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Vectorcardiography

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THE CONCEPT of the vectorcardiogram was first stated by Mann\(^1\) in 1920. He obtained the trace by manually plotting several successive instantaneous vectors from the standard leads of the electrocardiogram by the method described by Einthoven, Fahr, and de Waart\(^2\) in 1913 for determination of the mean manifest potential. This was accomplished by plotting vectors determined from points considered to be simultaneous on the QRS complexes of two of the standard leads of the conventionally recorded electrocardiogram. A trace was then made which began at the origin of the plot and coursed through the termini of the successive instantaneous vectors and ended at the origin of the plot after passing through the terminus of the vector which appeared last in time in the series. Because this trace incorporated data from several leads of the electrocardiogram into a single “loop,” Mann called it the “Monocardiogram.”

This method of manual construction of the monocardiogram was applied to the waves of auricular depolarization (P waves), waves of ventricular depolarization (QRS complexes) and waves of ventricular repolarization (T waves). Because the resultant traces were all loops of variable shapes, the traces were referred to as P loops, QRS loops and T loops. As is known from the concepts of spatial orientations of the vector quantities, these were projections of spatial loops upon the frontal plane. In fact, Bayley\(^3\) attempted to standardize nomenclature and symbolic representation of the spatially oriented loops by introducing \(s\) into the symbols for the loops, \(E\) to indicate electric quantities of vectorial (\(\pm\)) nature and the “\(s\)” to indicate that these are spatial in orientation. Therefore, today, \(P\) \(sE\)-loop, \(QRS\) \(sE\)-loop and \(T\) \(sE\)-loop indicate the loops as they appear oriented in space, and \(P\) \(E\)-loop, \(QRS\) \(E\)-loop and \(T\) \(E\)-loop indicate the frontal plane projections of the respective spatial loops, unless otherwise stated.

It is of interest to mention that Fahr,\(^4\) using a method of vector analysis, recognized the error in identification of right and left bundle branch currents at that time. These observations, which were later confirmed by Barker, Macleod, and Alexander,\(^5\) provide an early example of the usefulness of vector methods applied to the electrocardiogram.

The manual method of obtaining the monocardiograms graphically was tedious and inaccurate. Mann, therefore, attempted to employ the cathode ray oscilloscope to obtain “monocardiograms” directly but found the cathode ray tubes of that time unsatisfactory for the purpose. He then constructed an ingenious three-coil galvanometer capable of responding to the potential differences of the three standard leads simultaneously.\(^6\) Despite the inevitable mechanical limitations of such an instrument, it was successfully employed to obtain direct recordings. Probably because of the difficulties of manual graphing and the difficulties of mechanical or automatic recording, the monocardiogram was ignored by most observers for many years. Then successful use of the cathode ray oscilloscope for automatic recording was reported by Schellong\(^7\) in 1936.
and by Hollmann and Hollmann in 1937 and Wilson and Johnston in 1938. Wilson and Johnston suggested the name vectorcardiogram as more descriptive than “monocardiogram.”

Following introduction of the use of the cathode ray oscilloscope to record the vectorcardiogram, there was little study of such records for several years. Interest has revived during the past few years as an inevitable result of the trends in electrocardiographic research and because of greater availability of suitable apparatus. Notable improvement in the design and construction of both cathode ray tubes and the necessary vacuum tube amplifiers has been made since 1937. Study of the vectorcardiogram has developed with vigor recently because of growing recognition that spatial analysis of the electric phenomena associated with the heartbeat is likely to yield information not furnished by the conventionally recorded electrocardiogram.

As indicated previously, Mann employed the method of vector plotting introduced by Einthoven, Fahr and de Waart and later used by Williams for obtaining the “vector diagram.” This method employs the equilateral triangle of Einthoven as the reference system and results in a trace of the projection of the spatial vectorcardiogram upon the frontal plane. Mann later suggested that electrocardiographic leads be taken from appropriate electrode sites to allow plotting a “transverse monocardiogram,” in effect a projection of the spatial vectorcardiogram upon a transverse plane. Arrighi made observations with leads from electrode sites defining a three-dimensional reference frame, and Wilson, Johnston and Kossman introduced the equilateral tetrahedron as a spatial reference frame.

During the past five years the number of reports of both basic and clinical studies relating to the vectorcardiogram has increased. The studies are too extensive to permit a complete review in this presentation. Among the many observations are those by Duchosal and Sulzer, Schellong, Vastesaeger and Roget, Burch and collaborators, Burger and van Milaan, Donzelot and Milovanovich, Den Boer, Jouve and co-workers, Milnor and co-workers, and Grishman and Scherlis. Selected references to the observations made by these workers and others will be cited in the remainder of this text.

