Relative Dipolar Behavior of the Equivalent T Wave Generator

Quantitative Comparison with Ventricular Excitation in the Rabbit Heart

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SUMMARY We studied the relative dipolar and nondipolar content of signal energy throughout ventricular excitation and recovery in 34 isolated, perfused rabbit hearts, suspended in an electrolyte-filled spherical chamber. Computer-processed signals were derived from 20 evenly spaced tank-surface electrodes, and a single, moving, equivalent cardiac dipole generator was optimally fitted to the recorded potentials for each 1-msec sampling interval. Superimposed, time-based plots of signal energy for the 34 preparations showed ventricular excitation to be strikingly more nondipolar than was recovery. In terms of the summed square ratio of nondipolar residual energies, overall nondipolarity of QRS exceeded that of ST-T by 41%. Furthermore, the maximum instantaneous ratio during QRS was considerably greater than during the ST-T. Evaluation of paired differences, comparing nondipolar behavior throughout QRS with all of ST-T, proved highly significant ($P < .005$). We also found that in contrast to the considerable mobility exhibited by the equivalent QRS dipole, the ST-T dipole locus remained nearly stationary during most of ventricular recovery. Presumably because repolarization is temporally and spatially a relatively diffuse process, it may generate electrical fields which are notably more dipolar than those caused by depolarization.

BEGINNING with Einthoven's concept of manifest potential,1 most efforts to delineate the equivalent generator properties of the beating heart have been concerned with the electrical current produced during ventricular excitation. (The manifest potential concept was not specifically limited to the forces of ventricular excitation. However, the numerical example given in the paper, which was presented in tabular form, was derived from the QRS deflections of a given subject.) A notable exception has been the study of Taccardi2 which included body surface maps of isopotential distribution in man and dog during ventricular recovery. In 15 normal human subjects these body surface maps provided strong qualitative evidence for predominantly dipolar behavior throughout generation of the ST-T portion of the electrocardiogram. However, as stated by Taccardi, “While the distribution of recovery potentials is always dipolar in normal human subjects, multipolar patterns can be observed in experimental animals and in heart patients.”

Harumi et al.3 subsequently described a “theoretical model of the T wave” which aided greatly in the understanding of T wave genesis. A number of reports by this same group have appeared in which their model T generator was tested, applied, and refined.4-5 In one of these, the concept of multiple recovery boundaries was adduced in an attempt to explain why the ventricular recovery process is more dipolar than is ventricular excitation.6

Spach and Bar4 have recently described a model of the ST-T wave which they used to represent epicardial potential distributions in dogs during ventricular repolarization following ectopically stimulated excitation. This model computes extracellular potentials from the second spatial derivative of the intracellular potentials, using known action potential shapes, measured excitation sequences, and simplified ventricular geometry.

In the present study we, also, have undertaken to examine the nature of ventricular repolarization. For this purpose we have employed the isolated, spontaneously beating rabbit heart, and have applied a quantitative method for analyzing the electrical field generated by this preparation.

Methods

The experimental preparation has been previously described in detail.7-9 A white New Zealand rabbit weighing approximately 3 kg is heparinized by ear vein injection and stunned by a heavy blow to the occiput. The left thorax is quickly entered and the heart is rapidly excised. The cut end of the aorta is tied to a perfusion cannula, and the heart is perfused with modified Krebs-Henseleit solution warmed to 37°C. The perfused, spontaneously beating heart is suspended within an accurately fabricated, 6.35 cm-diameter spherical chamber provided with 20 evenly spaced sensing electrodes on its inner surface and filled with additional warmed Krebs-Henseleit solution.

Thirty-four preparations were studied. Electrocardiographic potentials derived from the 20 electrodes were amplified approximately 6,000-fold by a bank of accu-
rately calibrated amplifiers. By means of a laboratory-oriented computer (PDP 7), the 20 amplified signals were digitized at the rate of 1,000 samples per second per channel for every 3rd heart beat, and stored on magnetic tape. Overall noise levels of these amplifiers was 4 μV root mean square (RMS). Following a computerized quality-control check of waveform reproducibility, random noise content of the signals was reduced 4-fold by averaging a stored sequence of 16 morphologically similar beats with normal activation patterns. Each of the 20 averaged signals was then reduced from bipolar to “unipolar” form by numerical referencing to the average potential of all 20 electrodes. Time skew in successive channels due to signal multiplexing rate was corrected by numerical interpolation.

