Ventricular Activation and the Vectorcardiogram in Bundle-Branch Blocks

Clinical and Experimental Studies with a Critical Appraisal of the Vectorcardiographic Methods of Frank and Grishman

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In recent years, several vectorcardiographic methods have been proposed.1-6 The methods of Frank' and Rijlant,5 which have far better physicomathematical bases, give curves that according to their authors represent the electrical field of the heart as generated by a single or equivalent dipole for each instant of the cardiac cycle. The curves obtained with the methods of Grishman,1 Wilson,3 and Duchosal4 are generally regarded as showing a certain degree of correspondence with the electrocardiographic curves.

In a previous publication from this laboratory,7 the relationship between the ventricular activation and the vectorcardiographic curve according to the method of Grishman was studied in normal cases and in one case of right bundle-branch block. The correlations were generally found to be satisfactory, although they probably could have been more so, according to Johnston,8 had a method different from Grishman's been evaluated.

This paper was planned to study the relationship between the equivalent dipole and the activation of the heart in clinical and experimental cases of right and left bundle-branch block. The observations were limited to the methods of Frank and Grishman, taken as representative of the two main groups of vectorcardiographic methods in use today.

Methods

Clinical Bundle-Branch Blocks

The electrocardiograms of right (RBBB) and left bundle-branch block (LBBB) were reviewed from the files of the department of electocardiography of the Instituto Nacional de Cardiología de México. Typical cases were selected, and in these, frontal and horizontal vectorcardiograms, according to the methods of Frank2 and Grishman,1 were recorded.

In cases of LBBB (fig. 1), three points were chosen in the frontal and horizontal vectorcardiograms of both methods. Point 1 corresponded to the end of the rapid portion of the QRS loop, point 2 corresponded to the peak, and point 3 to the end of the slurred portion of the loop.

In cases of RBBB (fig. 2), three points were also chosen in the vectorcardiographic loops of both methods. Point 1 corresponded to the end of the rapid portion of the QRS loop, which was directed from left to right, point 2 corresponded to the peak, and point 3 to the end of the slurred portion of the loop.

In all instances, after determining the locations of the points in the two planes, the magnitude and spatial orientation of the corresponding three vectors were calculated for both methods. Wooden sticks, cut a length proportional to each vector, were embedded in a wax ball and photographed (figs. 1 and 2). The directions of these three main vectors of ventricular activation in LBBB and RBBB for the methods of Frank and Grishman were then analyzed in light of our knowledge of the sequence of activation in bundle-branch blocks.9-14

Experimental Bundle-Branch Blocks

Frontal and horizontal vectorcardiograms according to the methods of Frank2 and Grishman1 were recorded in six mongrel dogs after the experimental production of either LBBB or RBBB.

Bundle-branch blocks were produced following the standard preparation and techniques of this laboratory.5,10 After obtaining the stabilization of the wanted degree of block, vectorcardiograms were recorded with the animal in the dorsal decubitus. Immediately afterwards, the thorax was widely opened and the heart exposed. An average of 26 epicardial points and five different endo-
BUNDLE-BRANCH BLOCK

The magnitude of the vectors of apparent maximum potential gradient was calculated from the algebraic differences of the values for the maximum positive and negative potentials. It is convenient to point out that, although the vectors of apparent maximum potential gradient cannot be identified with the vectors representing the dipolar component in Stratton's series (vide infra), there are mathematical reasons to suppose that the electrical axis (dipolar component) and the apparent maximum potential gradient vectors are approximately parallel.

The calculated vectorcardiographic curves from the vectors of instantaneous apparent maximum potential gradients were obtained according to the procedure published in a previous publication.7 The calculated curves were then compared with the curves obtained by the methods of Frank and Grishman.

The apparatus was a Dual-Beam DuMont type 322-A cathode-ray oscilloscope coupled with two Grass stimulators model S4 connected to the Z axes of the oscilloscope. The timing was set with stimul duration of 0.001 second at a rate of 500 (fig. 5) or 400 per second (fig. 8). Recording was made with a Grass C-4C high-speed camera, using film speeds of 250 mm./sec. Before being studied, the films were amplified three times.

