Absolute Quantitative Comparison of Instantaneous QRS Equipotentials on a Normal Subject with Dipole Potentials on a Homogeneous Torso Model

By Ernest Frank, Ph.D.

Quantitative results of a critical experiment designed to determine influence of human-body inhomogeneity and applicability of fixed-location dipole hypothesis for ventricular depolarization are presented. Results reflect in pictorial form, conclusions that the fixed-location dipole representation is approximately 95 per cent accurate for the QRS complex at any body-surface point; influence of inhomogeneities on surface potentials is roughly ±10 per cent.

A CRITICAL experiment in electrocardiography, representing the climax and integration of years of investigation, was performed from March to June 1954 on a normal male subject. A pictorial, non-mathematical summary of a representative portion of overall results of this experiment is presented here in terms of “true” unipolar boundary surface equipotentials at three different instants of the QRS complex on a normal subject, and also for a fixed-location dipole immersed in a three-dimensional homogeneous torso model which was accurately moulded to the same subject.

CRITICAL EXPERIMENT

A synopsis of the critical experiment follows. The two-fold objective was to determine in quantitative terms the degree to which the fixed-location dipole hypothesis is applicable for the normal QRS complex, and the extent to which human body inhomogeneities influence body-surface potentials. The overall method was indirect; recorded QRS complexes at points distributed over the entire torso of the subject were compared in exacting quantitative detail with potentials produced at corresponding points on the surface of an accurate homogeneous torso model of the same subject by a fixed-location dipole whose moment and orientation were variable. The experiment was carried out in four phases.

Phase 1. Quantitative investigation of the fixed-location dipole representation of ventricular depolarization. If ventricular depolarization is exactly representable by a fixed-location equivalent dipole insofar as body-surface potentials are concerned, theory dictates that innumerable unique pairs of body-surface points must be found at which QRS complexes (measured with respect to any arbitrary junction of resistors connected to any two or more body-surface points) possess exactly the same shape, opposite polarity, and usually different amplitude. In short, exact mirror patterns must exist. Therefore, the degree to which two QRS waveforms lack this exact mirror property (assuming the closest match has been found experimentally) is a measure of the inapplicability of the fixed-location dipole concept. Direct experimental measurements of instantaneous differences between pairs of complexes were conducted using a precision four-electrode cancellation technic. Thirty eight independent cancellations at points widely dispersed over the entire body surface of the subject were obtained. Directly measured and highly amplified maximum instantaneous potential difference between two nearly exact QRS complex mirror patterns was typically 0.05 to 0.1 millivolt, while the complexes themselves ranged from about one to five millivolts, peak. The quantitative interpretation of these results, which included many cases in which one and two precordial electrodes were employed, is that approximately 95 per cent of the QRS complex at any body-surface point on this subject could be attributed to a fixed-location equivalent dipole.

Phase 2. Precision determination of the fixed location of the equivalent dipole in the human subject.

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FIG. 1. Front view of normal subject in tailor-made vest used to locate body-surface needle electrodes at points corresponding to those on torso model. (See figs. 4 through 6 for model photographs.) Electrode reproducibility error is ±1/2 cm with vest technique, but somewhat greater errors exist in absolute correspondence of human and torso electrode locations. Vest and model grid arrangements consist of parallel transverse loops around trunk in planes spaced 2 inches apart. Human measurements were made from level 3 (at shoulders) to level 10 (at navel). Radial lines emanating from longitudinal body axis, spaced 22.5° apart, establish 16 equiangular points on each transverse level, designated by letters A through P. Equivalent dipole location under conditions of "normal" respiration which produced substantially the same surface potentials as ventricular depolarization was in transverse plane mid-way between levels 5 and 6, 2.1 cm (8.4 percent of thorax width) to the left of the sagittal plane containing front and back midlines (angles E and M, respectively), and 4.7 cm (18.8 percent of thorax depth) forward of the frontal plane containing the right and left midaxillary lines (angles I and A, respectively).