Using a previously described iterative, numerical method of “dipole ranging,”9 a locatable equivalent cardiac dipole was optimally fitted to the 20 unipolar field potentials for each 1-msec interval of QRS, and each 3-msec interval of ST-T. This procedure amounts to a six-parameter fit of chamber surface voltages, three of the parameters being the orthogonal components of dipole moment, and the remaining three being the corresponding components of dipole location. The iterative process was continued until a least squares fit of electrode potentials was achieved for each time interval. Resistivity within the entire chamber, including the volume occupied by the heart was assumed to be 57 ohm cm, i.e., the resistivity of the electrolyte solution.

Potentials due to the optimally fitted equivalent cardiac dipole were subtracted from the unipolar electrode potentials for each sampling interval throughout ventricular excitation and recovery. The residual potentials thus obtained were viewed as the nondipolar content of the electrical signals. By squaring these nondipolar residuals, a summed square (SS) value of nondipolar signal content was obtained for each sampling interval.

To avoid errors due to low signal to noise ratios, results of the dipole ranging procedure were not examined for very early and late portions of the QRS signal, in which the summed square QRS voltage over the chamber surface was less than 1% of the peak SS value. Likewise, repolarization potentials less than 1% of the peak SS value of ST-T also were excluded from statistical processing.

The three axes which were employed in data analysis form a conventional Cartesian reference system. The choice of axes was selected to correspond to customary practice in engineering and mathematics, rather than to ordinary usage in clinical vectorcardiography. The V axis is directed vertically upward, coinciding with the polar axis of the spherical chamber. The UV and VW planes of the coordinate system correspond to meridional planes which are mutually orthogonal and, of course, orthogonal to the equatorial plane. The positive W axis is directed forward toward the observer, and the positive U axis, following the right hand convention, is directed toward the observer’s right. The suspended heart is rotated about the vertical V axis so that its frontal plane projection, as viewed from the positive W axis, is divided into equal right and left ventricular areas by the anterior interventricular groove.

Results

COMPARISON OF NONDIPOLAR SIGNAL CONTENT DURING QRS AND ST-T

Each set of sum-squared values of nondipolar signal content was normalized to a standard time interval and plotted as a time-dependent display of nondipolar activity. Plots from all 34 preparations for the QRS and ST-T periods are superposed on each other in panels A and B, respectively, of Figure 1. The lower portions of this figure show the geometric (sum-squared) mean nondipolar behavior of the group, together with the plus-minus 35% range during ventricular depolarization (panel C) and repolarization (panel D). Since negative values of SS potential would be impermissible, these were avoided by logarithmic transformation of the SS values, determination of standard deviation of the transformed values, and antilogarithmic reconversion.

With a 12.5% nondipolarity as a convenient but arbitrary reference level of comparison, it is evident from the 34 superposed plots of QRS (panel A, Fig. 1) that there are numerous peaks of SS nondipolar potential which exceed 12.5% during ventricular depolarization. Indeed, many peaks exceed the 25% level. In contrast, distin ction, at the onset of the ventricular recovery plot (panel B, Fig. 1) there are six examples in which the 12.5% level is exceeded, and only two of these exceed 25%. In a seventh

Figure 1 Summed square nondipolar potentials during QRS and ST-T demonstrating that repolarization is more dipolar than is depolarization. The percent of the chamber surface electrode potential that cannot be accounted for by a single locatable dipole is plotted vertically. Time duration of the QRS (panels A and C) and ST-T (panels B and D) are plotted horizontally and are normalized to permit comparison of the 34 preparations. All cases are plotted individually in panels A and B. In panels C and D the middle of the three lines represents the average value for the 34 preparations. The confidence level lines flanking either side of the average were determined by logarithmic conversion of the individual summed square values, calculation of the standard deviation of these transformed values, followed by antilogarithmic reconversion of the standard deviation. Since values of summed square potential cannot be less than zero, this procedure ensures that the confidence level will also be non-negative. The vertical lines M and N in panel C indicate the two instants of minimum nondipolar residual (i.e., maximum dipolarity) early and late in QRS.

