIN CASTELLANOS, JR., M.D., Associate Professor of Medicine, Division of Cardiology, University of Miami School of Medicine, Miami, Florida 33146

CESAR CASTILLO, M.D., Clinical Assistant Professor of Medicine, Co-Director of Cardiovascular Laboratory, Mercy Hospital, Miami, Florida 33133

HECTOR DA RUOS, M.D., Member of Staff, Department of Electrocardiography, Argerich Hospital, Buenos Aires, Argentina

C. J. DE SANDO, M.D., Cardiology Fellow, George Washington University Division, District of Columbia General Hospital, Washington, D.C. 20003

MARCELO V. ELIZARI, M.D., Chief, Department of Electrocardiography, Argerich Hospital, Buenos Aires, Argentina

GUNGOR ERTEM, M.D., Cardiology Fellow, George Washington University Division, District of Columbia General Hospital, Washington, D.C. 20003

NANCY C. FLOWERS, M.D., Professor of Medicine, Medical College of Georgia and Chief, Section of Cardiology, FHD, Veterans Administration Hospital, Augusta, Georgia 30902

HENRY GELBAND, M.D., Assistant Professor of Pediatrics, University of Miami School of Medicine and Staff Physician, Veterans Administration Hospital, Miami, Florida 33125

M. SUSANA HALPERN, M.D., Member of Staff, Service of Cardiology, Salaberry Hospital, Buenos Aires, Argentina

BRIAN F. HOFFMAN, M.D., Professor and Chairman, Department of Pharmacology, Columbia University College of Physicians and Surgeons, New York, N.Y. 10032

LEO G. HORAN, M.D., Professor and Vice Chairman, Medical College of Georgia and Chief, Medical Service, Veterans Administration Hospital, Augusta, Georgia 30904

THOMAS N. JAMES, M.D., Director, Cardiovascular Research and Training Center, Professor of Medicine, and Professor of Pathology, University of Alabama School of Medicine, Birmingham, Alabama 35233

ANDRÉS KRETZ, M.D., Member of Staff, Department of Electrocardiography, Argerich Hospital, Buenos Aires, Argentina

JULIO O. LÁZZARI, M.D., Member of Staff, Department of Electrocardiography, Argerich Hospital, Buenos Aires, Argentina

DANILO LEE, M.D., Cardiology Fellow, George Washington University Division, District of Columbia General Hospital, Washington, D.C. 20003

EUGENE LEPESCHKIN, M.D., Professor of Medicine, Department of Medicine, Cardiovascular Research Unit, University of Vermont, Burlington, Vermont 05401

RAÚL J. LEVI, M.D., Member of Staff, Service of Cardiology, Salaberry Hospital, Buenos Aires, Argentina

ALVARO MARTINEZ, M.D., Cardiology Fellow, Jackson Memorial Hospital, Miami, Florida 33136

RASHID A. MASSUMI, M.D., Professor of Medicine (Cardiology) and Chief, Electrophysiology Section, University of California School of Medicine, Davis, California 95616

ROBERT J. MYERBURG, M.D., Assistant Professor of Medicine and Physiology, University of Miami School of Medicine and Chief, Cardiology Section, Veterans Administration Hospital, Miami, Florida 33125

GERARDO J. NAU, M.D., Member of Staff, Service of Cardiology, Salaberry Hospital, Buenos Aires, Argentina

MAURICIO B. ROSENBAUM, M.D., Chief, Service of Cardiology, Salaberry Hospital, Buenos Aires, Argentina

ALLEN M. SCHER, Ph.D., Professor, Department of Physiology and Biophysics, University of Washington, Seattle, Washington 98105

LIBI SHERF, M.D., Senior Lecturer in Medicine, Chaim Sheba Medical Center, Tel Hashomer, Israel

MADISON S. SPACH, M.D., Chief, Division of Pediatric Cardiology, Duke University Medical Center, Durham, North Carolina 27706

BORYS SURAWICZ, M.D., Professor of Medicine and Director, Cardiovascular Division, University of Kentucky College of Medicine, Lexington, Kentucky 40506

ZAKAUDDIN VERA, M.D., Cardiology Fellow, George Washington University Division, District of Columbia General Hospital, Washington, D.C. 20003

A. CALHOUN WITHAM, M.D., Professor of Medicine and Chairman of Cardiology, Medical College of Georgia, Augusta, Georgia 30902

Preface

As a rule, medical knowledge is not created at a constant rate of speed. Over a period a time, there are spurts of great progress and years when little progress is made. New knowledge in electrocardiography is no exception to the rule. Einthoven's description of the string galvanometer electrocardiograph machine in 1903 was the starting point. Since then, there have been several periods of marked progress in electrocardiography, produced by creative men such as Sir Thomas Lewis, Frank Wilson, Robert Grant, and others.

