CLINICAL ELECTROCARDIOGRAPHY

Clinical Electrocardiography

THE SPATIAL VECTOR APPROACH

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Preface

It is not generally realized that there are two quite different methods for using vector analytic methods in clinical electrocardiography. In the first method, four body-surface electrode locations and a cathode-tube oscilloscopic recording system are used to define what are believed to be properties of the resultant electrical forces actually generated within the heart. This is the method which has been most widely studied during the past decade, and several monographs on its use have been published. So far, however, this approach has been of little practical clinical usefulness.

The other method, which has been less studied but promises to be of much greater clinical value, is the approach with which the present book is concerned. It makes use of a different application of vector analytic methods. In it the vector is used simply as a way for integrating and schematizing the information contained in the various leads of the clinical tracing. The vector becomes, in effect, a graph similar to other graphs used in clinical medicine on which a number of independent measurements of a given process are related to one another, such as the temperature chart and the glucose-tolerance test curve. Most graphs used in medicine are two-dimensional plots of magnitude against time, while the vector is a three-dimensional plot of magnitude against the three dimensions of space. However, its function is exactly the same; just as one can predict from the curve of the glucose-tolerance test the approximate blood level of glucose at all instants during the test, so one can predict from the vector plotted from the clinical leads the approximate contour of the deflection at any region of the body surface. This is one of the more powerful aspects of the vector method, for it makes

the clinician master of QRS and T deflections, no matter in what lead or where on the body surface they may have been recorded.

In using the vector this way it is not necessary to assume that the vector has any certain relationship to the electrical forces generated within the heart. The vector, in this use, is nothing more than the electrical force which, if generated at the center of a cylindrical volume conductor, would produce a distribution of potential on the surface of the cylinder similar to that which was encountered in the leads of the clinical tracing. This is another important aspect of the method, for it means that no assumption need be made regarding the internal electrical properties of the body—any more than one needs to know the cause of a fever before a temperature chart can be plotted. There is therefore no question regarding the validity of the method, which is not true of the oscilloscopic method of vectorcardiography.

To be sure, when the vector is plotted from the clinical tracing, the temptation is often strong to consider it also a picture of an electrical force generated from one to another region of the heart. And from time to time in the following presentation this temptation is yielded to, in order to offer an explanation for one or another characteristic of the electrocardiogram. However, it must be recognized that such conclusions are entirely speculative and of uncertain validity.

Finally, the vector converts the information contained in the deflection into its proper physical "units." An electrocardiographic deflection is, after all, simply a measurement of components of electrical forces, and therefore the most rational and objective method for handling this information is to express it in the form of directed electrical forces or vectors. In this sense, vectors are to the electrocardiographer what milligrams and milliequivalents are to the biochemist.

It is not meant by this that vector methods should supplant the more familiar "pattern" methods of interpretation, but rather that they should supplement them. From the clinical point of view, when a tracing has the classic pattern of acute myocardial infarction, it is no more necessary to convert it into vectors than it is necessary to get an accurate measurement of body temperature when the patient has an obvious raging fever. However, when the tracing is perplexing or borderline, or when there is a slight difference in a follow-up

tracing which is difficult to evaluate, then the vector method is the most accurate, objective, and rational method for interpretation that is so far available.

The present volume is an outgrowth of a monograph written in collaboration with Dr. E. Harvey Estes, Jr., and privately published in 1949 for the medical students and staff of Emory University Medical School. Interest in the vector approach grew, and in 1951 The Blakiston Company published it under the title "Spatial Vector Electrocardiography."

The present book is a new effort and hopes to fulfill the role of a textbook in clinical electrocardiography by including many aspects of clinical electrocardiography which were not covered earlier. Relevant electrophysiology has been added in as nontechnical a form as possible, with particular attention to the needs of the beginner. Sections on P-wave abnormalities and on the more common arrhythmias and tachycardias are included, and there is an up-to-date section on the ventricular electrocardiogram, with a discussion of such recently discovered syndromes as peri-infarction block and parietal block. The electrocardiogram in childhood and in congenital heart disease is also discussed, an aspect of clinical electrocardiography which is of growing importance.