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preparation nondipolarity peaked slightly above 12.5% about one-third of the way through recovery, and in an eighth example nondipolarity rose sharply toward the end of recovery.

Examination of group mean activity (panel C, Fig. 1) shows nondipolar minima of approximately 4.5% and 2.5%, respectively, early and late in ventricular depolarization, with an intervening peak value of 11%. During recovery (panel D, Fig. 1) mean nondipolar signal content is 7% at the outset, and declines steadily to a minimum value of 1.8% toward the end of repolarization.

The total signal energy was unit-normalized for each QRS complex. The nondipolar fraction was then compared with the like datum for the corresponding ST-T signal. It was found, on the average, that the nondipolar signal energy of QRS exceeded the nondipolar energy of ST-T by 41%. Evaluation of paired differences, comparing nondipolar behavior throughout QRS with all of ST-T, proved highly significant, giving $P < 0.005$.

COMPARISON OF DIPOLE LOCI

Movement of the group average dipole locus, together with the plus-minus 1 SD, were computed for the same normalized QRS and ST-T time bases as in Figure 1, and plotted in Figure 2. Signal distribution tends to be strongly dipolar early and late in ventricular depolarization; therefore, equivalent dipole location can be determined with considerable confidence at these times. During the intervening time segment the equivalent cardiac generator may become strongly nondipolar, and the computed dipole loci will then sometimes rapidly move large distances with several abrupt changes in direction in a short period of time. This erratic behavior contributes greatly to the width of the bands in Figure 2 which represent 1 SD to either side of the average locus.

In contrast to the QRS, ST-T tends to be strongly dipolar and the equivalent dipole locus tends to move quite smoothly throughout the course of the entire deflection. This well-conditioned behavior of the data reduction is probably responsible, at least in significant measure, for the relatively small amount of T locus dispersion. Of greater interest, however, are the contrasting observations that (1) there is considerable movement of equivalent dipole location between the beginning and end of ventricular depolarization, whereas (2) there is relatively little movement of the equivalent T dipole during much of repolarization. Specifically, it was determined that the equivalent QRS dipole moved an average spatial distance of 10.6 mm between the early and late temporal points of minimum nondipolarity; in comparison, the average T dipole moved a distance of only 2.0 mm during the first two-thirds of ventricular recovery. During the terminal one-third of ventricular recovery another 5.7 mm of spatial movement occurred; which was anterosuperior in direction.

RELATIVE TIME COURSE OF VENTRICULAR RECOVERY

In an effort to discover whether the relative order of ventricular repolarization exerted a significant influence on T wave dipolarity, a scattergram was prepared (Fig. 3) in which the ratio of T/QRS SS dipolarities was plotted against the spatial angle between the mean QRS and T vectors. As illustrated by the scattergram, a significant relationship does not exist between these two parameters ($r = 0.29$; coefficient of determination, $r^2 = 0.09$). Eight of the 34 points have an ordinate value of less than unity, indicating that in the corresponding preparations ST-T was less dipolar than QRS.

![Figure 2](image-url)  
**Figure 2** Locus of the moving cardiac dipole for QRS (left column) and ST-T (right column) intervals showing the relative lack of dipole motion during repolarization. Dipole positions are shown as time-dependent function of their U, V, W coordinates. Time duration have been normalized as in Figure 1. The middle curve represents average values; the two outside curves indicate 1 SD to either side of average. Positive W is direct anteriorly, positive U toward the left ventricular free wall, and positive V superiorly. The origin of the coordinate system is the mean location of the dipole during QRS (left column) or ST-T (right column). Vertical lines M and N indicate those points of time during QRS that correspond to points M and N in panel C of Figure 1.

