Vectorcardiographic Assessments of the Surgical Results
Congenital Cardiovascular Malformations*

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Advances in theory and application of electrocardiography have been numerous since Waller's first successfully recorded human cardiac action potentials. Einthoven made several basic contributions, and his broad discussions of concepts and theory are still influential. The fundamental theoretic basis of vectorcardiography is the dipole theory, as proposed by him in collaboration with Fahr and de Waart. Its basic tenet is that the electrical field generated by cardiac activity behaves as though it were produced by a single battery with positive and negative poles in closest proximity, immersed in an essentially homogenous volume conductor of body fluids and tissues. Cardiac activation will cause the stimulated area to become relatively negative in comparison to the surrounding musculature, as yet not stimulated. Thus, across the boundary of the two, dipoles are in closest proximity to each other through the apposition of excited, negative muscular segments and the non-excited, resting non-negative musculature which is, therefore, relatively positive. The electric field created within the body represents an electromotive force and has three properties: magnitude, which depends on the size of the contributing components; direction, which is the axis along which the dipoles are oriented; and sense or polarity, which is the relative position of positive and negative poles to each other. Because it is a directed quantity, it is referred to as a vector quantity, in contradistinction to scalar quantities such as mass, volume and potentials which have no reference to direction. An arrow is employed to express a vector quantity. Its length indicates the force's

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magnitude, its orientation is coincident with the axis formed by the dipoles, and its tip points toward the positive side of the field. The last-named factor should be viewed as an arbitrary but uniform convention based on Einthoven's original suggestion.

As the excitation wave, predetermined by the anatomy of the bundle of His and Purkinje's fibers, spreads over the heart, innumerable segments will be discharged simultaneously. Only their composite or resultant effect can be measured with techniques applicable in human beings. This balance of forces at any instant is a result of the confluence of numerous elementary fields to one resultant field, of all elementary vectors to one resultant vector. The heart, which is three-dimensional, will have a three-dimensional distribution of its elementary vectors and, therefore, a three-dimensional or spatial orientation of its resultant vector. The cardiac vector is the spatial curve inscribed by the arrow tips of the spatial vectors of all instances of observation during one cycle. In the vector concept, it is assumed that all areas of the myocardium contribute to one electrical field and that this is the only substrate available to analysis, as none of them is available individually.

Electrocardiographic leads are derivatives or projections of the cardiac vector and are, therefore, interrelated. The present status of knowledge, gained through theoretic deduction and direct experimentation on human beings and animals, seems to corroborate the validity of Einthoven's original tenet that the electrical potentials created by cardiac activity can, for practical purposes, be represented by a single dipole. Experimental evidence that local or non-dipolar potentials are sometimes pre-

Figure 4: Normal vectorcardiogram. The QRS loop is mainly oriented to the left posteriorly and inferiorty. The direction of inscription in the horizontal plane is counterclockwise.

Figure 5: Normal vectorcardiogram in a normal infant. The QRS loop is oriented mainly anteriorly. The direction of inscription of the QRS loop in the horizontal plane is counterclockwise.
FIGURE 7: Preoperative vectorcardiogram in a patient with pulmonic stenosis. In the horizontal plane, the direction of inscription is clockwise. Notice that the initial segment is directed anteriorly giving origin to the RSR' QRS complex in the right precordial leads.

FIGURE 6: Vectorcardiogram in a patient with funnel chest. Notice the terminal portion of the QRS loop in the horizontal plane is directed posteriorly and to the right giving an RSR' QRS complex in right sided precordial leads. The direction of inscription in this plane is also counterclockwise.

sent has yet to be proved of clinical significance. At present, the dipole theory, and the vector concept on which it is based, adequately explain available facts about the electrical field created by cardiac activity. The techniques based upon it are applicable and logical. Great accuracy cannot always be achieved when a biologic substrate is analyzed, since variations of the latter often exceed the theoretic accuracy attempted. Those who criticize the dipole concept often fail to consider this fact.

Techniques used today for vectorcardiography are essentially of three types. The first is an extension of Einthoven's equilateral triangle to a three-dimensional scheme. This method, introduced by Wilson and associates, was first applied to clinical vectorcardiography by Burch and coworkers. With it, frontal and sagittal plane projections of the spatial cardiac vector are obtained. In the technique which is probably most widely used at present, and we have had more clinical experience, the electrodes are placed on the thorax in a rectangular coordinate fashion, and lead lines between them usually form the edges of a cube. In this cube technique, upon which the illustrations in this discussion are based, frontal, sagittal, and horizontal plane projections are recorded (Fig. 1). The relationship of the horizontal plane to unipolar chest leads and correlation of the sagittal plane leads to the esophageal leads and the
frontal plane projection to the six extremity leads (leads 1, 2, and 3, Vr, Rl, Vp) are seen in Figures 2 and 3.