The creative views of Grant came to fruition while he was working in the Department of Medicine at Emory University School of Medicine from 1947 to 1950. His new vector concepts created an exciting wave of interest in electrocardiography which lasted until about 1960. Following this, the interest in electrocardiography waned and young men turned their interest to other exciting pursuits. The teaching of electrocardiography seemed to falter and a maintenance type of education ensued. During the last decade, a need to focus on the advances in electrocardiography was not stressed because we were in the midst of a period in which little progress was evident.

Now we are experiencing renewed interest and progress in electrocardiography. There are two reasons for this. First of all, new views are being expressed by a number of creative people. Second, other factors, such as the demand for new knowledge stimulated by the development of coronary care units, have forced us to learn more about dysrhythmias and the drugs that control them. This being true, we in the Department of Medicine of Emory University School of Medicine invited a group of experts to participate in a symposium that would highlight the recent advances in electrocardiography. The symposium was held on May 10 to 13, 1971, and was attended by approximately 500 people. The content of the symposium itself and this book that has emerged from it were created by the individual speakers and authors. We, the Editors, have simply organized and edited the material so that we and the readers of the book could learn from our colleagues. Accordingly, the Editors of this book wish to thank the authors for teaching us about the recent advances in electrocardiography.

We also wish to thank Mrs. Farrar Edwards, Miss Barbara Hoertz, Miss Bobbi Vilensky, and Mrs. Kathy Tucker, secretaries of the Division of Cardiology, Department of Medicine, Emory University School of Medicine, for their expert assistance in the preparation of the manuscript. We also thank Mr. John de Carville of Grune & Stratton for his assistance and guidance in the preparation of this book. Mr. Alex Nelson, Business Manager of the Department of Medicine, Emory University School of Medicine, was vital in the innumerable arrangements for the symposium upon which this book is based.

Our goal in having the symposium and developing the book was to emphasize the recent advances in electrocardiography. We hope that advances will continue to be made, and if the progress is rapid we will update the book promptly. In the meantime, we urge our friends—the authors—to keep working. If they do, there is little doubt they will create new knowledge to teach us.

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

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I. General Electrophysiology of the Heart

ALLEN M. SCHER, Ph.D.

Trends in Electrocardiographic Recording

Most of our discussion at this symposium 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 detectable, 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.

From the Department of Physiology and Biophysics, University of Washington School of Medicine, Seattle, Washington.

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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.

THE CELL

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 is not necessary for this discussion. We can consider this type of change standard (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 6, Excitation of the Heart: A Progress Report).

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 (E_P) 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

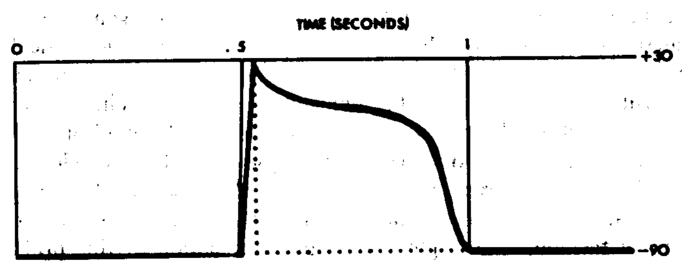

Figure 1. The action potential of a cardiac muscle cell. At rest, the cell is electrically polarized, the inside of the cell showing a negative potential of 90 mV. With depolarization, this potential reverses polarity so that the inside becomes positive with respect to the outside. The action potential of cardiac cells has a duration of up to 0.5 second. Action potentials in nerve and muscle cells have a duration of about 1 msec (as shown by the dotted line).

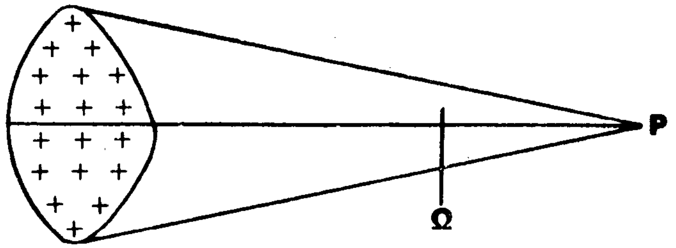

Figure 2. The potential at recording point P, due to the polarized surface shown, is determined by the conductivity of the medium, the charge density per unit area of the polarized surface, and the solid (three-dimensional) angle subtended at the recording point by the surface.

the real case with an inhomogeneous, bounded torso was impossible until 1964 when Gelernter and Swihart [6] and later Barr et al. [1] 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.

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 an historical discussion of the past and present techniques in electrocardiographic recording.

THE EINTHOVEN OR MEAN VECTOR PERIOD

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. [4] 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.

THE PERIOD OF THE UNIPOLAR LEAD

Wilson and co-workers' description of the unipolar leads [18] is nearly coincident with investigations in which he and his collaborators recorded potentials from the exposed heart in both the animal and human [16]. 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. Thus the present-day system of electrocardiographic recording and interpretation evolved, often empirical and based on a variety of qualitative assumptions, but obviously very useful.

THE INTRODUCTION OF THE VECTORCARDIOGRAM

Shortly thereafter, and without concern for the contradiction, Wilson and Johnston [17], following the earlier work of Mann [11], 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 dipole. 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 [9] 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 [2] 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. [14] and by Frank [5].