![Figure 3](image-url)  
**Figure 3** Ratio of T/QRS dipolarity vs. mean QRS-T spatial angle demonstrating their lack of correlation among the 34 preparations. Dipolarity = 1 - summed square (SS) nondipolar potential residual.
FIGURE 4. Isopotential maps on the chamber surface for a heart at the instant of summed square (SS) peak amplitude of the T wave illustrating the predominantly dipolar nature of the potential distribution. The five views are spaced 72° apart about the vertical V axis. Panel A is a view along the positive W axis of the anterior surface of the right and left ventricles; panel B is a view of the right ventricle; panels C and D are of the posterior aspect of the heart; and panel E is of the left ventricle. Isopotential lines are spaced 10 μV apart. Solid lines are positive potentials; marked lines are negative; and the line of zero potential is dashed. The single minimum is seen in panels B and C. The single maximum is seen in panels D and E.

FIGURE 5. Isopotential maps indicating the nondipolar nature of the potential distribution for another heart at the peak of the T wave. The single voltage maximum is best seen in panel E. The two minima are best seen in panel C. See Figure 4 for additional description.

Discussion

The isolated heart preparation employed in this and related studies was developed for the purpose of extracting as much intrinsic electrophysiological information as possible from the electrical field which surrounds the beating heart. The method has yielded gratifying results in dealing with equivalent cardiac generators which are predominantly dipolar in nature. Applied to a numerically modeled pure dipole in a homogeneous medium, the input parameters of dipole moment, orientation, and location are precisely recoverable for generator eccentricities of up to 90%. Acceptably accurate determination of these same parameters is also achieved when tested on approximately dipolar electromotive surfaces produced by ectopic pacing or epicardial searing of the isolated heart. Further, the method provides both a qualitative and, of greater importance, a quantitative measure of the relative dipolar energy content of the equivalent generator. This information, in turn, indicates whether a determination of generator location (dipole ranging) can be made with confidence.

Apparently isochronous maps of the ventricular excitation process have not been prepared for the rabbit heart, as they have been for dog and man. Nevertheless, the low early and late QRS nondipolarity which we demonstrated for the rabbit heart are consonant with the published isochronous maps for the other species, particularly with the detailed studies of isolated human hearts. During the intervening temporal segment of the activation sequence, the associated electromotive surface spreads out throughout the myocardial substance in a manner which would seem to require two or more separated cardiac dipoles for adequate representation. Separated dipolar sources, particularly if tending to be oriented in opposing directions, would be characterized by strongly nondipolar net activity. An extreme theoretical example, consisting of a pair of equal but opposite dipolar sources, would prove completely nondipolar. Further, the matter of relative dipolar-multipolar content of electromotive surfaces, as related to the complexity of their rim configurations, has received extensive theoretical treatment. Generally speaking, simply bounded electromotive surfaces, corresponding to early and late ventricular depolarization, would be expected to exhibit strongly dipolar properties; complexly bounded surfaces, corresponding to the intervening phases of depolarization, would be expected to develop strongly nondipolar characteristics.
In contrast to the behavior of the equivalent cardiac generator during ventricular excitation, the present study demonstrates that there is a significantly smaller component of nondipolar content during ventricular recovery. Although the reasons for this difference remain unclear, it must, of course, be related to the nature of the repolarization process. Although the process has been described as diffuse, it must also be somewhat ordered; otherwise it would not give rise to external manifestation in the form of ST-T deflections. Extensive experimental study of the intramural excitability cycle has provided great insight into the temporal sequence of repolarization as an ordered process.\textsuperscript{5} It has also led to the concept of multiple electromotive layers during repolarization.\textsuperscript{2} These layers may be viewed as a multiple discretized representation of a diffuse transmural process.

Epicardial and intramural isopotential maps during depolarization and repolarization have recently been presented by Spach and Barr.\textsuperscript{19,20} Although determined in a canine model, the sequences presented may be similar to those occurring in other mammalian species, e.g., the rabbit. Two features are pertinent to the present study. First, near the J point, multiple intramural regions of positive potential exist corresponding to simultaneous repolarization and depolarization of different cardiac areas. This was reflected in epicardial recordings as mixed negative and baseline potential zones. Second, later in the ST segment and T waves the entire ventricular epicardium yielded positive potentials, corresponding to the greater positive potentials in subepicardial than subendocardial layers with a unidirectional gradient between them.