Results

Clinical Bundle-Branch Blocks

Left Bundle-Branch Block

Figure 1 shows the electrocardiogram of a case with an advanced degree of LBBB. In the frontal plane AQRS is located around 0°, and AT around ±180°; in the horizontal plane AQRS is oriented to the left, and posteriorly at about -60°, and AT points to the opposite direction, i.e., right and anteriorly close to +120°.

In the same figure 1, the vectorcardiograms according to the methods of Frank and Grishman are also presented. The QRS loop in the frontal vectorcardiogram of Grishman is oriented approximately to 0°, and the T loop to ±180°, showing a good correlation with the axes of QRS and T calculated from the electrocardiogram. The QRS loop in the frontal plane of Frank is oriented toward +45°, and the T loop is close to ±180°, showing a correspondence with the peripheral electrocardiogram only for the T loop.

In regard to the horizontal plane, the cor-
Figure 1
Clinical case of LBBB. Electrocardiogram and vectorcardiograms in the frontal (above) and horizontal plane (below) according to the methods of Grishman and Frank. The three main vectors (1, 2, and 3) of ventricular activation calculated for each method are represented on the far right of the figure.

Relation between electrocardiogram and vectorcardiograms is better borne out by the method of Grishman, by which the QRS loop is seen to point toward -60° and the T loop toward +120°. By Frank’s method, the QRS loop is located around -80°, which does not account for the positive areas of the QRS complex in V5 and V6.

The three main vectors of left ventricular activation, as mentioned earlier, are represented for each method (fig. 1). Vectors 1 and 2, which correspond to the activation of the left septal mass, are oriented downward in both methods. This hardly correlates with the upward and leftward direction described for the septal activation in LBBB. Vector 3, which corresponds to the activation of the free left ventricular wall, appears to be horizontal in both vectorcardiographic curves. On the other hand, the peripheral electrocardiogram shows that, while vectors 1 and 2 are practically horizontal, vector 3 is oriented upward (S wave in VF), thus reflecting better the orientation of the potential variations of the septum and free left ventricular wall in the presence of LBBB. Frank’s method reflects less faithfully than Grishman’s the possible direction of ventricular activation, since vectors 1 and 2 are pointing more downwards.

Figure 2
Clinical case of RBBB. Electrocardiogram, vectorcardiograms according to the methods of Grishman and Frank, and the calculated vectors (1, 2, and 3) in the same order as in figure 1. (The electrocardiogram and the vectorcardiograms have been slightly retouched.)

Right Bundle-Branch Block

Figure 2 shows the electrocardiogram of a case with an advanced degree of RBBB. In the frontal plane, AQRS is located around +120°, and AT around -30°; in the horizontal plane, AQRS is oriented to the right and anteriorly at about +165°, and AT points mainly anteriorly.

Both vectorcardiographic curves (fig. 2) are similar in the frontal plane and correlate well with the orientation of AQRS calculated from the electrocardiogram. In the horizontal plane, Frank’s method reflects better than Grishman’s the position of AQRS around +165°.

The three main vectors of right ventricular activation are represented for each method (fig. 2). Vectors 1 and 2 correspond to the activation of the right septal mass and vector 3 to the activation of the free right ventricular wall. In both methods, vectors 1 and 3 are practically horizontal; in Frank’s method they point almost exclusively to the right, and in Grishman’s anteriorly as well. From previous investigations, it is known that vector 1 is nearly perpendicular to
the interventricular septum; consequently, in view of the usual anatomical position of the septum, vector 1 has to point to the right and anteriorly. It is evident that Frank's method does not correlate with the sense of activation of the interventricular septum. For vectors 2 and 3 both methods agree with our knowledge of the sequence of ventricular activation in RBBB.\textsuperscript{12, 14}

**Experimental Bundle-Branch Blocks**

*Left Bundle-Branch Block*

Figures 3 and 4 illustrate the most representative of three experiments. The maximum source and sink (fig. 3) and the corresponding calculated vectorcardiogram (fig. 4) are represented for every 0.008 second after the production of LBBB.