Theoretic analyses of idealized models and experimental measurements on torso models reveal that boundary surface potentials are extremely sensitive to location of the immersed dipole which produces them. Indeed, dipole location is the most influential parameter in the electrical system. Consequently, a meaningful comparison between human and model for the purpose of investigating inhomogeneity influence must first provide for establishing the fixed location of the dipole in a precise manner. An experimental technique employing the same precision cancellation methods of Phase 1 was utilized in a novel method for finding the anatomic location of the equivalent dipole. The method is based on a property of homogeneous torso models concerning the anatomic level around the chest whose plane contains the dipole. At this transverse level there is negligible contribution to the chest potential of the dipole component, pₐ, aligned with the longitudinal anatomic axis, even for considerable dipole eccentricity. Therefore, mirror-pattern cancellations of QRS complexes can be sought around the entire human chest at this anatomic level and results may be matched, independent of particular waveform, to torso model chest data obtained from immersed dipoles of experimentally known locations. Equivalent dipole location for ventricular depolarization was established within ±1/2 cm anatomically by this sensitive technique. A byproduct of this determination also permitted construction of a two-resistor terminal tailored to the individual subject which was within ±0.2 millivolts of the dipole mid-potential. This terminal is far more accurate than the Wilson central terminal, which had a peak-to-peak amplitude of 0.8 millivolts with respect to the two-resistor junction for this subject; consequently, potential differences between body-surface points and the two-resistor junction are called "true" unipolar potentials and are the body-surface potentials presented in this paper.

Although inhomogeneity influence was established at this stage by quantitative comparison of human cancellation data in Phases 1 and 2 with predictions from the homogeneous torso model, the results were in rather abstract form. Therefore, Phases 3 and 4 were undertaken to illustrate in more tangible terms the composite effects of both inhomogeneity and dipole discrepancies between the human being and model.

Phase 3. Quantitative determination of instantaneous amplitude of the three dipole components for the QRS complex. Knowledge of the equivalent dipole anatomic location enabled selection of innumerable bipolar leads on the homogeneous torso model which bear known proportionality to any one of the model dipole components. For a designated dipole component, potential differences measured at corresponding points on the human subject, even in the complete absence of experimental errors, will not result in waveforms which have exactly the same shape or proportionality corresponding exactly to model predictions because of human-body inhomogeneities and non-dipolar effects. However,
FIG. 2. Instantaneous average dipole components, presented in form of vector loops using coordinate system shown in upper right, were determined on normal subject for QRS complex using 3 groups of 6 bipolar leads each at pairs of points on human surface where "pure" components were predicted from known dipole location in homogeneous torso model. Components are expressed in absolute units, ma-cm, based on the assumption of an average body resistivity of 1000 ohm-cm at heart frequencies. Relative amplitudes are estimated to be accurate to ±10 percent. While not entirely clear from these projections, the spatial loop lies nearly in a plane. Time is indicated by points spaced 5 milliseconds apart, with reference to time $t = 0$, coinciding with peak of R-wave in lead II. Experimental errors in relative timing of components is estimated to be within ±2 milliseconds (see fig. 3). Instantaneous equipotentials produced on surface of homogeneous torso model by fixed-location dipole varying with time in the manner above are given in figures 4 through 6 at the following instants of time: $t = -20, 0, 10$ milliseconds, respectively.

potential differences on this subject at points based on the homogeneous model results conformed sufficiently in shape and proportionality to make sensible an averaging procedure. Accordingly, six independent potential differences were measured on the subject at widely scattered anatomic points dictated from the model for each dipole component, a total of 18 leads, and instantaneous average of six determinations was taken as the best estimate for each component. Results are given in figure 2 and differ substantially in shape, amplitude and relative timing from deductions made from all systems of vectorcardiography presently in use.