This volume is intended as a highly practical book. In the interests of keeping it as short as possible the material has been presented from a single, personal point of view, stressing the vector aspects. More extensive treatment of experimental and basic electrophysiologic aspects of the electrocardiogram is now available in a number of other excellent books, notably those of Lepeschkin and of Sodi-Pollares. In the interest of keeping the cost of publication as low as possible, line drawings instead of photographic reproductions of tracings are used. This is considered justified since the message of this particular book is not contained in the particular contours of the deflections but in the vectors which they represent. With the kind permission of the editors of *Circulation* and *The American Journal of Medicine,* several illustrations have been drawn from figures that appeared in those journals.

The contribution of Dr. Estes in the early development of this method was extremely important and is greatly valued. Later development of the method took place at the Marine Hospital in Baltimore and at the National Heart Institute in Bethesda in collaboration

with Dr. Raymond H. Murray, now of Grand Rapids, and Dr. Harold T. Dodge, now of Seattle. Their contributions have been so important, and the author's association with them so deeply valued, that had they not been prevented by geography and the assumption of other duties, they would have shared authorship of this book.

Finally, it is a particular pleasure to acknowledge the generous and loyal assistance of Rosalie Madison, chief technician of the Heart Station at the Grady Memorial Hospital in Atlanta when the author was working there, and Clara V. King, who was in charge of the laboratory when we were in Baltimore and continues as our chief technician here in Bethesda. Their efficient and cheerful handling of so much of the drudgery that was involved in the work on which this book is based will always be deeply appreciated.

ROBERT P. GRANT

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Theory and Methods in Vector Electrocardiography

The Electrical Energy of the Heart

The electrical energy which produces the electrocardiographic deflection is caused by the movement of charged particles across the membranes of the myocardial cells. Such a movement of charged particles constitutes a flow of electrical current. In biological systems the charged particles forming the current are ions, whereas in other more familiar electrical systems the charged particles are electrons. The flow of ions is under a "head of pressure," just as the flow of water in a water-supply system is under a head of pressure. The pressure behind the flow of electrical current is called *electrical potential,* and this is the property of the electrical events in the heart which is responsible for the electrocardiographic deflection.

The flow of electrical current in the heart is confined to the microscopic environment of the membranes surrounding the myocardial cells and does not extend significantly outside the heart. However, the potential behind the current flow creates an electrical orientation throughout the body, in much the same way that a magnet sets up an invisible magnetic field around it. This electrical orientation is called the *electrical field* for that potential. It extends to the body surface, and it is this property of the electrical activity of the heart that makes it possible to record the electrical events of the heart from the surface of the body.

The galvanometer, which is the basic component of all electrocardiographs, measures the potential manifested at the body surface. It consists of a delicate string or other writing element suspended movably within a magnetic field. A wire extends from each

end of the string; one wire is called the positive electrode and the other the negative electrode. When the two electrodes are attached at different points on the body surface they form a *lead.* Since the two electrodes for the lead are at different locations in the electrical field of a given cardiac potential, they are at different points of electrical pressure produced by that potential. Therefore there is a minute flow of current through the electrodes and through the string in the galvanometer to equalize the difference in electrical pressure between the two electrodes; the amount of current flowing through the galvanometer is a precise function of the difference in electrical pressure at the two electrodes. With the string suspended in a magnetic field, the flow of current through the string causes it to deviate, and it is the photographed or otherwise recorded movement of the string at this moment which forms the deflection. Thus the electrocardiographic deflection is a measurement of the way in which the lead intercepts the electrical field of the cardiac potential.

A basic property of all living excitable cells is the semipermeability of the cellular membrane to ions. Because of the semipermeability, the anions and cations tend to become aligned on opposite sides of the membrane. When the ions are so aligned, the cell is called *polarized,* a state which is analogous to the accumulation of particles of opposite charge on the two plates of a condenser. If some factor suddenly reduces the semipermeability of the membrane, there is a rush of ions across the membrane, constituting a flow of current analogous to the "sparking" that takes place when a condenser is discharged. In excitable tissues this discharging is called *depolarization;* and in the heart and other muscle tissues it is this event which triggers the contractile mechanisms within the cell.

