Measurement and Significance of Cancellation Potentials on the Human Subject

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A versatile four-electrode single-channel system is described which is useful for precise research measurements of mirror patterns on the intact human subject, and the theoretic significance of results obtained on normal subjects for the QRS complex is presented in detail. It is concluded that the QRS complex at all points on the body of normal human subjects, including the precordium, can be considered to arise from a fixed-location equivalent heart dipole to an average accuracy of 5 per cent. Therefore, the "proximity" potential concept is untenable for the normal QRS complex.

The degree to which electrical activity of the human heart may be represented by a dipole has been an important issue in electrocardiography for the past half century. The question of relative "electrical remoteness" of electrodes placed at various points on the body surface has often been debated, and, in particular, whether "proximity" potentials (owing to physical closeness to the heart) on the precordium are real or apparent. An associated question attending the dipole hypothesis concerns the degree to which the dipole location remains fixed during heart-muscle electrical activity. Despite their importance, these questions are unresolved to this day. However, pertinent evidence can be obtained by direct experiments on humans, both normal and abnormal, using a precision cancellation technique requiring a simple pre-amplifier in conjunction with a standard single-channel electrocardiograph. It is the purpose of this paper to describe methods, apparatus and techniques for performing cancellation experiments on humans and to discuss their significance.

The existence of mirror patterns on the human subject may be readily shown qualitatively by recording heart signals at a given point on the body surface and then finding some other body-surface point which gives a signal of the same instantaneous waveform but opposite in polarity, and usually of different amplitude. Both signals are recorded with respect to some fixed reference point; usually the Wilson central terminal. While conventional mirror patterns give a qualitative idea of the potential distribution on the human torso, they are of questionable quantitative significance in view of the false mirror patterns that can be observed. The cancellation technique to be described is, essentially, the application of a null technique, inherently capable of high precision, to the study of mirror patterns in fine detail. Application of this technique leads to quantitative results which have significance with respect to the fixed-location dipole representation of heart activity. The experimental method and procedure extends the work of Schmitt and associates by taking a more general view of cancellation rather than restricting it to the Wilson central terminal, and also employs simple equipment within reach of any research electrocardiographer. The theoretical foundation of the method is an extension of the works of Burger and van Milaan, and can be interpreted geometrically in accordance with the image surface viewpoint, as shown in appendix I. It is hoped that both the generality of the method as well as the reasonable equipment requirements will stimulate cancellation experiments on such a scale as to establish to the satisfaction of all a quantitative measure of the degree to which the fixed-location dipole hypothesis is applicable to humans.

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Experimental Method

Null technics have been used widely in many fields where precision is a requirement. The chemical balance, for example, is essentially a null device in which zero deflection of the balance indicator is the criterion for equality of weights. There are thousands of devices of this type which generally possess the advantages of high precision, high sensitivity and accuracy relatively independent of the characteristics of the null indicator. Electric measurements employing null technics are usually called bridge measurements in which a zero or minimum indication of a detector enables deductions concerning elements in the bridge circuit.

Electric null technics may be applied to the human subject in a variety of ways. One method has been discussed in detail. The method to be presented here is more general and entails the use of two electrode pairs affixed to the human torso with potentiometers (micropots) connected between the electrodes as indicated in figure 1. The objective is to seek combinations of electrode locations and potentiometer settings such that a potential difference approaching zero is established between the two sliding taps of the potentiometers. This phenomenon, called "cancellation," is an extremely sharply defined condition experimentally. The electrodes 1, 2, 3, 4 need not be confined to any particular sites and there is no requirement that the anatomic lines joining the electrodes pass anatomically through or even near the heart. Indeed, when cancellation is obtained the anatomic lines joining the electrodes will not even intersect each other.