Methods in Vectorcardiography

Graphic construction from electrocardiographic leads and use of the cathode ray oscilloscope constitute the two main methods in use today to obtain the vectorcardiogram. There is no doubt that the latter is the method of choice. Construction of vectors from leads of the electrocardiogram, even when they are recorded simultaneously, is subject to considerable error. It has been shown by oscillographic recordings that shifting the time phase of two electrocardiographic leads by as little as 1 millisecond may appreciably alter the contour of a normal vectorcardiogram resulting from the same set of potential differences and may actually change the direction of inscription of a plane projection of a QRS sF-loop of normal duration. Since the temporal scale conventionally employed in electrocardiography does not permit distinction of such small intervals, vectorcardiograms derived by manual graphing from electrocardiograms are likely to be erroneous. Vectorcardiograms derived from electrocardiographic leads which are not simultaneously recorded are obviously subject to even greater error.

The use of precordial leads of the electrocardiogram to indicate the direction of spatial vectors, whether they be successively obtained from a single complex to record a spatial vectorcardiogram or from average values of complexes to obtain a spatial mean electric potential, introduces possible errors related to the proximity of the exploring electrode in addition to errors in construction described in the preceding paragraph. This is considered in greater detail under the discussion of the relation of the electrocardiogram to the spatial vectorcardiogram.

Methods of Recording. Details of the methods for recording the vectorcardiogram will not be presented here. The preferred methods involve the use of the cathode ray oscilloscope as the recording “galvanometer.” Techniques differ, depending on the amplifier circuits, photographic equipment, reference frame, and special
switching devices for automatic recording of selected aspects of the trace which are employed. Although suitable cathode ray oscilloscopes exist, there is room for considerable improvement in electric circuits, in simplification of procedures of photography, and in interpretation of recordings. Detailed information of accomplishments existing today may be obtained by consulting the original publications.

Permanent recordings of the trace impressed upon the screen of the cathode ray oscilloscope may be obtained by photographic technics. The usual practice involves photographing plane projections of the vectorcardiogram of a single cardiac cycle. A 35 mm. camera and film are satisfactory. Although larger film has many advantages, its cost is proportionately greater. By means of suitable switches and other devices it is possible to record automatically any selected portion of the vectorcardiogram or successive complexes with automatic advancement of the film in the camera, to make a continuous recording on moving film or to make cinegraphic recordings. The advantages of these and other special photographic procedures are obvious.

Unfortunately, temporal characteristics of vectorcardiographic phenomena are inadequately recorded by the methods commonly employed in this country. Continuously moving photographic film or paper as reported by Donzelot and Milovanovich28 may permit adequate recording of temporal data. At present it seems that if vectorcardiography is ever to attain as extensive application in clinical cardiology as electrocardiography, the registration of time in the records must be greatly improved.

The cathode ray beam may be interrupted by means of an oscillator circuit, which results in a trace consisting of a broken line. Each segment of the trace represents a given time interval, such as 1/600 second. The interruption may be of such nature that the segments of the trace are comet-shaped, with the blunt end in the direction of rotation. This permits easy identification of the direction of rotation. Because the trace may move slowly during parts of the cardiac cycle, especially during inscription of the P and T loops and those portions of the QRS loop near the isoelectric point, timing by means of an interrupted beam without use of continuously moving photographic film or paper is difficult and usually imperfect by this technic.

The vectorcardiogram obtained by methods generally employed today not only fails to record intervals between the various loops of the vectorcardiograms but also fails to indicate those cardiac mechanisms whose recognition requires recording of the electric events of many consecutive cardiac cycles. The use of continuously moving photographic film or paper results in a series of connected scrolls which indicate in a complex fashion voltage variations with time. This method has the additional advantage of clearly indicating the direction of inscription of the component loops. Visualization of the data in space presents special problems, however. Despite this limitation, the method deserves further study.

Stereoscopic recording directly from cathode ray tubes by photographic methods is a promising method of approaching the study of spatial vectorcardiograms. Direct visualization of three-dimensional relationships has obvious advantages over study of plane projections alone. To date three schemes have been utilized to obtain such records. Vastesaeger and Rochet15 placed electrodes on the shoulders in such a manner as to define two plane projections tilted out of the frontal plane, each recorded on separate oscillographic screens. When these were viewed through a stereoscope, a single stereoscopic image was seen. A somewhat similar method was reported by Cronvich and associates,22 but the rotation out of the frontal plane was accomplished by a simple electric network, thus eliminating the need for placement of additional electrodes and its possible attendant errors. Schmitt24 has also employed electric circuits to achieve stereoscopic recordings of the spatial vectorcardiogram. By means of special circuits, he was able to view the spatial vectorcardiogram stereoscopically from many selected vantage points. Because of the relatively complex electric circuits, Schmitt's method is unlikely to receive general application at present,
especially since the same information may be obtained with less complex apparatus and circuit arrangements.