Phase 4. Synchronous, high-speed, high-gain recording of the QRS complex. A special two-channel electrocardiograph with uniform amplitude response up to approximately 300 cycles per second was used to obtain precise high-speed records at paper speeds of 300 to 500 mm per second. One channel recorded the complex under study; the other channel always recorded lead II whose R-wave peak was used to establish a common time reference for synchronizing all records. A typical record is given in figure 3. A wide variety of leads was recorded including "pure" dipole-component leads of Phase 3, miscellaneous bipolar leads, Wilson central-terminal leads, and "true" unipolar leads in which the two-resistor terminal of special design was employed. A total of 100 different records of the QRS complex (whose peak-to-peak amplitudes averaged 1.57 millivolts) was made on the same subject over a period of three weeks. These records were compared analytically in both peak amplitude and shape with potential differences produced on the homogeneous torso model at corresponding surface points by a dipole (fixed in the location determined in Phase 2) which varied in time in accordance with the components established in Phase 3. Peak-to-peak
Instantaneous potential distribution over the body surface of humans and animals resulting from ventricular depolarization has been studied by various investigators in search for a fundamental understanding of electrical properties of the heart generator. The distribution may be represented pictorially by equipotentials, body-surface lines joining all points of the same instantaneous potential. As early as 1889 Waller presented a qualitative sketch of such lines for a human subject. Since that time additional detail has been pursued.

At any given instant during ventricular depolarization, potentials measured with respect to the Wilson central-terminal potential is about —0.15 millivolts at this instant. Potential difference between adjacent equipotentials is only 0.1 millivolts in this case. Total dipole moment equals 0.23 ma-cm at this instant. The dipole is in the transverse plane and is directed forward and to the left making an angle of 45° with the x-axis (fig. 2). Systematic errors could be reduced by very slight leftward change in model dipole orientation. Wilson central-terminal potential is —0.15 millivolts at this instant.

Shifts calculated from torso model agreed within ±10 percent with those measured on the human subject for 48 percent of the 190 cases; three quarters of the cases agreed within ±20 percent. Amplitude correlation coefficient \( r = 0.94 \) was calculated for all 190 cases. In two-thirds of the cases agreement between calculated and recorded waveshape was about the same or better than shown in figure 3. It was concluded, therefore, that influence of inhomogeneities on body-surface potentials in this normal subject was not excessive; approximately ±10 percent. This last figure is a rough estimate based on numerous sources of experimental error in both subject and model, errors inherent in methods employed in Phases 2 and 3, and errors of record analysis, all of which contribute to discrepancies obtained in Phase 4. These errors have been estimated to be about ±15 percent.

Conclusions drawn from the results of this critical experiment indicate that a quantitative theory, accurate to approximately ±15 percent, for body-surface potentials produced by normal ventricular depolarization may be based on the assumptions of a fixed-location equivalent dipole and a homogeneous linear resistive conducting medium. Torso shape and, more important, dipole location are critical factors which cannot be ignored.

**Equiopotentials**

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Conclusions drawn from the results of this critical experiment indicate that a quantitative theory, accurate to approximately ±15 percent, for body-surface potentials produced by normal ventricular depolarization may be based on the assumptions of a fixed-location equivalent dipole and a homogeneous linear resistive conducting medium. Torso shape and, more important, dipole location are critical factors which cannot be ignored.

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Conclusions drawn from the results of this critical experiment indicate that a quantitative theory, accurate to approximately ±15 percent, for body-surface potentials produced by normal ventricular depolarization may be based on the assumptions of a fixed-location equivalent dipole and a homogeneous linear resistive conducting medium. Torso shape and, more important, dipole location are critical factors which cannot be ignored.

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Conclusions drawn from the results of this critical experiment indicate that a quantitative theory, accurate to approximately ±15 percent, for body-surface potentials produced by normal ventricular depolarization may be based on the assumptions of a fixed-location equivalent dipole and a homogeneous linear resistive conducting medium. Torso shape and, more important, dipole location are critical factors which cannot be ignored.
QRS EQUIPOTENTIALS AND DIPOLE POTENTIALS

location in all cases (see Fig. 1 caption for location). The line of zero potential on the human subject is the potential of the specially constructed two-resistor terminal which is within ±0.2 millivolts of the mid-potential of the equivalent dipole of the human ventricles. On the model the error between the zero equipotential, obtained by a different more accurate technique, and the immersed dipole mid-potential is less than ±0.05 millivolts. Thus, in an extreme case it is possible that the link between corresponding equipotentials on model and human may have an uncertainty approaching ±0.25 millivolts.