At first sight it might appear from figure 1 to be hopelessly difficult to obtain cancellation because of the large number of variables (four electrode locations and two potentiometer settings) at the disposal of the experimenter. However, a systematic cancellation-search procedure may be devised as follows: Electrodes 1, 2 and 4 may be initially fixed at arbitrary locations and the setting of the potentiometer joining electrodes 1 and 2 may be fixed. Then, with the remaining two variables it is usually possible to obtain cancellation by trial of different locations of electrode 3, varying the setting of the potentiometer connected from 3 to 4 for each trial location of electrode 3. The tap of the potentiometer joining electrodes 1 and 2 may be regarded as an arbitrarily fixed reference potential. (It need not be at the electrical center of the heart to obtain cancellation.) The potential from electrode 3 to this tap should be an exact mirror pattern (except for amplitude) of the potential from electrode 4 to this tap to obtain perfect cancellation, and this can serve as a guide to trial search locations of electrode 3. Frequently as much as one hour of cancellation search is required before the best cancellation is obtained.

Practical difficulties attending cancellation measurements of this type on the human subject are not to be minimized and may be placed conveniently in two categories: control of parameters and control of sources of variable error.

Control of Parameters. The parameters of the electrical system comprised of heart and body must be held constant if sensible measurements are to be performed. Exactly the same respiratory state (insofar as is practicable) should exist throughout the cancellation attempt. The anatomic location of the heart, even though changed only slightly by normal breathing, is a factor of major importance in influencing body-surface potentials, especially when potential differences of less than 0.1 millivolt are being measured. Posture should be maintained as constant as practicable throughout each cancellation attempt. While some electrode sites are relatively insensitive to posture changes, others are affected pronouncedly by slight shifts of body position.

Control of Sources of Variable Error. There are certain sources of error which can introduce difficulties if they are allowed to fluctuate. The skin must be rubbed thoroughly before affixing the electrode in order to achieve low electrode polarization impedance. If this impedance is low, it can change somewhat without causing ill effects, and also helps to minimize 60 cps interference. A direct current ohmmeter may be employed as a rough measure of electrode resistance, which should be small compared with the 100K potentiometers. (See appendix...
III.) It is desirable to use the smallest size electrodes compatible with low polarization impedance in order to obtain sharply defined nulls with respect to body-surface locations of electrodes. Although standard size precordial electrodes are too large for highly precise work, they may be used if only cancellation existence is to be shown. For precise delineation of body-surface points which produce cancellation, 27 gauge hypodermic needles or \( \frac{3}{4} \) inch diameter electroencephalograph electrodes give good results, but one-half inch or \( \frac{5}{8} \) inch diameter disc electrodes are also satisfactory. Contiguity of electrode jelly must be avoided. Reproducibility of electrode placement is a critical factor, depending upon both electrode size and location, but is not a major concern if the objective is only to demonstrate cancellation existence in a given instance. Electrodes should be fixed firmly during each cancellation attempt. Despite these obstacles, the development of good techniques leads to accurate, conclusive results.

**Typical Experimental Results**

Schmitt and associates\(^3\) have presented detailed reports of cancellation experiments with respect to the Wilson central terminal on human subjects with normal and diseased hearts. Although they did not employ the four-electrode system of figure 1, the same principles of cancellation discussed here are applicable to their studies. Their erroneous contentions that cancellation is dependent upon the Wilson central terminal being at the electrical center of the heart and that anatomic lines joining the electrode locations which produce cancellation must cross through the anatomic heart center in no way invalidates their experimental observations of cancellations, or their interpretation of the significance of cancellation as a measure of the validity of the dipole hypothesis.

The four-electrode system of figure 1 has been applied to several normal subjects and QRS-complex cancellations have been obtained from a wide variety of electrode sites.* Most of these entailed the application of at least one electrode, and in many cases two electrodes, on the precordium in close anatomic proximity to the heart. The existence of QRS-complex cancellations on normal human subjects has

* The author is indebted to Dr. Paul H. Langner, Jr. for some of these results and also for the use of facilities of the Provident Mutual Life Insurance Company, Philadelphia, Pa. while establishing equipment requirements and techniques for the cancellation method.