Reference Frames

Although there is general accord that study of the electric events associated with the heartbeat in planes other than the frontal is likely to be profitable, there is little agreement concerning the placement of electrodes to define such planes. In one of the earliest studies of "spatial vectorcardiography" Savyaloff placed electrodes at selected points on the body to obtain the projections of the spatial vectors on a transverse plane. Arrighi used electrodes at still different sites to define a three-dimensional reference frame. The equilateral tetrahedron is employed as a spatial reference frame by placing electrodes on the forearms, the left leg, and the back. Rectangular or cubic reference frames, employed by some observers, are defined by means of electrodes placed at selected points on the trunk. The original publications should be consulted for details concerning electrode placements and polarity arrangements.

Considerable error is inherent in all reference systems applied to the human body. Their use necessitates several assumptions which are known to be untrue but which apply satisfactorily within clinically and experimentally defined limits. The human body is not a tetrahedron, rectangular parallelepiped or cube, nor is it a homogeneous conductor. The heart is not a point source of potential. Although it is possible in a given subject to make satisfactory corrections or allowances for some of these "deficiencies" of the human body, the existence of these difficulties must always be remembered. Burger and his associates and Wilson and co-workers have attempted to correct some of these difficulties by the tedious process of introducing suitable resistances in the leads, but it does not appear that such elaborate methods are practical except for special circumstances. Since no planar or spatial reference system can be applied to the human body without some intrinsic error, the choice among them must be based partially on other considerations. The selection of a spatial reference system must, therefore, be the result of adequate considerations of the advantages and disadvantages of the various possibilities available. Claims of merit of some systems and claims of disadvantages of others have been advanced by various workers. At the present time there are insufficient data to evaluate these claims adequately. Since different groups of investigators employ different reference frames, it is difficult to compare results. In some respects this practice may delay progress, but in others it may be of benefit to the fundamental development of vectorcardiography.

It is contended that spatial vectorcardiograms recorded with the rectangular and cubic systems of electrode placement conform more closely to the configurations predicted from the precordial leads than do those recorded with the tetrahedral reference frame. If this is true, it implies that the precordial lead electrode positions are as remote as the electrode positions which comprise the spatial reference frame. This is in disagreement with the concept of Wilson and associates, whose experiments indicated that the electrode positions employed for precordial leads act as "semidirect" rather than remote points with respect to the heart. It is our opinion that available evidence indicates that the detailed form of the precordial leads cannot be derived from vectorcardiograms recorded with any reference system composed of remote electrode positions.

There is no doubt that it is advantageous, at least at present, to be able to compare vectorcardiograms and electrocardiograms, but there is no convincing evidence that this is particularly applicable to vectorcardiograms recorded by rectangularly shaped spatial reference frames. The rectangular parallelepiped and cubic spatial reference systems of lead placement have the disadvantage of requiring several electrodes on the trunk, which is more inconvenient and somewhat less reproducible than the placement of electrodes on the extremities.

The placement of electrodes to define a tetrahedron has the advantage of utilizing the limbs for three of the electrodes. This is advantageous not only because of greater convenience and reproducibility of electrode
positions but also because those electrode sites which define the frontal plane, constituting the well-known and important equilateral triangle of Einthoven, are the same as those from which the standard electrocardiographic leads are recorded. This is of considerable importance, since it means much general information about both normal and abnormal vector cardiograms can be obtained from the extensive knowledge already existing in electrocardiography. It seems desirable to exploit all available knowledge to orient vector cardiography in the field of experimental and clinical cardiology.