In the heart the pacemaker impulse released from the SA node rapidly spreads throughout the atria, causing depolarization of the atrial muscle. The potential generated by depolarization of the atria is recorded in the electrocardiogram as the *P wave.* After depolarizing the atria, the impulse enters the AV node and spreads down the conduction system of the ventricles, producing depolarization of the ventricular myocardium. The potential generated by ventricular depolarization is recorded in the electrocardiogram as the *QRS complex.* Immediately after depolarization, cellular metabo-

lism proceeds to repair the semipermeability of the membranes, and there is another, slower ion movement as the polarized state is restored. This process is called *repolarization*. The potentials generated by repolarization of atrial muscle are too small to be recorded in the body-surface electrocardiogram. Repolarization of ventricular muscle normally produces a large potential recorded in the electrocardiogram as the *T wave*.

The Cardiac Vectors

Since depolarization and repolarization are associated with the movement of a fixed number of electrical charges, the potentials generated by these processes must be measurable. The measurable properties of an electrical potential are its magnitude and its direction. There is a very simple method for graphically indicating the magnitude and direction of an electrical force or potential. This is by the use of a vector. Properly speaking, a vector is any quantity that has known magnitude and direction. Mechanical, electrical, chemical, and other forces can all be represented by vectors when their magnitudes and directions are known. The symbol for a vector resembles an arrow. The length of the arrow indicates the magnitude of the force, the direction or inclination of the arrow indicates the direction of the force, and the location of the caret, or arrowhead, indicates the "sense" of the force, which for electrical forces is the location of electrical positivity.

When the electrical forces of the heart are represented by vectors, it becomes quite easy to explain the relationship between the deflection written in the electrocardiogram and the electrical activity taking place in the heart. The hypothetical line joining the sites on the body surface where the two electrodes for a given lead are placed is called the *axis* for that lead. Briefly, the electrocardiographic deflection is a measurement of the projection of the cardiac vector on the axis of the given lead. To explain this definition in a little more detail, the projection (or component, as the physicist would call it) of a vector on a lead is simply the extent to which the vector is parallel with the axis of the lead. An easy way to look at this is to consider the projection of a vector as its "shadow" on the lead axis when there is a light source perpendicular to the axis

of the lead. The electrocardiographic deflection is a measurement of the size of the "shadow." In Fig. 1 is shown a vector with three different directions relative to the lead axis and the deflection which the lead would record for each. In the upper example the vector is *perpendicular* to the lead axis; it can be seen that under these circumstances the vector casts no "shadow" on the axis of the lead, and the lead therefore records no deflection from the vector. When the vector has another direction, as in the middle example, the size of the "shadow" depends upon the particular direction of the vector. In the lower example the vector is *parallel* with the lead axis; and, as can be seen, the "shadow" (and therefore the deflection) is the largest possible under these circumstances.

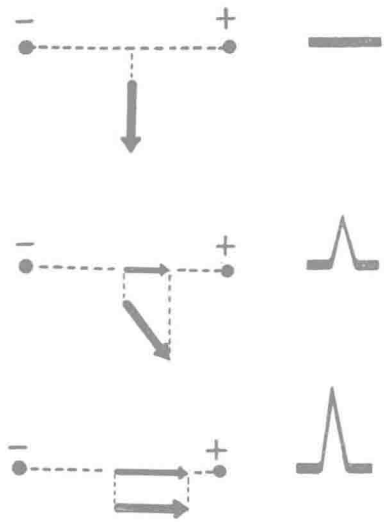

FIG. 1. The electrocardiographic deflection as a measurement of a vector. The dotted line represents the axis of the lead. The arrow drawn on the axis is the projection of the vector on that lead axis. The deflection in a given lead is an accurate measurement of the magnitude of the projection of the vector on the axis for that lead. Note that when the vector is *perpendicular* to the lead axis, there is no projection, and the galvanometer records no deflection. On the other hand, when the vector is *parallel* with the lead axis the projection has its maximal magnitude.

The galvanometer is so built that when the "shadow" points toward the positive electrode of the lead the deflection is positive or upright, and when the "shadow" points toward the negative electrode the deflection is negative or inverted. In summary, the amplitude of the deflection in a given lead and whether it is upright or inverted is an accurate measurement of the projection of the vector on the axis of that lead. In the next section we will consider the characteristics of the P, QRS, and T vectors generated by the heart, and then we will be able to see how the P, QRS, and T deflections on the various leads of the clinical tracing are simply measurements of projections of these vectors.