**Fig. 2.** Typical example of mirror patterns and cancellation potentials for the QRS complex in a normal male subject. The upper records show potential differences of electrodes 3 and 4 with respect to tap 4 of the potentiometer joining electrodes 1 and 2 at the usual standardization used in clinical electrocardiography. These potential differences are nearly exact mirror patterns; one is recorded with reversed polarity for convenience in comparing wave shapes. The potential difference between potentiometer taps at and \( b \) is also shown at normal standardization in the middle record. The arrows indicate the noncancelling portion of the QRS complex which is barely discernible, and shows the need for increased amplification. The lower records, using approximately 10 times the usual amplification, enable a quantitative measure of the residual voltage which has its smallest value with a potentiometer setting of \( n = 0.34 \). With \( n = 0.35 \) the residual voltage is significantly larger and is a typical example of the criticalness of the potentiometer setting and the extreme sharpness of the cancellation phenomena.
Fig. 3. Mirror patterns and cancellation potentials for the QRS complex in a normal male subject in cases where the P and T wave cancellation is far inferior to the QRS cancellation. The arrows indicate the non-cancelling portion of the QRS complex in records taken at about ten times normal standardization. In each case one of the mirror patterns has been recorded with reversed polarity so as to obtain potentials of nearly identical shape.

been established irrefutably and can be reproduced accurately for all subjects tested.

A typical example of cancellation records for the QRS complex is given in figure 2. Mirror patterns of electrodes 3 and 4 with respect to potentiometer tap \( a \), connected between electrodes 1 and 2, and the residual voltage \( V_a-V_b \), the potential difference between potentiometer taps, are shown at the usual standardization. The residual voltage is almost imperceptible and illustrates the need for additional amplification provided by the preamplifier. The amplified residual may also be seen in figure 2 where a potentiometer setting of \( n = 0.34 \) results in a minimum residual voltage of approximately 50 microvolts, which is a direct quantitative measure of the differences in shape and timing of the two patterns.

In general, when cancellation is obtained for the QRS complex, neither the P nor T waves cancel to the same degree, signifying either that the center of electrical activity for these last complexes differs from that of the QRS or that the degree to which the dipole hypothesis applies is different. Two representative cases showing noncancelling P and T waves are given in figure 3. In the lower case illustrated the noncancelling portion of the T wave is seen to be far in excess of the QRS residual voltage despite the fact that the T wave itself is small compared with the QRS complex.

The degree of cancellation may be described quantitatively by a cancellation coefficient, as discussed in detail in appendix II, which involves the potential differences across electrode pairs 1-2 and 3-4, and the residual or uncancelling portion of the heart signals. In the records of figure 2, the cancellation coefficient is 3 per cent which signifies that 97 per cent of the potentials at any of the four electrodes can be explained by postulating an equivalent heart dipole, assuming each electrode contains approximately the same percentage of nondipolar potential. If one electrode is assumed to be entirely responsible for the residual potential, with the remaining three electrodes all perfectly dipolar, the per cent cancellation coefficient indicates approximately one half the per cent nondipolar potential. Cancellation coefficients of 6 per cent and 8 per cent are illustrated in figure 3. The histogram in figure 4 shows 38 cancellation coefficients for the QRS complex obtained on one normal male subject from various electrode locations distributed over the entire torso. No correlation between electrode location and quality of cancellation was observed; precordial potentials were explainable by the dipole hypothesis equally well as those of anatomically distant electrodes.

The theoretical basis for cancellation presented in appendix I reveals that the existence and quality of cancellation does not rely upon anatomic lines crossing through the heart, nor upon the potential difference between the potentiometer taps and the electrical center of the heart, contrary to the claims of Schmitt and associates. This can be demonstrated readily by direct experiment. For example, electrodes 1, 2 and 4 may be fixed in position as shown in figure 5, with electrode 4 on the precordium directly over the heart. With the 1-2 potentiometer set to position \( a \) (mid-position), a location of electrode 3 somewhere on the back
can be found such that cancellation is obtained when the 3-4 potentiometer is appropriately adjusted. Then the 1-2 potentiometer setting may be changed to either $a_2$ or $a_3$ (leaving electrodes 1, 2 and 4 unchanged) and different electrode 3 locations (and 3-4 potentiometer settings) for cancellation will be obtained as indicated schematically in figure 5. Several experiments of this type have been performed and there is no significant difference in the quality of cancellation for the various conditions, despite the fact that the potentiometer junctions are at widely different potentials in each case and the lines joining the electrodes differ markedly in each case. This is exactly what is expected from theoretical considerations. Indeed, if the quality of cancellation did depend upon the degree to which the potentiometer taps approach the electric center of the heart, this would be fortunate for it would then provide a precision method for determining the electrical center of the heart. Instead, the electric center of the heart proves to be a much more evasive quantity and is not determinable by so simple a means. There is a method, however, taking advantage of the precision of the cancellation technic itself, which can be devised to determine the location of the center of electric activity of the human heart with remarkable accuracy.\(^7\)