At 0.008 second before the beginning of QRS in lead 3 (fig. 3, scheme 1), the first site of maximum positivity is recorded at the mid-anterior epicardial surface of the right ventricle, and the site of maximum negativity is recorded at the mid-level of the right ventricular cavity.

At 0.00, 0.008, and 0.016 seconds after the beginning of QRS in lead 3, the sources are located in the high and lateral regions of the right ventricle (fig. 3, schemes 2 to 4), and the corresponding sinks are located inside for the first 0.008 second (fig. 3, schemes 2 and 3), and outside the right ventricle at 0.016 second (fig. 3, scheme 4).

At 0.024, 0.032, and 0.040 seconds (fig. 3, schemes 5 to 7), the maximum sources move abruptly to the high and anterior regions of the left ventricle, and the sinks move to the anterior and lateral regions of the right ventricle. Since we are actually exploring the "Gaussian potentials" (see footnote, page 1099), the sources and sinks recorded at the ventricular epicardial surfaces are referred to the activation of the interventricular septum in a right-to-left direction. In fact, at later times (0.048, 0.056, 0.064, and 0.072 seconds; fig. 3, schemes 8 to 11) new and greater sources of current are localized in the anterior wall of the left ventricle, where most of the sinks are also located.

The last source is registered in the posterolateral region of the left ventricle (fig. 3, scheme 12) at 0.080 second after the beginning of QRS in lead 3, and the corresponding sink is recorded in the low posterior region of the left ventricle.

The vectorcardiogram calculated from these maximum potential gradients and the actual curves obtained with the methods of Frank and Grishman are shown in figure 4.

A similarity between Frank's method and the calculated curve is seen only in the horizontal plane. Frank's frontal vectorcardiogram and both of Grishman's curves show no correspondence at all with the respective calculated curves. Moreover, it should be appreciated that all of the important forces due to early activation of the right ventricle (fig. 4, points 1 to 4) and some of the late forces of the left ventricle (fig. 4, points 10 to 12) are not recognized in the methods of Frank and Grishman as clearly as in the calculated vectorcardiogram.

It is of interest to note the great magnitude of the forces of the right ventricle, particularly of those corresponding to point 4 (fig.
4) in the frontal plane of the calculated vectorcardiogram. In theory, it is expected that these forces will be small, since it is hard to visualize a magnitude of this extent for right ventricular vectors in cases of LBBB. However, epicardial leads from the right ventricle show that the positivity recorded in the anterior region (fig. 5, section 1), as well as the negativity in the posterior region of the right ventricle (fig. 5, section 2), present a greater voltage than the positivity recorded over the left ventricle in subsequent intervals of the cardiac cycle (fig. 5, sections 3 and 4). Point 4 (fig. 4) in the frontal plane of the calculated vectorcardiogram is then explained by the strong vector of maximum potential gradient that goes from the greatest sink located in the low and posterior region of the right ventricle (fig. 3, scheme 4; fig. 5, section 2), toward the greatest source located in the high and anterior region of the right ventricle (fig. 3, scheme 4; fig. 5, section 1). It follows that this vector points mainly upward (fig. 4, point 4 in the frontal plane) and slightly to the right (fig. 4, point 4 in the horizontal plane). As mentioned above, this important potential gradient is recognized neither in Frank’s nor in Grishman’s method.

Right Bundle-Branch Block

Figures 6 and 7 illustrate the results of the experiment which showed better similarity among the various vectorcardiographic curves after production of RBBB. The maximum source and sink (fig. 6) and the corresponding calculated vectorcardiogram (fig. 7) are represented for every 0.005 second of the cardiac cycle.

At 0.005 second after the beginning of QRS in lead 3 (fig. 6, scheme 1), the site of maximum positivity is recorded at a low level of the right ventricular cavity, and the site of maximum negativity is recorded at a high level inside the left ventricle.