The Instant-to-instant Electrical Events in the Heart

Depolarization and repolarization spread through the ventricles in such a way that at each region QRS and T vectors can be considered to be directed from endocardium to epicardium. Of course not all regions of the heart are undergoing depolarization or repolarization at the same instant. Both processes spread from one region of the heart to another during a single QRS or T cycle. However, at any single instant during either the QRS or T cycles, the galvanometer records the sum of all electrical activity taking place at that instant as if there were but a single electrical force or vector responsible for it. This vector is called an *instantaneous* resultant vector.

For simplicity's sake let us assume that the first region of the ventricles to undergo depolarization is the left side of the septum. The resultant of the electrical activity during this first instant is shown by vector 1 in Fig. 2*A*. An instant later, depolarization will have spread to other regions of the ventricles, and the resultant QRS vector at this instant will have another magnitude and direction, perhaps like that shown by vector 2 in the diagram. At each subsequent instant during the QRS cycle, with different regions of the heart becoming depolarized, the resultant vector for each instant will have a different magnitude and direction and effective origin, as shown by the later vectors in the diagram. Thus depolarization of the ventricles is recorded by the galvanometer as if there were a series of single instantaneous QRS vectors of successively changing magnitude, direction, and origin, one for each instant during the QRS cycle.* A similar sequence of resultant instantaneous vectors is generated during the P interval and during the T interval.

The galvanometer records the instantaneous resultant vectors as though they were all generated from the same point at the center of the chest. The instantaneous vectors are redrawn in Fig. 2*B* as the galvanometer sees them, all arising from the same zero point. Drawn this way, the simplest method for indicating the change in magnitude and direction of the QRS vectors from instant to instant is to draw a continuous line through their termini, as

* Of course, the resultant vector at a given instant may have any direction in three-dimensional space; for simplicity only the frontal plane projections of the spatial vectors are shown in the diagrams.

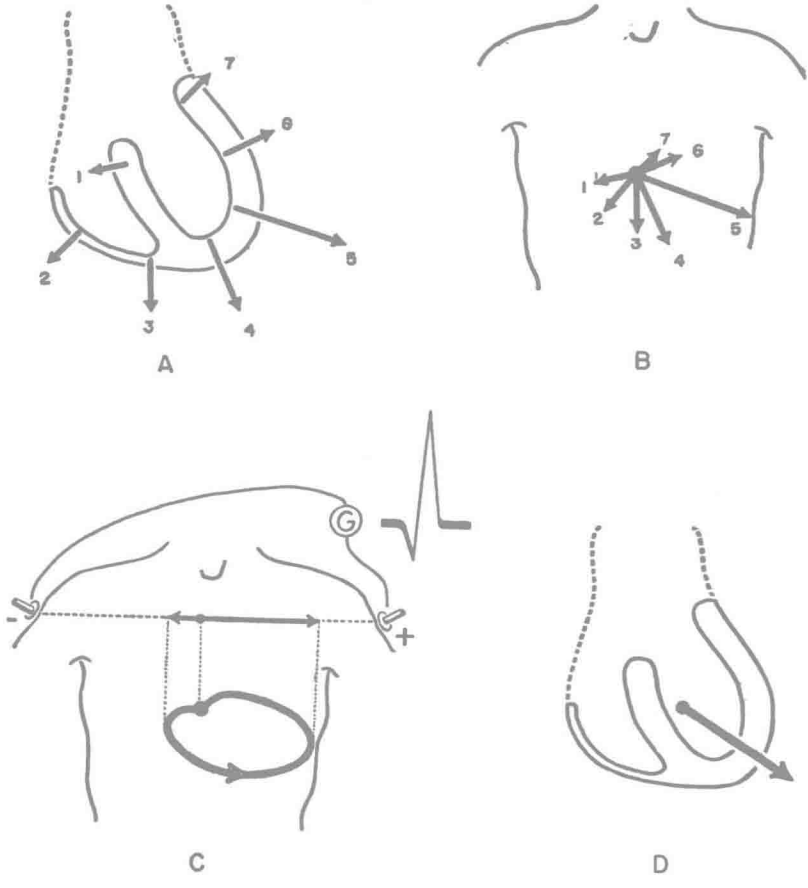

FIG. 2. Instantaneous QRS vectors. *A*. The instantaneous vectors are numbered in the sequence in which they are generated during a single QRS cycle. Each vector is perpendicular to the region of the heart undergoing activation at that instant. *B*. The same vectors drawn as if they all arose from the same point at the center of the body, which is the way the galvanometer "sees" them. *C*. A line is drawn through the termini of the instantaneous vectors in *B* with an arrowhead to indicate their sequence. This is called the *QRS loop*. The QRS complex written by the galvanometer is a measurement of the projection of the QRS loop on the axis of the lead indicated by the dotted line. *D*. The mean QRS vector, the resultant of all instantaneous vectors of a single QRS cycle.