Many salient features of cancellation experiments have been discussed by Schmitt.\(^3\) The experimental definition of the potentiometer settings is extremely sharp; changes of 2 per cent may be detected readily in typical cases (fig. 2). However, in special cases where the potentiometer joins electrodes displaying small transitional complexes, a situation which can be encountered when the QRS loop is nearly in a plane, the potentiometer setting can become relatively insensitive. If small electrodes are used, changes in anatomic location of one electrode by as little as \(\frac{1}{2}\) inch produces measurable effects as cancellation is approached, but this depends considerably on the region of the torso being explored. Usually, the right side and back are not as critical of elec-
trode placement as the rest of the torso, but this depends to some extent on heart eccentricity and the specific dipole variations of the subject under test. The highly sensitive nature of these experiments is indicative of their inherent precision capabilities, and underscores the need for careful control of respiration, posture and other disturbing influences.

Significance of Cancellations

The theoretical significance of experimentally observed cancellations on the human subject, which unquestionably exist for the QRS complex in normals, is presented in quantitative mathematical terms in appendix I. Before discussing cancellation significance, one important point should be emphasized. The basic electrical phenomenon involved is the existence of mirror patterns. The four-electrode system of figure 1, the system of Schmitt, or any other cancellation systems that may be devised merely represent precision technics designed to measure the degree of mirrorness with high accuracy and objectivity. The success of the technic relies on the principle of examining directly the difference between two wave shapes, automatically compensating for their unequal amplitudes, rather than examining the wave forms themselves. A distinction must be made between the technic and the phenomenon. By the use of this technic it may be said that two wave forms are mirror images to within a certain per cent, very accurately defined by direct experiment. Hence, the question that must be answered is, really, what is the significance of exact or nearly exact mirror patterns on the human subject?

Generally speaking, an hypothesis or theory is a logical set of ideas which may be used to account for experimental observations. A theory is useful so long as it can explain all the experimental phenomena (to an accuracy sufficient for the problem) which fall into its province. Such a theory enables prediction, given a set of conditions, and therein lies one of its major values. There is, however, nothing fundamentally unique about a theory; a group of different theories might all yield explanations and predictions of comparable accuracy. Of all possible theories, however, the usual choice in science is the simplest one. Thus, in discussing the significance of cancellation, one approach is to propose the simplest theory which would have predicted cancellation and which is also consistent with other known observable experimental phenomena concerning body-surface potentials on the human subject. If a theory is constructed which represents the electrical effects in the human heart by a fixed-location dipole, it can be predicted from this theory that perfect cancellations will be found. Hence, the degree to which cancellations exist experimentally constitutes a measure of the accuracy of the fixed-dipole theory. It is imperative to recognize that no claim is made that the heart is a dipole; indeed, this is known to be untrue. But, insofar as the potentials produced at the body surface are mirror patterns, the heart may be represented by a dipole.