In Figures 5 and 6 potential difference between adjacent equipotentials is 0.25 millivolts; hence, numbers on the equipotentials may be converted to millivolts by dividing by 4. For instance, equipotential 3 corresponds to an instantaneous surface potential of 0.75 millivolts. In figure 4, however, where the dipole moment is smallest, potential difference between successive equipotentials was selected to be only 0.1 millivolt. Hence, numbers on these equipotential lines must be divided by 10 to obtain millivolts. It is remarkable that such uniform 0.1 millivolt lines are obtained (as in fig. 4) despite many sources of experimental error owing to posture and respiration changes, reproducibility of electrode placement and others, and especially when one considers that data were not obtained simultaneously in the experiments but over a period of weeks!

Comparison of equipotentials must be approached cautiously, since certain effects are deceptively magnified while others are suppressed. This is not a matter of attempting to falsify results or to make them appear better than they are, but merely recognition of experimental errors and the way in which they influence equipotentials. For example, the "heart-shaped" equipotential labeled —4 in the rear view of figure 4 appears, superficially, to depart considerably from the corresponding small circle on the model back. However, this is a region of very gradual change in potential where equipotential shape has very little, if any, significance. In this case the maximum potential on the back of the subject was —0.43 millivolts and on the model was —0.40 millivolts; a difference of only 30 microvolts which is far smaller than experimental error and, in fact, comparable to changes in QRS complexes from one heart beat to the next under the rigidly controlled conditions of this experiment. Thus, agreement between these two equipotentials is essentially perfect, despite deceptive appearances.

Another important fact to recognize is that dipole location and orientation in the model at any specific instant can be found which brings about even better agreement with human results than shown, as suggested in figure captions. These systematic experimental errors have not been corrected for, and are included in the illustrations as well as in the numerical results cited in Phase 4. It should be emphasized that model dipole location is fixed in precisely the same location for all cases, and that dipole orientation and strength were
FIG. 6. Absolute comparison of instantaneous equipotentials at $t = 10$ milliseconds for normal QRS complex and dipole in homogeneous torso model. Potential difference between adjacent equipotentials is 0.25 millivolts. Total dipole moment equals 0.72 ma-em at this instant. Dipole is directed almost entirely backward but is slanted a little downward and slightly to the right (Fig. 2). Systematic discrepancies between model and human can be reduced by a downward change in model dipole orientation. Maximum disagreement on the back is about 0.25 millivolts which is approximately equal to the average experimental error. Wilson central-terminal potential is 0.56 millivolts at this instant.

determined from only 18 arbitrarily selected leads which may not have been an entirely representative sample and which may not have emphasized sufficiently critical regions so far as equipotential appearance is concerned. For example, in figure 6 a slight downward alteration (within experimental error limits) in model dipole orientation would move lines 3 and 4 downward on the back and cause line 5 to disappear. Moreover, this same alteration improves correspondence in the front view. Differences shown on the back are about 0.25 millivolts, approximately equal to the average experimental error. It may also be seen from precordial lines in some cases that changing the model dipole location very slightly can improve agreement. The amount of movement required is minute, estimated to be about $\frac{1}{2}$ cm or less, and is within experimental error of $\pm \frac{1}{2}$ cm in dipole-location determination.
Finally, observations concerning smoothness of lines on the torso model as compared with less smooth lines in corresponding human results must be interpreted carefully. In practically all cases the waviness of the lines lies within experimental error, which is smaller on the torso model than on the human subject. Hence, smoother results for the model are expected purely from practical experimental considerations. There might be a few cases, however, where inhomogeneities account for the differences in line shape. Since inhomogeneities nearest the heart are most influential on surface potentials, it is difficult to give even a speculative interpretation for these small effects.

**DISCUSSION**

Representation of body-surface potential distribution by equipotentials has the advantage of giving a pictorial idea of the instantaneous situation, but has the disadvantage of creating false impressions unless interpreted with care. Although equipotentials are quantitative, they sometimes permit only semi-quantitative interpretation. For example, consider the question of the applicability of the equivalent dipole concept. Equipotential lines determined for the QRS complex are similar to those for the model, but a quantitative answer to the question is not easily obtained from the equipotential comparison which also contains other effects such as imperfect dipole location and orientation, and influence of inhomogeneities. However, mirror-pattern cancellations do give a direct and much more precise measure of dipole-concept applicability, since they do not rely on model comparisons or inhomogeneity characteristics. Despite these limitations, inhomogeneity effects and influence of other errors of absolute comparison have not masked the ability to see that QRS complex equipotentials on this subject follow behavior that is quantitatively similar to dipole equipotentials. Many discrepancies, already small, can be seen to arise from systematic errors traceable to imperfect experimental matching of model and human.

