A New Quantitative Basis for Electrocardiographic Theory: The Normal QRS Complex

By Ernest Frank, Ph.D., Calvin F. Kay, M.D., George E. Seiden, M.D. and Robert A. Keisman, M.D.

A theory of electrocardiography based on a fixed-location, eccentric-dipole representation of ventricular depolarization and a homogeneous, resistive, linear medium in the shape of the human torso yields quantitative predictions of instantaneous amplitude and shape of QRS body surface potentials on one normal human subject to an accuracy of approximately ±15 per cent for electrodes dispersed over the entire torso.

Although electrocardiographic theory has been in a formative state since the time of Beethoven, progress has been slow for a variety of reasons. First, the complexity of the electrical system comprised of heart and body and its variability from one human to another have tended to obscure basic characteristics common to all subjects. Second, attention has too often been concentrated, and understandably so, on diseased hearts rather than probing into basic aspects of normal cases. Third, ability to recognize heart disorders, based on purely empiric electrocardiographic observations, which has indeed been fortunate, has at the same time exerted a negative influence on development of an accurate theory. Fourth, background and training of research electrocardiographers has often been inadequate in mathematics, physics, electrical theory and measurement which are fields of extreme relevance to electrocardiography. The result has been, in many instances, noncontributing research effort, acceptance of erroneous concepts and formation of opposing schools of thought.

These formidable difficulties are gradually being overcome by an increasing number of research teams with members trained in complementary disciplines seeking an accurate quantitative theory. As in all science, establishment of such a theory gives insight into complexities, provides a basis for penetrating research and leads to growth of knowledge outstripping by far that which could take place solely on an empiric basis. For the theory of electrocardiography proposed here, quantitative experimental methods and resulting data provide a basis for ascertaining its validity. This theory is shown to predict results of extensive measurements of the QRS complex on one normal male subject to an accuracy of approximately ±15 per cent. It is the first complete three-dimensional theory of electrocardiography which wedd precordial and limb potentials in a unified manner, which has been tested in an exacting and comprehensive manner, and which displays an accuracy comparable to experimental errors inherent in measurements of the human system. It is presented as a foundation upon which to continue quantitative developments in this field.

The Theory

The complete unified theory for the normal QRS complex is based on the following assumptions: (1) It is assumed that ventricular depolarization may be represented at each instant of time by an equivalent dipole whose strength and orientation are variable with the individual but whose location is fixed at a single (but generally different) anatomic point for each individual. (2) It is assumed that the medium in which heart currents are produced is homogeneous, resistive and linear for all individuals, but has boundaries the same as the individual subject. These assumptions specify completely an electrical system in which a unique and determinable relationship exists between poten-
tials on the boundary surface and the internal dipole. A discussion of the experimental and theoretical bases for each of the above assumptions follows.

**Ventricular depolarization.** Despite substantial and continuing effort, the mechanism, sequence and factors influencing ventricular depolarization are not completely understood. This does not present a barrier to analysis of body surface potentials because it is fundamentally impossible to obtain information concerning the detailed activity of the internal heart generator exclusively from body surface measurements anyway. Therefore, it is feasible to define an equivalent generator which produces body surface potentials quantitatively similar to those produced by the actual ventricles. The simplest choice of equivalent generator is a single fixed-location dipole. Several important aspects of the equivalent dipole concept should be emphasized. The heart dipole is a conceptual entity and does not exist in the actual system. While it can be derived, in principle, from the detailed generator, it is extremely difficult to do so practically because of the complexity of the generator and limited knowledge of its detailed operation. (Presently used ideas of simple vector addition for the multitude of dipoles believed to be distributed through the ventricles are unsound.) However, it is relatively easy to determine this hypothetical source from body surface measurements. In principle it is not always possible to obtain a fixed-location dipole which produces precisely the same boundary potentials as any arbitrary set of time varying internal generators.\(^1\)