Assumptions in addition to the fixed-location dipole are obviously required to develop a complete theory for the human heart-body electrical system, since the medium characteristics play an important role, and these assumptions must not be contrary to known observations. It is reasonable to assume that the conducting medium is finite and has a boundary shape the same as that of the human body; that the fixed location of the equivalent heart dipole is not restricted to any particular point within the chest, since it is to be expected that different individuals will have different heart locations; that the medium is not necessarily homogeneous but, for simplicity, it is assumed to be linear and resistive. None of these assumptions violate the prediction of cancellation. However, the existence of cancellation does not validate these additional assumptions. For example, cancellation would be predicted from a theory which postulated either a homogeneous or an inhomogeneous conducting medium; thus, the existence of cancellation in itself sheds no light on the homogeneity question. Again, cancellation would be predicted for any fixed location of the equivalent dipole within the medium and hence the existence of cancellation cannot in itself reveal information about the dipole location. Since a general theory has not yet been developed for the case of a non-uniform reactive medium, or a nonlinear medium, it cannot be stated conclusively at this time whether or not cancellation would still be predicted in such systems. Certain qualitative reasoning indicates that cancellation would not be expected in such media, but this has not been established rigorously. Fortunately, this question is not important for the present, since the simplest theories should be exploited fully and only made more complicated when
experimental evidence demands that they be changed. However, the minute current density in the human torso resulting from heart action suggests that the linearity assumption is applicable. Moreover, it has been shown in dogs that the medium phase shift is negligible at heart frequencies,\(^8\) indicating that the resistive assumption is probably accurately applicable to humans.

Summarizing, the simplest complete theory which accounts for exact or nearly exact mirror patterns on the human subject, which at the same time does not place unrealistic restrictions on the rest of the system, is one in which heart activity is represented by an equivalent dipole fixed in location in an inhomogeneous resistive linear medium with a boundary the same as the human figure.

In terms of this hypothesis, the cancellation coefficient gives a measure of the maximum percentage error with which heart action may be described in terms of an equivalent dipole. It gives a maximum limit because several factors in addition to the nondipolar behavior of the heart contribute to the measured residual voltage. For example, changes in location of the dipole during the measurement give rise to a residual voltage even though heart action itself were perfectly dipolar. The tolerable dipole movement in a typical normal subject is very small; it can be shown\(^7\) that a dipole motion of 0.5 cm., or even less in some cases, can produce a residual voltage equal to that which gives 5 per cent cancellation. Thus, the fixed location is pinned down rather tightly by a small cancellation coefficient. Indeed, it may well be that dipole movement during the QRS complex is responsible for a substantial portion of the residual voltage. A measurable factor, which typically accounts for about 10 per cent of the residual voltage, is the imperfect common-mode rejection of the right leg (ground) signal in the system of figure 1, and is discussed in appendix III. Also, location of the search electrode, despite great care, is never perfect. In addition, inadequate respiration and posture control during cancellation search as well as non-thoroughness of search can account for part of the residual. Atrial depolarization effects may also be present during the QRS complex. In view of all of these factors which may contribute to the residual voltage it is remarkable that such excellent cancellations can be consistently obtained. The contributions of each factor, separately considered, must be small since they could not conceivably compensate for one another for a large number of cancellations obtained from many different widely distributed electrode sites.

**Discussion**

The accuracy with which the human heart may be represented by an equivalent dipole during the QRS complex, despite its substantial anatomic dimensions compared with the size of the chest and despite its eccentric location within the chest, may be estimated roughly by theoretical analysis. Such an analysis has been presented in detail,\(^9\) in which the boundary potential produced on the surface of a homogeneous resistive sphere by an eccentric, dome-shaped double layer, representing the depolarization wave in the ventricles, was compared with that produced by an equally eccentric dipole. For a representative eccentricity equal to 30 per cent of the sphere radius and for a double-layer diameter equal to 60 per cent of the sphere radius (see fig. 6), it was found that the dipole approximation entails errors of less than 5 per cent for about 97 per cent of the spherical surface, and not more than 10 per cent for the remaining 3 per cent of the surface.

While several idealizations are embodied in this analysis, it does include effects of eccentricity and finite boundary, thus improving on previous theoretical attempts at assessing this approximation. The result indicates that the dipole hypothesis seems reasonable during the QRS complex in normals, which indeed is found to be the case experimentally. Other theoretic analyses and statements in the literature which suggest that the dipole hypothesis entails sizeable errors on theoretic grounds have either been interpreted incorrectly or have not taken proper account of the influence of dipole eccentricity and finite boundary.