The statement that the vectorcardiogram cannot yield more information than the electrocardiograms from which it is extracted is only partly correct. A lucid discussion of the subject is found not only in Einthoven's writings, but also in the classic paper of Williams, who first indicated the significance of phase relationships in electrocardiograms made at known geometric positions with respect to each other. A vector curve should be viewed as the graphic presentation of the phase (time) relationships of two such electrocardiographic leads. This information is not available from individually recorded electrocardiograms and must be calculated from tracings recorded simultaneously in appropriate combination. However, the required plotting technique is time-consuming and technically limited. For example, differences in phase relationships of less than 0.01 second cannot be measured. This effort is unnecessary if the same electrocardiographic signals are directly applied to a cathode ray oscilloscope, which computes the information accurately in the vectorcardiogram.

The revival of the vector concept and the introduction of vectorcardiography have profoundly influenced clinical electrocardiography. The unitary character of the vector concept and vectorcardiography, which is based upon it, facilitates a simple deductive mode of teaching clinical electrocardiography.

Vectorcardiographic differentiation of normal infants and children from those with right ventricular hypertrophy is simple. In infants older than two months of age, the direction of inscription of the horizontal vector loop is the same as that in adults (Fig. 4) but the orientation is somewhat more anterior. Thus, in infants more than two months old, a normal balance of forces can be identified. Cardiac displacement may create RSR' patterns in right-sided chest leads in the electrocardiogram. In congenital heart disease, most of these will be associated with right ventricular hypertrophy. However, more certain information is desirable. We have seen patients with funnel chests, in whom high R waves in right-sided chest leads were clearly identified by vectorcardiography as attributable to cardiac rotation. The vectorcardiogram reverted to normal following surgical relief of the deformity. Similarly, the most ready differentiation of right bundle branch block from right ventricular hypertrophy is made from the vectorcardiogram. Although in both conditions an RSR' pattern is seen in right-sided chest leads, the vectorcardiographic appearance is distinctly different. On the vectorcardiogram, right bundle branch block is characterized by a right anterior terminal appendage, often slowly inscribed and well identified in the horizontal plane projection. In right ventricular hypertrophy, a similar electrocardiographic

Figure B: Vectorcardiogram of right bundle branch block. Notice that the terminal segment is slowly inscribed and is directed anteriorly to the right giving the electrocardiogram an RSR' complex in V1. The initial and middle segments in the horizontal plane are counterclockwise.
projection can be produced by a clockwise-inscribed right anteriorly-placed vector loop. The vectorcardiographic separation is distinct and diagnostic.

Vectorcardiography is an adjunct to electrocardiography. Little additional information can be expected from further analyses of clinical electrocardiograms alone. For the best possible diagnostic accuracy, refinement of such analyses by different means is desirable, and in our own experience, the vector approach seems to furnish much information of clinical usefulness.

During the formative period of cardiac surgery, it is of utmost importance to have techniques available which can assess its results. Although cardiac catheterization and/or angiocardiography are the best information we can obtain, to utilize these techniques frequently has proved impractical because of the time factor involved and discomfort to the decreasing cooperation of the patient. Appraisal of surgical results by conventional radiography have proved rather disappointing. On the other hand, the serial electrocardiographic and vectorcardiographic data have proved particularly useful. As we will see in the discussion of follow-up studies in interatrial septal defect, pulmonic stenosis, A-V canal, and in part also ventricular septal defects, the vectorcardiogram is most useful because of its ability to unravel directly the background of a given RSR' configuration in V1.

Let us consider first isolated pulmonic valvular stenosis. During the period when the transventricular surgical approach of Sellors and Brock was followed, several facets of the surgical results were well illuminated by serial analysis of the electrocardiogram. It soon became apparent that even with adequate removal of the obstruction, therefore, from the surgical point of view satisfactory result, it sometimes took a year or more for the regression of the electrocardiographic and vectorcardiographic evidence for right ventricular hypertrophy. This in turn suggested that regression of muscular hypertrophy took an equally long time. Furthermore, at times what appeared to have been

Figure 9: Preoperative and postoperative vectorcardiograms in a patient with atrial septal defect. Notice that the vectorcardiogram became essentially normal seven months after surgery.
Vectorcardiographic Assessments

A successful surgical intervention, as judged from the determination of pressure gradients at the end of the procedure, may have been greatly misleading. In about 20-30 per cent of the cases, if one can judge from our own data, and from those published in the literature, the operation had to be regarded a failure because of the limited appreciation in years back that an associated infundibular, purely muscular obstruction requires adequate surgical provision. Here the informative comments and observations of Brock have been most important. In our experience, serial electrocardiograms and vectorcardiograms have been a critical guide appraising the surgical results without the necessity of repeated catheterizations. With good results obtained, the regression of symptoms, in the electrocardiograms and particularly in the vectorcardiogram as to the degree of right ventricular preponderance, was always dramatic. On the other hand, failure to abolish the right ventricular pulmonary arterial gradient effectively was equally well reflected in the clinical picture and in the electrocardiographic and vectorcardiographic data. On the basis of vectorcardiographic observations with no further regression apparent, a final appraisal of the dynamics through cardiac catheterization should be obtained. Although changes of spatial orientation proved significant, most important were the appearance of normal or almost normal QRS loops in the horizontal plane projection of the spatial vectorcardiogram. The transitional appearance of an RSR' configuration in V1 unipolar electrocardiograms does not indicate right ventricular conduction defects as postulated by some, presenting merely a lesser degree of right ventricular preponderance as shown by the vectorcardiogram. Counterclock-wise rotation with anterior displacement of the QRS loop in the horizontal plane projection has been seen in mild pulmonic stenosis and in the postoperative period in those with mild residual right ventricular pulmonary arterial gradients of 20-35 mm. Hg.