Equipotentials on the human subject can be determined using an arbitrary reference potential such as left leg or Wilson central terminal. Distribution and shape of equipotential lines would be the same regardless of reference, but identification of the dipole mid-potential cannot be made from such bipolar measurements and movement of a given equipotential from one instant to the next can only be estimated. Results presented here are the first which have used an accurate dipole reference terminal (from which the Wilson central terminal deviates substantially for this subject). However, there is no basic practical virtue (only theoretical nicety) in knowing which equipotential is the dipole mid-potential. This fact has not been appreciated in electrocardiography where many needless quests for the "zero" of potential have been undertaken. One reason for presenting an absolute comparison has been to show that the Wilson central terminal does not fulfill claims of its advocates which, fortunately, is of little consequence. Absolute comparison of equipotentials is extremely difficult and beset with many errors not present in bipolar comparisons, and provides a good example of the way in which needless effort must be expended to correct misconceptions.

Overall equipotential characteristics in figures 4 through 6 are similar to those already known, such as positive and negative regions, steep gradient across the precordium, gradual potential changes on the back. It is hoped that the present study will clarify and unify these observations in terms of the relatively simple dipole concept. Most human equipotentials obtained here are smoother than reported by other investigators\textsuperscript{14, 16}, probably owing in large measure to the faster paper speed, with accompanying improvement in accuracy, used in recording. Very small timing errors, inescapable in low-speed records, become enormously exaggerated when results are expressed in terms of equipotentials and can easily account for substantial irregularities. In recent studies\textsuperscript{19} of equipotentials produced by internal current electrodes on the surface of dogs, very smooth equipotentials were obtained, owing in part to accurate measurement techniques and control of experi-
mental conditions which were much better than afforded by low-speed records of the QRS complex.

One property deserves emphasis; namely, the steep gradient which exists in the left shoulder region owing to the leftward and forward location of the normal heart. This suggests that lead I, which for other reasons cannot be relied upon for accurate representation of the horizontal dipole component $p_x$, is highly susceptible to anatomic structure of the left shoulder. For example, two individuals with hearts essentially identical in all respects but with somewhat different left-shoulder structure might easily yield drastically different results for lead I because the averaging process determining the left arm potential would have different weighting in the two individuals. As a matter of fact, it was found in this study that poorest agreement between model and human was in the left shoulder region, traceable in part to differences in left shoulder structure of the model which was not faithful enough to the left arm of the subject to stand up as accurately as other surface points in the face of so steep and critical a potential gradient.

It is concluded that model and human results are the same for all practical purposes. Results agree, for the most part, within range of experimental errors of ±15 per cent and it is difficult to say whether differences are measures of experimental error or of real differences in the two systems. Indeed, results obtained may be interpreted to mean that the method of heart-center determination was satisfactory, that the constructed two-resistor terminal is accurate, and that the method of dipole-component determination was sound. It is almost incredible that a homogeneous torso model with fixed-location dipole is so nearly applicable for the QRS complex in this individual, and implies that his human coefficients have been determined by this indirect method to an accuracy far better than obtainable by other means. Although results pertain to only a single subject, and are thereby limited, it is nevertheless suggestive that characteristics of accurate three-dimensional homogeneous torso models may prove to be surprisingly pertinent to human electrocardiography.

**Summary**

Results of a critical experiment for indirect quantitative determination of human-body inhomogeneity influence and applicability of fixed-location dipole hypothesis for the QRS complex are presented in terms of absolute boundary equipotentials at three different instants of the QRS complex on a normal male subject and for a fixed-location dipole immersed in an accurate three-dimensional homogeneous torso model of the same subject. Results reflect, in pictorial form, conclusions that the fixed-location dipole representation accounts for approximately 95 per cent of the QRS complex at any body surface point and that influence of inhomogeneities on surface potentials account for fluctuations estimated to be roughly ±10 per cent. Steep potential gradients at the left shoulder give evidence of complexity of left arm potentials as compared with other limbs.

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