Quite apart from the mathematic treatment of this problem, it is not unreasonable on qualitative grounds to expect the dipole representation to be applicable, even for precordial potentials. The limb-lead potentials are only about 1 or 2 per cent of the potential difference across the depolarization wave in the myocardium, owing to the internal short-circuiting
Fig. 6. Scale drawing of idealized theoretic model useful in estimating the degree to which the dipole approximation is applicable to an eccentric uniform dome-shaped double layer representing ventricular depolarization. For the case illustrated, a dipole (of moment equal to that of the double layer) located at the center of the circular rim of the double layer produces a boundary potential \(V\) which differs by less than 5 per cent from the double-layer potential except within a cone defined by \(\theta = 20^\circ\) where the dipole approximation error rises to 10 per cent. The results of this analysis give theoretic support for experimentally observed cancellations on normal humans which are indicative of heart-dipole behavior.

Effects of the torso medium and to the anatomic distance from heart to boundary. This implies that the limbs are in the very distant field of the heart and the dipole representation seems, therefore, quite appropriate. Normal precordial potentials being about 3 to 6 times the magnitude of the limb potentials are still only about 3 to 12 per cent of the double-layer potential difference. This suggests that the dipole representation may still not be seriously in error even for precordial electrodes.

A variety of factors make it understandable in terms of dipole behavior how the ‘proximity’ potential idea could have been falsely deduced on an intuitive basis. The rapid changes in potential with electrode location on the precordium, the larger magnitude of these potentials as compared with limb leads, and the rather sudden changes in shape of the potentials when the precordial electrode is moved only slightly are effects which suggest a proximity type interpretation; yet they are also clearly explainable in terms of dipole behavior. A study of the potentials produced on the precordium by an eccentric dipole indicates that the potential changes extremely rapidly with anatomic distance. An anatomic change of as little as 1 inch corresponds to a change in electrical angle from which the dipole is viewed of about 30 degrees.\(^{10}\) Thus, for certain dipole variations one might expect rapid changes in both amplitude and shape of pattern, even though the electrode anatomic positions are shifted slightly. Moreover, a study of dipole potentials around the chest at the transverse level of the heart\(^7\) reveals that contributions of the head-to-foot component of the dipole to precordial potentials depends very critically on the up-down location of the electrode. If the electrode is moved up or down slightly, the head-to-foot dipole component which may differ considerably in shape from the other components, may contribute very little or enter rather substantially, with one polarity or the reverse, and could easily account for drastic shape changes. Finally, the matter of localized damage may also be given a sound dipole interpretation, although no claim is made here concerning the degree to which the dipole hypothesis is applicable in such cases. A local area of damage causes the dipole variations to be altered but does not necessarily invalidate the concept that the potentials are still dipolar in nature. Thus, local damage which causes the dipole components to change will produce changes in the precordial (and other) electrode potentials, and the concept of proximity effects may not be necessary. The dipole changes owing to local damage can be shown in many cases to account for apparent proximity potentials; indeed, both concepts might lead to the same conclusion in some cases.\(^{11}\)

Acceptance of the heart dipole representation rules out the so-called ‘proximity’ potentials,\(^1\) for these could not be explained on the basis of dipole behavior. The existence of nearly exact mirror patterns can be seen qualitatively to contradict the proximity potential concept. If proximity potentials did exist, then precordial waveforms would have a significant percentage
of potential traceable to the directly underlying portion of active heart muscle. Nearly identical waveshapes generally would not be found at some other body surface point such as on the back where the proximity effect contributes much less if anything at all. Cancellation would be very poor if substantial proximity effects existed, and the dipole hypothesis would have to be abandoned, at least for precordial electrodes. The fact that in normals the cancellation coefficients are typically 5 per cent for precordial electrodes paired with distant electrodes indicates that the contribution to the total wave form of the proximity potentials cannot be more than 10 per cent, and probably less. It should be clear that the proximity potential concept is untenable unless it can be demonstrated conclusively, using a precision cancellation technic, that it is not possible to obtain a high degree of cancellation in certain subjects using electrodes affixed to the proximity areas. Although this might appear to be unlikely, in view of the results for normals, because diseased hearts are not necessarily characterized by being in closer proximity to the anterior chest, it should be realized that drastic changes in the depolarization process could impair the accuracy of the dipole representation. Indeed, such effects though not very pronounced and perhaps traceable to other factors have been reported.3 No claim is offered that excellent cancellations would be found in all individuals, normal and abnormal. But precordial QRS cancellation, even in a single individual, demonstrates that dipolar behavior can and does exist, and that in any such individual the concept of "proximity" potentials is groundless for the QRS complex. The breadth of this conclusion remains to be defined.