The equilateral tetrahedron, therefore, has one more electrode position which is different from those already employed routinely for recording the standard limb leads in electrocardiography. This electrode is placed on the back of the thorax, 3 cm. to the left of the spinous process of the seventh dorsal vertebra. The same electrode positions may be considered to define an isosceles tetrahedron. The difference in the two systems lies in the assumption concerning the location of the center of the dipole representing the electric activity of the heart. The four faces of the equilateral tetrahedron are assumed to be equilateral triangles, each side and each plane surface being treated in the same fashion that the frontal plane equilateral triangle of Einthoven is applied in clinical and theoretic electrocardiography today. The advantages of this reference system have been described and discussed in detail elsewhere.32

The Relationships of the Electrocardiogram and the Vectorcardiogram

Even though much general information about the form of the vector cardiograms can be inferred from electrocardiograms and vice versa, there are definite differences in the data each presents directly. The electrocardiogram presents scalar quantities, that is, magnitude and sense are represented. The vector cardiogram presents vector quantities directly, that is, direction, magnitude and sense are indicated. Vector quantities can, of course, be derived from two or more electrocardiographic leads, but unless a greatly expanded time scale and simultaneous and satisfactory recording of the leads are used, they are only gross approximations of those indicated directly by the cathode ray tube. Therefore, even though the standard electrocardiographic leads and the frontal plane projection of the spatial vector cardiograms are recorded from the same electrode sites, the form of the spatial vectorcardiogram cannot be accurately derived from the electrocardiogram unless two of the leads are recorded simultaneously and at a much higher film speed than is commonly employed. Thus, even plane projections of the spatial vectorcardiogram contain data which are not available in the electrocardiogram. Whether or not the additional information furnished by the spatial vector cardiogram will prove to be clinically useful is not yet evident. It does provide information of considerable value for understanding the fundamental principles of the electric events associated with the heartbeat.

Relation of the Spatial Vectorcardiogram to the Precordial Leads

In the past the precordial leads have been utilized to a limited extent in conjunction with the limb leads to indicate the spatial orientation of the mean electric activity associated with the heartbeat. More recently attempts have been made to extend this type of correlation. Data have been reported to indicate that the same information furnished by the precordial leads is evident in the spatial vector cardiogram. In fact, it has been stated that the information contained in all electrocardiographic leads may be furnished by the spatial vector cardiogram. This opinion seems at variance with the concept of Wilson37 that "the potential variations of a precordial electrode are determined to a very large extent by the potential variations of the elements of ventricular surface nearest it." Evidence for the latter statement was furnished by Wilson's experiments, in which direct leads were compared with precordial leads and found to vary in magnitude but to have similar form. Because of this and other observations, he considered precordial leads as "semidirect" leads, dis-
tistinguishing them from leads derived from points more distant from the heart. The concept of semidirect leads has been clinically useful in electrocardiography, as evidenced by the identification and localization of anterior myocardial lesions which are not reflected in a recognizable form in leads recorded from electrodes located at more distant points on the body.

It is evident that any contention that electrocardiographic or vectorcardiographic records of the electric events associated with the heartbeat, even though recorded from different electrode positions, are not significantly different from each other must logically indicate that the electrode positions are not significantly different. Furthermore, if the electrode positions are not significantly different, then the potential variations at the respective electrode positions must be correspondingly similar. If all the precordial leads are obtainable from vectorcardiograms obtained with the cubic, rectangular, or tetrahedral reference frames, then the precordial electrode positions for all the precordial leads must be equally remote. Experience with the precordial leads in conventional electrocardiography does not bear out such contentions. At present it seems reasonable to state that although it is possible that the spatial vectorcardiogram contains some of the information contained in the precordial leads, differences must exist because of electrode positions.

LIMITATIONS OF THE VECTORCARDIOGRAM

Although the range of experimental and clinical usefulness of the vectorcardiogram has not yet been defined, it is apparent that certain limitations exist. For example, temporal characteristics, as previously mentioned, are not adequately recorded. With recording methods commonly employed, the duration of complexes is imperfectly registered, and the intervals between loops or complexes as well as the cardiac mechanism are not shown at all. These deficiencies can be overcome by recording on moving film, but the advantages of a single three-dimensional representation of the electric phenomena of the cardiac cycle are then lost. The probability that semidirect electrocardio-

graphic leads provide information which cannot be obtained from the spatial vectorcardiogram constitutes another limitation of the vectorcardiogram. These considerations indicate that if the spatial vectorcardiogram is to have clinical usefulness in the near future, it will be in the role of a supplement to the conventional electrocardiogram. The original papers may be consulted for further details of the possible applications and limitations of spatial vectorcardiography to experimental and clinical cardiology.

THE SPATIAL VECTORCARDIOGRAM AND CONVENTIONAL ELECTROCARDIOGRAM AND CLINICAL STATES

No good purpose would be served by a description of the spatial vectorcardiographic configurations and orientations for normal and abnormal states, primarily because they would differ for each of the spatial reference frames employed in recording. The reader must, therefore, consult the original papers to obtain such data, remembering always that, although there is some correspondence, the patterns hold only for the reference system employed. Obviously, there must be standardization of electrode positions in vectorcardiography.