The degree to which the equivalent representation of the heart as a fixed-location dipole may be applied to ventricular depolarization can be investigated in several ways. The most precise and direct method is mirror pattern cancellations.\(^2\) Experimental existence of nearly exact mirror patterns on the intact human subject, determined by precision cancellation methods, indicates that the fixed-location dipole concept is applicable for the QRS complex to an accuracy of about 5 per cent in most normals.\(^3\) \(^5\) Theoretical estimate is compatible with this experimental result, since a sizable dome-shaped double layer representing a simplified version of ventricular depolarization produces boundary potentials differing by only 5 to 10 per cent from those of an equivalent dipole.\(^4\)

**Conducting medium.** The assumption of homogeneity is based upon a variety of experimental works. Impedance measurements in living dogs reveal that the resistivity of various body constituents (lung, muscle, liver, kidney, heart muscle) is surprisingly uniform, approximately \(1000 \pm 200\) ohm-cm. at heart frequencies.\(^5\) Kaufman and Johnston\(^6\) obtained quantitatively different results which were disturbed by electrode polarization. Model studies of the relation between surface potentials and immersed dipoles have shown that the introduction of inhomogeneities exerts a small influence. Gabor and Nelson\(^1\) found that lung resistivity equal to four times that of the rest of the medium produced effects comparable to their small experimental error, and that insulating ribs and spine, remote from the current source, have minor influence. Surface potentials obtained with homogeneous torso models in this laboratory\(^7\) agree quantitatively, within approximately \(\pm 10\) per cent or less, with those of Burger and van Millaan\(^8\) for an inhomogeneous torso model. Also, in two-dimensional studies\(^9\) similar insensitivity to inhomogeneities is found. Finally, surface potentials produced by inserted current sources\(^10\) and reciprocally energized humans\(^11\) indicate homogeneous behavior of the conducting medium.

The assumption of a resistive medium also has experimental support. Impedance measurements of various body substances reveals only a small reactive component at heart frequencies.\(^5\) More directly, phase-shift measurements in dogs\(^12\) using a precision differential technique show that reactive effects are negligible at heart frequencies. While there is no doubt that capacitance effects exist in biological substances of which the human is composed, they do not become important except at higher frequencies; fortunately, heart signals are confined to the range 0 to 200 cycles per second.\(^13\) The assumption of a medium boundary the same as that of the human figure cannot be incorrect since air is so good an insulator. However, de-
tailed shape of the torso is relatively unimportant as has been shown by model studies with male and female torsos, and also by theoretic analysis of a circular chest contour and experimental comparison with a contour in the shape of a typical thorax. The assumption of linearity of the medium is mandatory to develop a sensible theory. While many body substances display electric nonlinear effects when certain thresholds of current density are reached, the current density produced by the heart is comfortably below these levels. Impedance measurements on body substances over a wide range of currents indicate linear behavior.

A Critical Experiment

In order to determine the quantitative accuracy of the foregoing theory, a critical experiment was carried out on a single normal male subject. The critical experiment consisted of a comparison of instantaneous QRS complexes on a normal male subject with results calculated from dipole potentials produced in a homogeneous torso model of the same subject. The experiment was carried out in four phases:

Phase 1: Investigation of the fixed-location dipole representation of ventricular depolarization.

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

Phase 3: Determination of the instantaneous amplitude of the three dipole components for the QRS complex.

Phase 4: Comparison of measured and calculated instantaneous QRS-complex waveforms over the entire torso.

Throughout all phases great care was exercised in control of posture and respiration of the sitting subject. Anatomic points on the subject corresponding to his torso model points were determined by means of a snugly fitting vest, shown in figure 1, to a precision of about \( \pm 0.5 \) cm. Electrodes consisted of 27 gage hypodermic needles in all tests.