shown in Fig. 2*C*. This line defines the sequence of change in magnitude and direction of the resultant instantaneous QRS vectors. The arrowhead on the line indicates the sequence in which the vectors are generated. For QRS forces, this line is called the *QRS loop* or *QRS vectorcardiogram.* There are also a *P loop* defining the sequences of instantaneous vectors during atrial depolarization, and a *T loop* defining the sequences of instantaneous forces during ventricular repolarization.

In Fig. 2*C* is also shown the way in which the projection, or "shadow," of the QRS loop on a given lead axis accounts for the particular amplitude and contour of the QRS complex on that lead. It can be seen that the very first forces during the QRS cycle have small "shadows" on the lead axis pointing toward the negative electrode of the lead. Therefore, the first part of the QRS complex is a small negative wave, a Q wave. The resultant vector is more or less perpendicular to the lead axis at the time vector 3 of the QRS loop is generated. No "shadow" is cast on the lead axis when the vector has this direction, and the deflection returns to the baseline at that instant, terminating the Q wave. Succeeding instantaneous vectors project larger and larger "shadows" on the lead axis, all of them pointing toward the positive electrode. Therefore, a positive deflection (an R wave) follows the Q wave. The maximal amplitude of the R wave is written at the time of the fifth vector, for at this instant the "shadow" of the QRS loop on the lead axis is largest. Later vectors write smaller and smaller positive components to the R wave as it returns to the baseline.

It is often useful in clinical interpretation to consider the average direction of all vectors during the P, QRS, or T interval. Such an average vector is called a *mean* vector (Fig. 2*D*); the method for measuring it will be described shortly. There are certain cardiac abnormalities which tend to affect only early QRS forces and other abnormalities which alter only later QRS vectors. Therefore, it is also useful to divide the QRS interval in half and to study the average direction of QRS vectors for the first half separately from the vectors generated during the second half of the QRS interval. The former is called the *mean initial* 0.04 *vector* and the latter is called the *mean terminal* 0.04 *vector;* the method for plotting these vectors will also be described later.

With this understanding of the relationship between the deflection

and the electrical forces generated by the heart, the electrocardiogram can be defined very simply. An electrocardiographic deflection is the measurement of instant-to-instant changes in magnitude and direction of the resultant electrical forces of the heart as manifested at the body surface. The deflections on the various leads have different contours because, with the axis for each lead having a different direction in the body, the projections of the vectors on the various lead axes are different. Therefore the various leads used in clinical electrocardiography can be looked at as simply so many different points of vantage for measuring the vectors generated by the heart.

Measuring the Cardiac Vectors

Since the heart is a three-dimensional organ, the resultant vectors may have any direction in three-dimensional space. The most rational method for electrocardiographic interpretation would be to use the deflections of the various leads as measurements of the three-dimensional, or spatial, properties of resultant vectors and base the interpretation on the characteristics of these vectors.

Earlier it was shown that the deflection on a given lead is a measurement of the projection of the resultant vector on that lead axis. From this, one might expect that it would be quite simple to measure the spatial magnitudes and directions of the cardiac vectors from body-surface leads. All one would need would be three leads: one in the horizontal plane of the body, another in the vertical plane, and a third in the anterior-posterior plane. These three leads would represent three axes in the three dimensions of space. The amplitudes of the deflections on each of the three leads would be plotted on a reference figure consisting of three axes at right angles to each other, one representing each lead. By dropping perpendiculars from the three plots and obtaining the point where the three perpendiculars intersected, one would define the terminus of the vector in three-dimensional space. In this way the magnitude and direction of the cardiac vector in space could be determined.

This approach to the spatial characteristics of the cardiac vectors cannot be used, which is unfortunate, for it would have greatly simplified clinical electrocardiography, requiring only three leads instead of the twelve leads commonly used. The explanation of why it cannot be used will help to make clear many of the properties