According to these concepts, we envision the entire ventricular myocardium, particularly the free walls of the ventricles, as being electrically active through most of the ST-T. This, in turn, may account for the relative dipolarity of recovery as compared to excitation. Referring in qualitative terms to the basic theory of electromotive surfaces,\textsuperscript{14} the simpler the configuration of the rim of an electromotive surface, the greater will be the relative dipolar content of its equivalent generator behavior. Thus, one may anticipate that the midportions of depolarization and the ST-T junction—each characterized by multiple epicardial and intramural wavefronts—would be less dipolar than would be the T wave, being characterized by a diffuse unidirectional transmural gradient.

This point is illustrated further in the numerical simulation presented in the Appendix. A simply configured electromotive surface fashioned after a mammalian ventricle is determined to be highly dipolar when uniformly active, but strongly nondipolar when the apical portion is electrically quiescent. These two conditions are analogous to segments of ventricular repolarization and depolarization, respectively.

Similar reasoning caused us to anticipate that the locus of the equivalent T dipole should not migrate a great deal throughout repolarization. This expectation was reasonably well confirmed by T dipole ranging (Fig. 2). Finally, the putative diffuse nature of repolarization after its initial phases should be predominantly independent of its time course relative to depolarization, thus accounting for the lack of correlation between QRS/T dipolar ratio and the QRS-T spatial angle.

Appendix

**NUMERICAL MODELING OF CONTINUOUS AND DISCONTINUOUS ELECTROMOTIVE SURFACES**

A paraboloid surface (Fig. 6) 2.5 cm in diameter at its base and 2.5 cm in depth was simulated as being centered within a bounded sphere, 6.35 cm in diameter. The surface was selected as approximating the size and shape of a rabbit heart while the simulated sphere matched the form of the chamber used for the isolated heart preparations described in the body of this report.

It has been documented\textsuperscript{41} that the electrical properties of such a surface, when electrically active, are related to the dipole density of the surface and to the geometry of its rim. Thus, the simulated surface may be replaced by the planar circular rim which forms its base. This, in turn, is known to be a predominantly dipolar generator, with small higher order multipolar terms related mainly to size and to eccentricity.

The circular layer so defined was subdivided into 2,500 segments, each containing a single, centrally located and normally oriented dipole of a strength directly proportional to the area of its containing segment. Potentials recordable at 32 sites on the surface of the simulated sphere due to each dipole were computed,\textsuperscript{21} and summed to give the potentials due to the entire circular layer. These potentials were then used to inversely determine the location and moment of the single dipole which best reproduced the surface potentials.\textsuperscript{9} Finally, the percentage of the sum-squared surface potentials that was and was not accounted for by this dipole was computed. Results demonstrated that, as expected, the best single dipole (D\textsubscript{1} in

![Diagrammatic representation of a paraboloid surface, 2.5 cm in depth and in basal diameter as simulated in the Appendix. D\textsubscript{1} represents the equivalent dipole generated by the basal circular rim when the entire surface is electrically active. When the apical portion, indicated by darker shading, is rendered inactive, a second dipole (D\textsubscript{2}) is generated by the resultant second circular rim.](image-url)
Fig. 6) accounted for 98.99% of the "measured" sum-squared surface potentials, leaving a residual of 1.01%.

Next, the apical portion of the original surface was "turned-off." This segment corresponded to the middle one-third of the arc of the underlying parabolic form. This, in effect, generated a second planar, circular rim at the apical end of the truncated surface which was modeled as being composed of 2,500 dipoles as was the basal rim.

Surface potentials due to the two rims were simulated and the best dipole was computed as above. Results demonstrated that 5.16% of the sum-squared surface potentials were not accounted for by this single, moving dipole fit. Thus, transforming the original continuous electromotive surface into a discontinuous one increased the nondipolar forces generated by a factor of 5.

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