At times 0.010, 0.015, 0.020, and 0.025 seconds (fig. 6, schemes 2 to 5), the greatest sources of current are found at the lateral or anterior regions of the left ventricle, while the corresponding sinks remain inside the left ventricle. At 0.030 second, both source and sink are located in the anterior wall of the left ventricle.

At 0.035, 0.040, and 0.045 seconds after the beginning of QRS in lead 3 (fig. 6, schemes 7 to 9), the maximum sources move abruptly to the lateral and posterolateral regions of the right ventricle, and the sinks still remain on the left ventricle.

At 0.050, 0.055, 0.060, and 0.065 seconds (fig. 6, schemes 10 to 13), the greatest sources are located approximately in the same sites of the anterior wall of the right ventricle, and the greatest sinks are in the high posterolateral regions of the left ventricle. These forces are referred to the activation of the interven- tricular septum ("Gaussian potentials," see footnote, page 1099 in a left-to-right direction, since at subsequent times (0.070, 0.075, and 0.080 seconds; fig. 6, schemes 14 to 16) the sources as well as the sinks of current are located in the high anterior regions of the right ventricle. At these times, then, the activation of the free right ventricular wall is taking place.

The vectorcardiogram calculated from these maximum potential gradients and the actual curves obtained with the methods of Frank and Grishman are shown in figure 7. A clockwise rotation is present in all curves.
Almost always the rotation was found to coincide for the actual and the calculated curves, although the loops differed greatly.

In the horizontal plane of the calculated vectorcardiogram there is a right posterior loop (fig. 7; points 7, 8, and 9), which is not seen in Frank and Grishman's horizontal vectorcardiograms (fig. 7). This loop is produced by forces of the right ventricle. Points 7, 8, and 9 of the calculated vectorcardiogram corresponded to anterior, lateral, and posterior regions of the right ventricle. The unipolar epicardial leads from these three sites (fig. 8, sections 1, 2, and 3, respectively) show frank positivities; their intrinsic deflections are inscribed progressively later. This indicates a sequence of activation from anterior to lateral and lastly to high posterior regions of the right ventricle, as is known in RBBB.12 This sequence of ventricular activation is not borne out by the methods of Frank and Grishman.

Discussion

According to Stratton's theorem of equivalence,16 any distribution of electrical charges inside a finite area of the space, e.g., a sphere, can be substituted by a new distribution of charges whereby all the charges can be located at any point chosen inside that circumscribed region. The new distribution will produce a potential field outside that region equivalent to that produced by the original distribution of charges.

This "equivalent" distribution always consists of a monopole (single charge), dipole, quadrupole, octupole, etc., in an infinite series of current multipoles. The magnitude of these multipoles, however, depends on the point or position considered inside the region. It follows that there will be as many different distributions as points considered. If the original distribution of charges inside a sphere is a single dipole, the equivalent distribution of this dipole will also be represented by an infinite series of multipoles (monopole, dipole, quadrupole, etc.) at any one point but the center of the dipole. It is evident, therefore, that the characteristics of the equivalent distribution are strictly related to the position or point considered.

The foregoing holds true for the electrical
field of the heart when recording at a distance, by assuming that the heart is included in a spherical surface of the smallest adequate radius. Applying Stratton's theorem,* all the charges within the heart at any given moment of the cardiac cycle can be represented at any one of its points by an equivalent distribution of charges in an infinite series of current multipoles. Mathematically, it has been proved elsewhere¹² that if we study the electrical field produced by this equivalent distribution at a point sufficiently distant from the center of a sphere of the minimum adequate radius (heart), all the terms of the infinite series but the dipole cancel out. Conversely, as the exploring electrode approaches the heart, the influence of multipoles (quadrupoles, octupoles, etc.) can no longer be discounted.