Cancellations obtained in this laboratory have been restricted to normal subjects and the QRS complex. Schmitt and associates5 have performed QRS cancellations on patients with heart disease and conclude that the dipole hypothesis is still useful but less accurate than in normals. Application of this technic to the P and T waves has not been attempted in detail and is technically more difficult than QRS cancellations because of the smaller signal amplitudes of the P and T waves and the increased muscle-tremor interference. However, Schmitt’s findings that the center of activity of the T wave is not the same as that for the QRS has been confirmed but has not been examined in quantitative detail. If the centers are substantially different, this would have important consequences, requiring a thorough re-examination of ventricular gradient concepts and also of the meaning of comparing QRS and T loop in spatial vectorcardiography when the same recording system is used for both loops.

Summary

A versatile four-electrode single-channel system requiring a simple one-tube pre-amplifier in conjunction with a standard electrocardiograph is described in detail. Experimental methods and sources of error in the application of this system for precision measurement of mirror patterns on the human subject are discussed. Results of thorough cancellation studies on normal subjects for the QRS complex are presented in terms of a cancellation coefficient which describes the nondipolar content of body-surface potentials. Theoretic significance of cancellation existence is discussed in qualitative and mathematics terms, and previous misinterpretations of cancellation experiments are clarified. It is concluded that the QRS complex at all points on the human torso, including the precordium, for normal subjects can be considered, to an accuracy of 5 per cent, to arise from a fixed-location equivalent heart dipole and, therefore, that the "proximity" potential concept is untenable for the normal QRS complex.

Summario in Interlingua

Es descrive in detalio un versatile systema quadrielectrodic a via unico que require un simple preamplificator monotubal in conjunction con un electrocardiographo standard. Es discutite metodos experimental (e lor fontes de errores) pro le application de iste systema al mesuracion precise de tracciamenti specular ab subjectos human. Resultatos de exacte studios de cancellation pro le complexo QRS in subjectos normal es presentate exprimite per
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medium-plus-skin resistance. Consequently, the potential of the sliding tap \( a \) with respect to the dipole mid-potential is

\[
V_a = V_1 - \frac{(V_1 - V_2)}{R} mR
\]

\[
= V_1 (1 - m) + m V_2
\]

\[
= [c_1 (1 - m) + mc_2] \cdot p = c_a \cdot p
\]

where \( m \) is the fractional setting of the potentiometer and \( c_a \) is defined as \( c_a = m(c_1 - c_0) + c_0 \). Therefore, as indicated in figure 7, the geometric interpretation of \( V_a \) is the projection of \( p \) onto the vector \( c_a \), times the length of \( c_a \), where the tip of the vector \( c_a \) can be moved along the vector \( c_0 - c_1 \) in image space as determined by the potentiometer setting \( m \). The tip of the vector \( c_a \) can be seen to be variable from electrode 1 when \( m = 0 \) to electrode 2 when \( m = 1 \). This proves that the locus of the tip of \( c_a \) when \( m \) is varied, is a straight line in image space (and, incidentally, constitutes a proof of the “synthetic” lead principle). Thus, the manner in which the potentiometer enables a point to be varied electrically with respect to the dipole mid-potential can be seen geometrically.\(^*\) Exactly similar reasoning leads to a geometric interpretation of point \( b \), the 3-4 potentiometer junction, in terms of the vector

\[
c_b = n(c_1 - c_0) + c_0
\]

shown in figure 7, and \( V_b = c_b \cdot p \).