Phase 1 was undertaken to examine separately errors traceable to the dipole hypothesis itself, as distinguished from other errors such as those traceable to the homogeneity assumption. The method employed was based on a finely detailed study of mirror patterns using a four-electrode precision cancellation technique, a generalization of Schmitt's system. The existence of exact mirror patterns and perfect cancellation is predicted theoretically from the fixed-location dipole hypothesis; in practice, the degree to which QRS complexes lack this exact mirror property is a quantitative measure of the nondipolar content of body surface potentials. A description of the method, techniques, experimental errors, basic theory and
results for the male subject investigated has been presented elsewhere.3

It was essential to undertake phase 2 because it had been observed in homogeneous torso models that the location of the immersed dipole exerted a pronounced influence on torso surface potentials. It became obvious that calculations from the model could not be expected under any circumstances to agree closely with measured QRS complex waveforms unless the dipole location in the model corresponded very closely with the center of ventricular depolarization in the human subject. A precision method15 was devised to determine the ventricles center, based on a unique property of dipole potentials produced around the chest at the anatomic level of the ventricles. Potentials at this anatomic level are essentially independent of the head-foot component of the dipole over a wide range of eccentricities characteristic of those expected in humans. The four-electrode cancellation scheme of phase 1 was arranged for obtaining numerous cancellations at the transverse level of the ventricles and cancellation data were matched, independent of waveform, with torso model data in which the dipole location was known, as described in detail elsewhere.15

With the dipole location established it was possible at this stage to determine the influence of inhomogeneities by quantitative comparison in three dimensions of human cancellation data in phases 1 and 2 with predictions from the homogeneous model. Because the results were in rather abstract form, phases 3 and 4 were utilized to illustrate in more tangible terms the composite effects of both dipole and inhomogeneity discrepancies between theory and measurement, but additional experimental errors are introduced in the process.

Phase 3 consisted of recording a series of specially selected bipolar leads with equipment of broader band width (400 cycles per second), higher amplification and faster paper speed than ordinarily used. The equipment consisted of a differential preamplifier possessing excellent common-mode rejection characteristics feeding a high-gain amplifier which drove a Hathaway mirror-galvanometer recorder. Since the dipole location in the homogeneous torso model had been established in phase 2 for the subject under test, numerous bipolar leads at a wide variety of sites on the torso model could be specified which would bear a known proportionality to only one component of the dipole. In other words, the torso image surface was known from which "pure" bipolar leads could be selected for measurement of the separate dipole components, in a manner previously described.15 Six pairs of model points for each dipole component were selected arbitrarily and records of bipolar leads at corresponding anatomic points of the human subject were made. These 18 measurements are included among the total cases given later.

Phase 4 consisted of additional high-gain, high-speed records. Bipolar leads consisted of "pure" dipole component leads, several leads of commonly used systems of vectorcardiography, and random bipolar leads. Unipolar leads were recorded with respect to a two-resistor terminal specially designed for the subject which was within ±0.2 mv. of the electrical center of ventricular depolarization. Unipolar measurements covered the entire torso, extending from about 2 inches below the neckline to about 2 inches below the belt line (see fig. 1 caption). A total of 190 bipolar and unipolar leads were recorded and analyzed. A typical two-channel record is given in figure 2. In all cases lead II was recorded and the peak of its R wave was taken as zero time for the purpose of synchronizing all records.

Results and Analysis

The results of extensive cancellation experiments in phase 1 in which 38 independent cancellations on the same subject were obtained for anatomic points dispersed widely over the entire torso including in many cases one, and sometimes two, precordial electrodes, have been presented in detail.3 Directly measured and highly amplified maximum instantaneous potential differences between two QRS complex mirror patterns was typically 0.05 to 0.1 mv. while the complexes themselves ranged from about 1 to 5 mv. The results indicate that the fixed-location dipole hypothesis entailed errors which average 5 per cent for the QRS complex
of this normal subject, and no correlation was found with anatomic location of the electrodes.