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.

THE ERA OF THE REVIVED MULTIPOLE

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; there has since been a search for the multipole. 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 [3, 12] 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 [15], 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. There were some surprises in this area. Our own study, which involved a factor analysis of body surface potentials [13], indicated that body surface potentials could be explained to a very high degree by the effects of three fixed, internal generators. 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).

Proposals about complicated recording procedures should be considered in the light of a simple electrocardiographic technique (spatial vector electrocardiography) devised by Dr. Robert Grant at Emory University [8]. This procedure, developed in 1949, has continued in use until the present. Its simplicity should be taken into account in any consideration of how complicated an electrocardiographic recording procedure should be. In the Grant system, for a simple "first pass," conventional electrocardiographic leads are used to draw two vectors or arrows, one representing QRS and the other representing T. If these two lie in the same half-space, that is, if they are separated by less than 180° in a planar projection, the individual is considered well. If not, there is an electrocardiographic problem. A more complicated version of this procedure uses a total of four such arrows, representing respectively the mean QRS, the initial and terminal portions of QRS, and the T wave. The success of this simple system makes one wonder about some of the complicated systems which are suggested.

THE COMPUTER ERA

The late 1960's 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. Research with computers has also concentrated on both the total body surface map and the multipolar approaches. Total body surface maps are also considered by some to be potentially useful in computer solutions of the inverse problem, that is, to reconstruct the state of the heart from body surface potentials and to uncover myocardial problems, either singly or in combination. The practical success of any particular novel approach remains to be demonstrated. Statistical approaches are generally weak because they consider the electrocardiogram as an isolated diagnostic instrument, and the addition of one diagnostic fact available to the clinician but not to the computer may tip the balance very importantly in favor of a particular diagnosis. Thus at present many computer programs may have a higher percentage of false positives or false negatives than the clinician. The use of total body surface maps has developed in a few laboratories, but the recording of such maps is probably about one thousand times more complicated than the recording of a conventional clinical electrocardiogram, and to date no one has proposed that such a technique be used for mass screening. If the recording of total body surface maps is about a thousand times more complicated than the conventional electrocardiographic recording, diagnosis by this procedure should cost about a thousand times as much. If the cost of one can be decreased, then so can the cost of the other. The ratio should remain about the same. Attempts to reconstruct the activation of the heart from a knowledge of body surface potentials and proposed solutions of the "inverse problem" are far more complicated than the derivation of body surface maps. The digital computer still has unused speed and capability, but, if we are to judge by progress in the use of the computer in recording electrocardiograms, there is no reason to expect a rapid breakthrough in the applications of the computer to these far more time-consuming procedures.

At times, the use of computers in electrocardiographic analysis reflects the general feeling that there is something magical about the electrocardiogram. The neophyte, isolated bioengineer feels that if only he could "massage" numbers from the potentials that are recorded at the body surface with a large enough machine, something magical about diagnosis would appear. In addition, with computers and otherwise, there is a certain tendency to empirically investigate almost any novel type of electrocardiographic presentation and display. The shifts in emphasis from a vector approach to a unipolar approach and back to a vector approach do not seem to have always been clearly motivated. We seem to use a system until it appears that it can go no further, then shift to another system. In the process we are accumulating more data, at least of a statistical and intuitive type, so that as we do this we do improve our diagnostic abilities, but we usually do not settle the problems mentioned previously about electrocardiographic theory. We seem to waver back and forth between a deterministic approach and a statistical one. The deterministic approach assumes that, knowing what happens on the body surface, one can uniquely relate it back to the heart and to the disease in that heart. The statistical approach assumes that one must take all kinds of probabilities into account and then be able to get a figure for a correlation without knowledge of mechanism, such a figure to be used as a guide. Much of our research, as indicated above, ignores the cost of the complicated procedures which are, if not directly at least indirectly, considered possible for electrocardiographic processing. Many advances have been made, such as the discoveries by the Duke group of potential differences which distinguish between different types of atrial septal defects [10]. Statistical studies by Goldman and Pipberger [7] represent real advances in indicating how far we can go with electrocardiographic recording procedures and in spelling out certain types of associations which are not available to the eye.

SUMMARY

The above is not intended to imply that there has been no progress in electrocardiographic recording. During the last 70 years, the ability to use the electrocardiogram has increased immeasurably. The major reason for this is that electrocardiograms have for years been paraded before large numbers of intelligent diagnosticians who have intuitively made the types of correlations which a computer makes, and who have often had the types of intuition about relationships between pathology and electrocardiography which a digital computer cannot always duplicate. Most of the progress has come from a type of quasi-statistical approach, but there have been the major advances of the unipolar leads and the vector approach. It seems likely that in the near future some type of careful study, based on what happens in the heart and on some type of computer processing that enables us to understand the electrocardiographic system, will lead us to settle on a technique of electrocardiographic recording that produces all necessary diagnostic information for a minimal investment.

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