Atrial septal defect of the secundum type is one of the most common congenital lesions. Its surgical correction is direct and its results most satisfactory. Here, RSR' configurations in unipolar lead V1 can be seen with successful closure even in the absence of right ventricular preponderance or any ventricular conduction defect. As can be seen from serial records, the vectorcardiographic presentation of the electrical data avoids confusion in this respect. Occasionally a persistence of right ventricular preponderance pattern has been observed for an unusually long period after surgery. These invariably were severe cases of the secundum type with mild to moderate pressure gradients between the right ventricle and pulmonary artery in the absence of pulmonic valvular stenosis.

![Figure 10](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/21375/)

**Figure 10:** Preoperative vectorcardiogram in a patient with common A-V canal. The QRS loop in the sagittal and frontal planes is superiorly directed and the direction of inscription in the frontal plane is counterclockwise.
The different speed of regression as seen in pulmonic valvular stenosis, in comparison to ostium secundum, should make us view critically our time-honored concepts of ventricular hypertrophy. Whereas in pulmonic valvular stenosis concentric hypertrophy occurs due to the increased pressure requirements (systolic overloading of the right ventricle), in most patients with ostium secundum type of interatrial septal defect, no increase of right ventricular pressure is found. On the other hand, a marked increase of right ventricular chamber size and crista supraventricularis hypertrophy or localized hypertrophy will occur due to a marked increase of blood volume handled (outflow tract hypertrophy).

Although great similarity exists between the electrical data from either congenital defect, important thoughts arise as to their genesis. Whereas true muscular hypertrophy develops in pulmonic stenosis, distension and stretch of the right ventricle are the dynamic bases in ostium secundum (diastolic overloading of the right ventricle). Prolongation of the excitatory process over the right ventricle could theoretically occur either due to increased muscle mass and increased intramural pressure (systolic overload) or due to a stretch of the ventricular muscular wall due to increased volume handling requirements. The electrophysiologic result may be similar, although their anatomic basis differs. What has been referred to as the electro — or vectorcardiographic evidence for ventricular hypertrophy in the past and present has no relationship to what is referred to as conduction defects of “bundle branch block” variety. In the case of right bundle branch, the conduct defect only becomes evident through a delay of the termination of the right ventricular excitatory process. In left bundle branch block, similarly delayed excitation or abnormal sequence of stimulus propagation rather than diffuse slowing appears to be the electrophysiologic basis.

The superior orientation of the vectorial forces as seen in ostium primum and atrioventricular canal are of greatest diagnostic value. Our own experience concurs with the original observations of Toscano-Barbosa and colleagues.19 The nature of the
electrical findings nevertheless is still obscure. Although one might feel tempted to ascribe them to a combined hypertrophy of the left and right ventricle, this could hardly be the case in some cases of ostium primum, namely those without significant mitral valve involvement. Experience with this group of cases is somewhat limited, and we have observed normalization of the P-R, and P waves, disappearance of rsR' in V1, and regression from a typically superiorly oriented vector to a normal vectorcardiogram in only one patient with ostium primum with mitral valve involvement. In most others, appearance of the vectorcardiographic curves, and correspondingly the electrocardiogram remained essentially unaltered. In spite of this one exception, we feel that an abnormal interventricular conduction gives us the best possible explanation for the characteristic vectorcardiogram.

The necessity of a right ventricular tricuspidostomy for the total repair in tetralogy of Fallot and interventricular septal defect often creates right bundle branch block. Vectorcardiographic curves clearly help to distinguish between right bundle branch block and right ventricular hypertrophy. Furthermore, they allow the recognition of the return to a normal balance of forces for the main QRS complex with superimposed right bundle branch block and also the assessment of successful repair in cases of tetralogy of Fallot and severe forms of interventricular septal defects.

We have found the electrocardiogram and vectorcardiogram in serial records a reliable and simple tool for the postoperative assessment of cardiac surgery as to its success or failure. The correlation of the vectorcardiographic curves with dynamic data is of satisfactory accuracy. Because of the simplicity and the directness with which right ventricular preponderance is presented in the vectorcardiogram, we regard the information obtained from it as less problematic and therefore superior to the presentation of the electrical data by the electrocardiogram.

References