The results of cancellation experiments around the chest at the transverse level of the ventricles in phase 2 for the purpose of determining the electrical location of the dipole associated with ventricular depolarization have also been presented. The dipole location for "normal" respiration was determined within an estimated error of ±0.5 cm. anatomicall.

The location for the subject tested was midway between levels 5 and 6 (see fig. 1), 2.1 cm. (6.4 per cent 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 per cent of thorax depth) forward of the frontal plane containing right and left midaxillary lines (angles I and A, respectively). This location agreed within 1.5 cm. with the anatomic center of the ventricles estimated by fluoroscopic examination. A byproduct of these studies also permitted construction of a two-resistor terminal whose potential was within ±0.2 mV. of the electrical center of ventricular depolarization. The potential difference between an electrode on the body and this specially devised junction for the particular individual tested is termed the "true" unipolar potential in this paper. While it was not essential to make unipolar measurements in carrying out this critical experiment, it was felt to have certain theoretical niceties such as making a direct record of the Wilson central terminal, which has been published.

The method of analyzing records in phases 3 and 4 may be explained with the help of figure 2. First, the peak of the R wave in lead II was used to establish a common point in time for all records. Next, the 0.04 second intervals between the timing lines were subdivided into 8 equal intervals of 5 milliseconds each. A baseline was drawn through the start and end of the QRS complex, as indicated, and graphical measurement of the amplitude of the QRS complex with respect to this baseline was made at each 5 millisecond interval. The data were converted to millivolts by measuring the ratio of the 1 mV. standardizing pulse amplitude to the peak-to-peak amplitude of the recorded QRS complex.

Final results of the QRS dipole determinations are presented in figure 3 in terms of individual components and heart-vector loops. It may be seen that the duration of the QRS complex is 0.085 second for this individual and that the QRS loop lies essentially in a plane. The dipole components are given in absolute units (ma-cm.) based on the assumption of an average resistivity of 1000 ohm-cm.5 for the subject. Each component represents the instantaneous average of six independent determinations which were remarkably selfconsistent, and their relative amplitudes are estimated to be accurate to ±10 per cent. The dipole components differ substantially in shape, amplitude and relative timing from deductions made from all systems of vectorcardiography presently in use. The consistency of these results with those predicted from the homogeneous torso model are included in the 190 cases given later.

A total of 190 records were made in phases 3 and 4; 58 bipolar leads and 132 true unipolar leads. The measured peak-to-peak amplitudes
of the QRS complexes in these records ranged from 0.3 mv. to 5.2 mv., distributed as shown in figure 4. The average measured amplitude was 1.57 mv., peak-to-peak.

Calculated instantaneous QRS complexes for each of the 190 cases were obtained using coefficients determined experimentally in a homogeneous torso model of the subject containing a dipole in the location determined in phase 2. Equations were used in the form \( V = c_xp_x + c_yp_y + c_zp_z \) in which \( c_x, c_y \) and \( c_z \) are torso model coefficients\(^7,\)\(^1\), which pertain to the particular electrodes in question and \( p_x, p_y \) and \( p_z \) are given in figure 3 and table 1 which shows a typical calculation. Since the absolute value of the equivalent dipole of the human subject was not known, an overall multiplying factor was determined and applied uniformly to all torso model coefficients such that the average peak-to-peak amplitude of the 190 calculated waveforms was equal to 1.57 mv. volts, the same as that of the measured waveforms. Agreement between individual calculated and measured waveforms was usually quite close and means that the calculated amplitude distribution was very similar to that given in figure 4.