It is understood that the more remote are the electrodes from the heart, the more correct is the assumption that a single dipole can represent all the charges within the heart at any given moment of the cardiac electrical cycle. Let us suppose that a human torso is immersed in a fluid medium of great extent (infinite) and with the same conductivity (homogeneous) as that inside the torso. It is evident that the more distant are the electrodes, the more valid is the concept of a single or equivalent dipole.

If the medium is neither homogeneous nor infinite, the theoretical analysis becomes even more complex.

Different vectorcardiographic solutions to the overall problem of electrocardiography have been proposed. Calculated electrical circuits and resistances are used in some vectorcardiographic methods²,⁵ for two main purposes: (a) "to move away" from the heart so that the potentials appear to be produced by a single dipole, and (b) to correct the torso shape and the inhomogeneities of the medium surrounding the heart.

As these methods show, there is always the possibility of finding a procedure by which all the forces of the heart can be represented by a single or equivalent dipole for each instant of the cardiac electrical cycle. The eventual usefulness of a dipole representation is doubtful, since for any such procedure the investigator has to neglect the effects which are produced by all the multipoles of the infinite series other than the dipole.

We are inclined to think that it is not always convenient to consider the "average" effect of the activation fronts obtained by means of a single dipole. On the other hand, most vectorcardiographists claim that vectorcardiography gives the same, if not more, information than electrocardiography.

In order to clarify our views on this controversy, it is pertinent at this time to enter here a discussion of:
Electrocardiography versus Vectorcardiography

To compare the diagnostic value of electrocardiography with vectorcardiography, it is necessary to consider the following main possibilities:

1. The heart is a fixed dipole and the surrounding medium is homogeneous and infinite. Vectorcardiography would give the orientation of the dipole for every instant of the cardiac cycle in a rapid and precise way. Equal information could be obtained by electrocardiography only by means of simultaneous leads requiring much time and great labor.

2. The heart is not a fixed dipole (the surrounding medium is homogeneous and infinite). Vectorcardiography would reflect only the orientation and not the movements of the dipole, and this would always be localized at the center or origin of the leads. Electrocardiography, on the other hand, can reflect the movements of the dipole by recording the asymmetrical effects secondary to those movements, when the electrodes are sufficiently close to the heart.

3. The heart is not a dipole (the inhomogeneities and limits of the surrounding medium are discarded). This is the actual situation since many “sources” and “sinks” are present during the cardiac electrical cycle.

As mentioned above, it will always be possible to devise a vectorcardiographic method which shows a single dipole; it will also be possible to demonstrate that the said dipole represents the “average” effect of all the electrical charges of the heart. However, the unavoidable handicap of such a method is that the dipole may correspond to the average effect of other electrical charges completely different from those of the heart under study. This is the same as in simple arithmetic: the average value of 8, 6, and 4 is 6. On the other hand, 6 is also the average value of 6, 6, and 6, and of 9, 6, and 3, etc.

In conclusion, by knowing their average effect, we do not know the charges of the heart; instead, by knowing the charges we do know their average effect. In order to know the electrical charges or activation fronts, it is necessary to “move close” to the heart; a distant exploration will never give as much information as a proximal exploration.

Let us illustrate some of the above considerations with examples seen in the practice of electrocardiography.

A. In cases of acquired heart disease, it is a frequent occurrence that the voltage of the
QRS complex in the transitional precordial leads is greater than that expected with reference to the same QRS voltage in the other precordial leads (fig. 9). An explanation of such tracings can be given by invoking effects of asymmetry for the equivalent dipole, if one wants to adhere to this concept. An alternative explanation can be given by invoking the effects of other multipoles, since the precordial electrodes are not sufficiently distant from the heart. (The inhomogeneities of the medium are discarded.)

B. In cases of congenital heart disease, it is relatively common to find positive QRS deflections in V1 and V6 and negative or isodiphasic QRS complexes in the intermediate precordial leads (fig. 10). It is evident that this distribution of potentials cannot be produced by a single dipole. Yet most vectorcardiographic methods register a loop, which is explained on the basis of a single dipole.