We have employed the equilateral tetrahedron as the spatial reference frame for reasons reported in detail elsewhere. Our studies of clinical cardiologic states have indicated that:

(1) The spatial vectorcardiograms of normal young adults were of two main types or patterns. The majority, 88 per cent, of normal QRS sF-loops had a smooth elliptoid configuration in which the width was less than one-third the length, and the majority of the area enclosed lay anterior to the iso-electric point. For purposes of description, these loops have been labeled as "type 1." The remaining 12 per cent had a more complex configuration classified as "type 2" and characterized by the enclosure of a wider total area and a larger area behind the isolectric point than in the "type 1" records. Most normal T sF-loops also had an elliptoid form, but in a few instances a roughly circular form was encountered. The wide variations of the various plane projections of the spatial vectorcardiogram were due not
to large differences in the spatial vectorcardiograms among individuals but to differences in spatial orientation of two easily identifiable fundamental patterns. Other rarer patterns may exist, since only several hundred normal subjects of a narrow age group have been studied. Furthermore, the fact that only a small number (only two defined to date) of fundamental spatial vectocardiographic patterns exists suggests that (a) the orders of depolarization and repolarization of the heart of man are similar, or that (b) the extracardiac tissues which influence and determine the electric fields around the heart are fundamentally similar, or that (c) both of these phenomena are true. That these phenomena may be genetically controlled is an important possibility deserving study.

(2) The spatial vectocardiograms in right and left ventricular hypertrophy were characteristic. The pattern of hypertrophy of the right or left ventricle could be identified even in the presence of complete right or left bundle branch block. Hypertrophy could be recognized with greater certainty from the vectocardiogram than from the conventional electrocardiogram. Many more recordings with postmortem correlations will be needed before the reliability of spatial vectocardiography can be fully evaluated in the diagnosis of right or left ventricular hypertrophy, especially when it is slight in amount and not detectable roentgenologically or by other clinical means.

(3) The spatial vectocardiograms of complete right or left bundle branch block and of myocardial infarction in various areas of the heart were of a sort already predicted from conventional electrocardiographic leads. The initial portion of the QRS sE-loop was spatially oriented as already known from electrocardiograms. Much more extensive study of bundle branch block and myocardial infarction is required before the value of spatial vectocardiography in these states can be determined. Thus far it has not been shown to offer any advantages in these states alone. It appears that the presence of right and left ventricular hypertrophy with these three cardiac states may be detected more readily by vectocardiography alone than by electrocardiography alone.

(4) Many more studies with adequate post-mortem examinations are necessary before vectocardiography can be considered clinically useful. At present it remains an experimental procedure.

**Summary**

Both theoretic considerations and actual studies suggest that spatial vectocardiography will eventually have practical applications. It is likely to furnish clinically useful information in addition to that provided by conventional electrocardiography. This is a statement of probability, however, and has not yet been established, nor have the circumstances in which it may apply yet been defined. For this reason the current status of vectocardiography is properly that of a research method, not yet suitable for general clinical application.

Many technics have been employed to obtain the vectocardiogram. The graphic derivation of vectocardiograms from electrocardiographic leads is of historic interest only. The use of the cathode ray oscilloscope with suitable amplifiers is the method of choice. Many modifications of technic, such as recording on moving film, recording of successive complexes, and stereoscopic recording, are possible with the use of the cathode ray oscilloscope. It is not yet apparent which recording technic will prove to be most informative, so that studies with a variety of technics seem advisable.

Several systems of electrode placement have been advocated for obtaining the spatial vectocardiogram. Since the application of any geometric reference frame to the human body necessitates several assumptions which are not actually true, it appears that the choice among reference frames cannot be made on the basis of their intrinsic validity. We are of the opinion that the equilateral tetrahedron introduced by Wilson and associates offers advantages over other reference frames because:

(1) Only one electrode is necessary in addition to those employed to obtain the standard electrocardiographic leads.
(2) Electrodes are easily applied, and their positions are readily reproducible.

(3) The knowledge already available from experience with the standard leads of the electrocardiogram may be applied to spatial vectorcardiography.

(4) Each of the four surfaces defined by the electrode positions is an equilateral triangle.

(5) The disadvantages of this reference system are common to those of other proposed reference frames.

Variations of the spatial vectorcardiogram in normal man and in man with a variety of disease states have been studied by several groups of investigators with a variety of technics. These studies are of considerable importance, but as yet nearly all lack pathologic confirmation of the presence, site and size of suspected lesions. These data must be obtained and thoroughly correlated with the vectorcardiogram before vectorcardiography can be employed with certainty in general clinical practice.

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Vectorcardiography
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