Quantitative comparison of measured and calculated QRS waveforms was made by means of two quantities: per cent amplitude deviation and per cent maximum shape deviation. The per cent amplitude deviation was defined as the difference between calculated and measured peak-to-peak amplitudes expressed as a per cent of the average of the calculated and measured peak-to-peak amplitudes (it can have a maximum possible value of 200 per cent). For example, if the calculated amplitude was 1.1 mv. and the measured amplitude was 1.3 mv. (average equals 1.2 mv.) the per cent amplitude deviation was \((1.1-1.3)/1.2 = -17\) per cent. A positive per cent amplitude deviation indicates that the calculated amplitude exceeded the measured; a negative per cent amplitude deviation indicates that the calculated amplitude was less than measured. The per cent amplitude deviation for 190 cases is given in figure 5 where it may be seen that 92 cases (48 per cent) showed amplitude deviations of \(\pm 10\) per cent or less, and 142 cases

![Fig. 3. Final results for the QRS heart dipole component determination are shown for the normal subject tested in terms of rectangular components \( p_x \) (right-left), \( p_y \) (head-foot) and \( p_z \) (chest-back) of the heart dipole and in terms of frontal, sagittal and transverse vector loops. Points on the loops are shown at 5 millisecond time intervals expressed in milliseconds from \( t = 0 \), the peak of the R wave in lead II. Dipole components are given in absolute units (ma-cm) based on the assumption of an average resistivity of 1000 ohm-cm\(^5\) for the human torso.](image)

![Fig. 4. Measured peak-to-peak amplitude of 190 QRS complexes obtained from a wide variety of electrode sites ranged from 0.3 to 5.2 mv. and were distributed as shown. The average amplitude was 1.57 mv., peak-to-peak. The amplitude distribution of corresponding QRS complexes calculated from dipole potentials in the homogeneous torso model of the subject showed a similar distribution, since their average departure from the measured human complexes was 0.23 mv. The range of unipolar amplitudes was smaller than that of the bipolar.](image)
(75 per cent) showed amplitude deviations of ±20 per cent or less. The average deviation is −1 per cent and the average magnitude of the deviation is 16 per cent. The distribution is not normal and there is no significant difference in distribution for the unipolar and bipolar results. These results may also be expressed in terms of a correlation coefficient $r = 0.94$ for 190 cases.

Shape comparison between measured and calculated QRS waveforms is more difficult to express in quantitative terms. Two independent methods were used; one based on a quantitative definition of per cent maximum shape deviation, the other on subjective evaluation of records such as shown in figure 6. Per cent maximum shape deviation is defined in terms of measured and calculated waveforms which are normalized to have exactly the same peak-to-peak amplitude. It is given by the magnitude of the maximum instantaneous difference between the normalized waveforms expressed as a per cent of the peak-to-peak amplitude (it can have a maximum possible value of 200 per cent). The distribution of maximum shape deviation is given in figure 7. It may be seen that 86 cases (45 per cent) showed maximum shape deviation of 10 per cent or less while 155 cases (82 per cent) showed maximum shape deviations of 20 per cent or less. The average deviation is 14 per cent. Subjective evaluation of the records showed rather consistent agreement with this numerical definition as indicated in figure 7. Of the seven possible ratings, from "very good" to "very poor", based on visual examination of superimposed, normalized measured and calculated waveforms as shown in figure 6, the correlation with maxi-
Fig. 6. Measured and calculated QRS complexes are compared for shape agreement by plotting the calculated results on the records with the same peak-to-peak amplitude as the record. Calculated points at 5 millisecond time intervals are shown by small circles, and dashed lines through these points are given when they depart appreciably from the recorded complex. Representative records are shown with both the maximum shape deviation S (in per cent) and the accompanying subjective judgment of the degree of agreement. Measured amplitudes are indicated on each record with corresponding calculated amplitude in parenthesis. All amplitude figures are rounded off to the nearest 0.1 mv. In categories “very good” and “good”, 54 per cent of the 190 cases were included, as may be seen in figure 7. A sample of a “very poor” record is omitted since only two cases of the 190 were in this category.