These and previous experiments have shown the existence of proximity potentials and their importance in clinical vectorcardiography. Better electrocardiographic diagnoses are reached, at least at our Institute, through the information given by proximal leads than by using the concept of a single dipole.

On the Comparative Value of the Methods of Frank and Grishman

Comparative values between the methods of Frank and Grishman can be set when the vectors calculated from their curves are analyzed in light of our knowledge of ventricular activation. Our impression, supplemented by the study of a number of vectorcardiograms corresponding to many different clinical conditions, is that the method of Grishman, in general, correlates well with the electrocardiogram and with the sequence of ventricular activation. However, some forces, e.g., the anterior-posterior components in high posterior infarctions, are exaggerated by this method. The diagnosis of such infarctions may then appear to be facilitated, but at the same time false diagnoses may be easily made.

The apparent superiority of Grishman's over Frank's method can be attributed to the fact that the potential differences at the body surface are recorded unaltered. Clearly, then, for this very fact Grishman's method does not adjust to the dipole concept. On the other hand, Frank's method adjusts more to the dipole concept and correlates less with our knowledge of the sequence of ventricular activation.

In summary, by adhering to the dipole concept as closely as possible, the movements of the many activation fronts are lost, and a situation is created which is entirely artificial according to our understanding of the activation process of the heart.*

A Possible Solution to the Problem of Vectorcardiography

All vectorcardiographic methods in use are intended to represent more or less faithfully the electrical activity of the heart as generated by a single dipole. In this respect, the

*Different mathematical studies on multipoles representation of current generators in a volume conductor show the inconsistencies of present-day vectorcardiographic methods. These authors agree that a multipoles representation as well as a sufficient number of surface measurements are needed to get the strengths and the localization of the multipoles. The vectorcardiographic curves do not contain all the available information concerning a complex heart generator. It should also be emphasized that a common misconception among vectorcardiographers is that separately located dipole sources can accurately be accounted by the locus of a single vector loop.
The concept of "lead vector" given by Burger and van Milaan is a very useful one. Recently, Brody et al. have insisted that the concept of lead vector does not apply directly to current multipoles but only to current dipoles. These authors have undertaken to discover higher-order lead parameters which could be applied to the equivalent cardiac multipoles. In this sense, the authors compare the heart field to a heart tensor of the fourth rank.

In essence, the lead tensor provides a method for divorcing intrinsic lead characteristics from the heart itself, whether cardiac representation be in the form of a cardiac multipole or an equivalent electromotive surface.22 The solution to the problem of vectorcardiography appears to lie in the possibility of finding lead tensors (covariant expression of the same rank of the "heart tensor").

The relationship between the ventricular activation and the vectorcardiogram was studied in clinical and experimental cases of bundle-branch blocks. The observations were limited to the methods of Frank and Grishman, taken as representatives of the two main groups of vectorcardiographic methods in use. In clinical cases of right or left bundle-branch block, the curves obtained with the method of Grishman showed a better correlation with the electrocardiographic tracings and with our knowledge of the sequence of the ventricular activation process. In dogs, after the production of either right or left bundle-branch block, the vectorcardiograms according to the methods of Frank and Grishman did not reveal important ventricular forces which were present in the vectorcardiograms calculated from the instantaneous apparent maximum potential gradients. The concept of equivalent or single dipole as representing the electrical activity of the heart was discussed. The limitations of its application to vectorcardiography were pointed out. Comparing the diagnostic value of electrocardiography versus vectorcardiography, the conclusion was reached that a distant exploration ("moving away" from the heart) will never give as much information as a proximal exploration ("moving close" to the heart). The apparent superiority of Grishman's over Frank's method was attributed to the fact that Grishman's method does not adjust to the dipole concept, which is closely adhered to in Frank's method. By adhering to the dipole concept as closely as possible, the movements of the many activation fronts of cardiac activity are lost, and a situation is created which is entirely artificial according to our understanding of the activation process of the heart. A possible solution to the problem of vectorcardiography may lie in the development of lead tensors.

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