maximum shape deviation could be made with few exceptions as follows: Very good, 0–5 per cent; Good, 5–11 per cent; Fair to good, 11–18 per cent; Fair, 18–28 per cent; Poor to fair, 28–40 per cent; Poor, 40–60 per cent; Very poor, greater than 60 per cent. The group of representative records in figure 6 gives an idea of the significance of these measures of shape agreement. Additional comparisons of measured and calculated waveforms have been presented elsewhere.16

Anatomic distribution and correlation between amplitude and shape errors was investigated. The correlation coefficient between per cent amplitude deviation and per cent maximum shape deviation was rather weak, $r = 0.45$. One definite trend was found. Potentials in the vicinity of the left arm were noticeably outside typical deviations, especially in shape. It is not known whether this effect is traceable to inhomogeneities or to a poor representation of the left arm in the torso model, which was capped off rather close to the shoulder. Since there was a steep potential gradient at the root of the left arm of the subject during most of the QRS complex,17 it is most likely that the average left arm coefficients determined in the model were largely responsible for the disagreement.

Discussion

It has been shown that a theory of electrocardiography based on a fixed-location dipole representation of ventricular depolarization and a homogeneous, resistive linear medium
in the shape of the human torso yields quantitative predictions of instantaneous QRS body surface potentials on one normal subject to an accuracy of approximately ±15 per cent in both shape and amplitude for electrode location dispersed over the entire torso. This accuracy is far better than obtained in present-day electrocardiography which is based on a simpler, qualitative theory. Comparison of the standard electrocardiographic records of the subject tested, shown in figure 8, with the results of this study reveal many significant quantitative differences. Some of these include: (1) The shape of lead I differs markedly from \( p_x \). The ratio of the R to S amplitude is 0.7 for lead I, but 3.6 for \( p_x \). Moreover, lead I crosses the baseline between R and S at a time 15 milliseconds earlier than does \( p_x \). (2) The ratio of R to Q amplitude is 2.2 for \( V_n \), but 3.9 for \( p_x \). Also, \( V_n \) crosses the baseline between Q and R at a time 5 milliseconds later than does \( p_x \). (3) While \( p_y \) displays a small S wave, this is completely absent in \( aV_r \). (4) Relative peak-to-peak amplitudes of dipole components deduced in this comprehensive study are 1.0:1.5:2.4 for \( p_x \), \( p_y \), and \( p_z \), respectively, while those deduced from standard electrocardiograph records are 1.0:2.5:0.8 for corresponding components. (5) Since the Wilson central terminal potential was 0.8 mv., peak-to-peak, for this subject, amplitude and shape of \( aV \) leads differ markedly from true unipolar limb leads. The worse case is \( V_R \) which has an amplitude of 0.4 mv. \((aV) \div 1.5 \) while the true unipolar right arm potential has an amplitude of 1.0 mv. and an entirely different shape. These examples serve to illustrate substantial deviations between results derived from current practices and those based on an accurate, quantitative theory.

Basic implications of this theory should be clearly recognized. The theoretical system may be described completely by coefficients associated with each boundary electrode \(^2\) and may be interpreted geometrically in terms of an image surface. \(^8\) The coefficients and associated image surface depend upon dipole location and torso shape. They are extremely sensitive to dipole location within the chest. \(^14\) Another basic implication is that there are only three independent data concerning heart generator activity that are obtainable from body surface measurements; the three components of the time-varying dipole. This means that after three independent potential differences are measured, additional leads give only redundant information, in principle. This also implies, as stated previously, that information concerning details of ventricular depolarization is fundamentally inaccessible \(^1\) from body surface measurements in normal subjects and can only be deduced by using additional hypotheses and experimental information not available at the body surface. In addition, this theory implies that “proximity” potentials do not exist at the body
surface in normals; all body surface potentials are derivable from an internal dipole and anatomic proximity to the ventricles is of no fundamental consequence. Finally, use of an indifferent junction which has a potential equal to the dipole midpotential is completely unnecessary; all available information from body surface measurements can be obtained with bipolar leads.

There are many secondary implications of this theory which reveal quantitative errors of current electrocardiographic practices. To illustrate, the Wilson central terminal is seen to depart substantially from the dipole midpotential in this theory.\textsuperscript{7, 14, 19} Methods of mean spatial vectorcardiography\textsuperscript{20} and vectorcardiography\textsuperscript{18, 19} are subject to considerable error in both principle and practice, which interferes with their objective of determining the heart dipole. Recognition of limitations of currently used concepts and practices should spur progress in electrocardiography by giving a meaningful direction to future research which should ultimately lead to more refined clinical methods.

Since dipole potentials produced in homogeneous torso models are closely related to QRS potentials on a normal subject, three dimensional models become a powerful experimental tool for investigating important factors which influence the QRS complex. Extensive studies\textsuperscript{7, 14, 16, 17, 18, 19} of such models reveal that the most important single factor in the system is the location of the dipole; so important that if it is not taken into account large errors are inescapable and that if it is taken into account it is probable that other factors such as torso shape and body inhomogeneities would not have to be considered, at least at the outset. It is felt that electrocardiographic practice in which dipole location alone is properly taken into account\textsuperscript{18} would represent a major step in improving the accuracy of the determination of the heart dipole from body surface measurements.

Many conflicting (as well as supporting) ideas in connection with the concepts and results presented here may be found in the literature. It is perhaps worthwhile to emphasize that the subject tested was selected by chance and the experiments reported here were conducted with high scientific standards. A careful study of the methods and procedures used reveals many different and unrelated steps at which relatively small errors would have impaired substantially the agreement between theory and measurement. For example, changing the dipole location in the model by only 1 cm. would have approximately doubled the errors in the correlation. Therefore, the correlation obtained cannot be fortuitous, and there is evidence that results on other normal subjects fall within similar quantitative limits of prediction. Moreover, it is known from this study that many factors shown to be of critical importance have been ignored in many other studies, and undoubtedly accounts for some of the conflicting results.

Since flaws in many works may be found in retrospect, it is not unrealistic to expect modern theories to be subject to change in the future. The theory presented here is the simplest which takes all major factors into account in the case of one subject. Because experimental support for the theory presented here is based on only a single normal subject, future modifications may result from investigations of a wide variety of individuals. Moreover, the application of this theory to abnormal subjects has not been investigated comprehensively. Because it has been a general characteristic in science that more refined theories inevitably lead to a sharper focus on the phenomena and a better understanding of the manner in which variables affect the system, it is likely that application of theories of the kind presented will eventually produce this desirable result.

**Summary**

1. A theory of electrocardiography based on a fixed-location eccentric dipole representation of ventricular depolarization and a homogeneous, resistive linear medium in the shape of the human torso is presented with supporting evidence for the assumptions. Implications of the theory are discussed.

2. A critical experiment is described which tests this theory by quantitative comparison of the instantaneous amplitude and shape of
190 different and independent QRS body surface potentials, over the entire torso of a single normal male subject, with dipole potentials produced in a homogeneous torso model of the same subject. Two-thirds of the results lie within the experimental error of ±15 per cent.

3. It is concluded that dipole potentials in homogeneous three-dimensional torso models are quantitatively related with good accuracy to the QRS complex in normals, and that this represents a theoretical basis for electrocardiography substantially superior to those presently used.

ACKNOWLEDGEMENTS

The authors express appreciation for the participation of Dr. P. H. Langner, Jr., using facilities of the Provident Mutual Life Insurance Co., Philadelphia, Pa., the cooperation of Dr. T. G. Schnabel, Jr. and the interest shown by Dr. H. P. Schwan. Dr. L. G. Thomson assisted in the data analysis, Miss R. Zauderer performed some of the calculations and Mr. L. A. Rubin assisted in obtaining torso model data and equipment construction. Their efforts are gratefully acknowledged.

REFERENCES


APPENDIX I. EXPERIMENTAL ERRORS

Experiments of the kind described are difficult to perform and subject to a wide variety of errors which, altogether, represent a significant portion of the differences between measured and calculated results. Most of these errors are mentioned below and an effort is made to estimate the overall experimental error of this study.

Data obtained on the normal subject was influenced slightly by nonconstancy of posture and state of respiration, despite great care to control these parameters. Throughout the measurements the body was never loaded by resistors smaller than 100,000 ohms but even this sizeable value exerts a slight effect on body surface potentials. The two-resistor terminal used for unipolar measurements had a possible error of ±0.2 mv because of uncertainty of heart dipole location and inhomogeneity effects. The correspondence between factors in the human subject and his model was not perfect: The dipole location error is estimated to be ±0.5 cm, surface electrode locations were not reproducible to better than ±0.5 cm and, in addition, there were larger errors in absolute correlation between model electrode locations and corresponding designations on the vest. The torso shape was obtained by moulding a form to the subject, but this was done about 2 years prior to the experiment and the subject's weight had been reduced by 10 pounds in the interim.

Analysis of the records entailed several errors. Careful examination of figures 2 and 6 shows that the paper speed was not exactly uniform during each QRS complex (slightly different paper speeds are of no consequence) but no attempt was made to correct this; each 0.04 second interval was subdivided into eight equal units. The line width and presence of 60-cycle and muscle-tremor interference led to several errors: (1) Judgment of the exact peak of the R wave in lead II was within an estimated ±2 milliseconds. (2) There was, in some records, a range of different baselines (indicated in fig. 2) that could be drawn for the QRS complex, probably owing to auricular depolarization. An average was usually used. (3) The exact height of the standardization pulse was sometimes difficult to judge to better than ±0.05 mv.

Some of the above errors were estimated in their conglomerate effect by direct measurements. For each record, several complexes were routinely recorded under conditions as constant as practicable. Typical variations from one beat to the next in the same record showed amplitude deviations of ±2 per cent from the mean of several successive complexes and the maximum shape deviation among successive complexes was typically 6 per cent. These results include record analysis errors. Since phases 3 and 4 extended over a period of several weeks, records were made at each session for self-consistency checks with records previously taken. These measurements provide a basis for estimating errors traceable to respiration, physiologic and posture changes and reproducibility of electrode placement. A total of 26 repeat measurements were performed and analyzed; usually about one and one half weeks elapsed between initial and repeated record. Per cent amplitude repeatability was defined as the change in the per cent amplitude deviation from the first record to the repeat record. Per cent shape repeatability was defined as the change in the per cent maximum shape deviation from the first record to the repeat record. These definitions are meaningful since the calculated waveform with which they are compared in each case is the same. Amplitude and shape reproducibility was ±5 per cent or less for 75 per cent of the repeat cases.

In addition to the errors mentioned above, there were also errors inherent in the calculated QRS complex waveforms. The dipole components used in these calculations, as shown in table 1, were average values of a group of independent determinations, and high-frequency detail was smoothed out. The torso model coefficients have an estimated uncertainty of ±5 per cent traceable to many factors such as reference potential drift, distortion caused by the dipole rod support and others which have been discussed previously. In addition the dipole location in the model was probably not exactly in the optimum location for best agreement between calculated and measured results. An appraisal of all of these factors suggests that an overall experimental error of ±15 per cent is not an unreasonable estimate and in fact represents satisfactory accuracy achievement for this type of investigation. Thus, it may be concluded that approximately two-thirds of the measured and calculated results agreed within the estimated experimental errors.
A New Quantitative Basis for Electrocardiographic Theory: The Normal QRS Complex
ERNEST FRANK, CALVIN F. KAY, GEORGE E. SEIDEN and ROBERT A. KEISMAN

doi: 10.1161/01.CIR.12.3.406
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1955 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/12/3/406

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org/subscriptions/