The potential difference between points \( a \) and \( b \), the sliding taps of the potentiometers, is measured by the arrangement shown in figure 1 and perfect cancellation is defined as the condition under which this potential difference is zero during a given complex. In general, it may be seen in figure 7 that \( V_a - V_b \) will not be zero. However, it is obvious from figure 7 and the geometric interpretation that has been presented that the only condition under which cancellation can exist (within the province of this theory) for all values of \( p \) is that the points \( a \) and \( b \) coincide in image space. Mathematically, the condition for cancellation is \( V_a - V_b = 0 = (c_a - c_b) \cdot p \) which can be true for all values of \( p \) only if \( c_a = c_b \); in other words, points \( a \) and \( b \) must coincide. Cancellation conditions are portrayed in figure 7. When points \( a \) and \( b \) coincide (in three-dimensional space) it follows that

\[
V_1 - V_2 = (c_2 - c_0) \cdot p
\]

and \( V_2 - V_3 = (c_2 - c_0) \cdot p \) are exact mirror patterns because \( c_2 - c_0 = c_2 - c_0 = (m - I)(c_1 - c_0) \) and \( c_1 - c_0 = c_1 - c_0 = m(c_1 - c_0) \) are vectors in opposite directions \( m \leq 1 \). In fact, under conditions of perfect cancellation, \( V_1 - V_2 \) and \( V_2 - V_3 \) will not only be exact mirror patterns but will also be in the ratio \( (V_1 - V_2)/(V_2 - V_3) = m/(m - I) \). In exactly the same fashion it may also be seen that \( V_3 - V_4 \) and \( V_4 - V_5 \) are exact mirror patterns under cancellation conditions and that

\[
(V_3 - V_4)/(V_4 - V_5) = n/(n - I).
\]

Thus, in searching for cancellation, the mirror image property may be utilized, and when cancellation is obtained the amplitudes of the measured electro potentials with respect to the potentiometer junctions may be compared for consistency with the potentiometer settings.

If electrode positions 1, 2, 4 and G are fixed, and if the 1-2 potentiometer setting is fixed, a search for cancellation may be undertaken with the two remaining variables; electrode 3 location and the setting \( n \) of the 3-4 potentiometer. The search process can be visualized very clearly in figure 7. The image surface of a typical homogeneous torso may be used fruitfully as a guide in selecting points and potentiometer settings for which cancellation may be expected.

The geometric interpretation of cancellation presented here is an exceedingly helpful viewpoint which gives insight into the three-dimensional nature of the cancellation search conditions, the way in which the variables enter into the experiment and the significance of the potentiometer settings. It is also helpful in the interpretation of the behavior of the four-electrode system; for example, in understanding why some cancellations are more sharply defined than others. A knowledge of the dipole component behavior of the subject under test is also helpful. However, despite its usefulness as an aid for procedures and reasoning, the geometric interpretation in terms of vectors is not an essential aspect of the theory since the entire matter may be expressed in terms of algebraic equations of the type given in equation (1).

It may be seen from the theory which has been presented that the existence of cancellation depends in no way upon the location in image space of the coincident points \( a \) and \( b \) with respect to the dipole mid-potential point \( 0 \), contrary to the claims of Schmitt and associates.\(^*\) This is also emphasized in appendix III where the preamplifier common-mode rejection characteristics are seen to be related to this independence of 0. It may also be seen that the medium shape and inhomogeneities do not prohibit the attainment of cancellation since the theory applies for any medium shape and for an inhomogeneous medium. In addition, if the location of the dipole moves with time, it is obvious that complete

\begin{footnote}
* Anatomic points within the body generally have higher potentials than body surface points. Thus, by definition of the fixed unipolar vectors, it may be seen that those associated with interior anatomic points are larger and lie further away from 0 in image space. Hence, the loci of both the points \( a \) and \( b \) lie outside the medium but inside the image surface.
\end{footnote}
cancellation cannot occur for then the formerly fixed unipolar vectors become variable; consequently, $c_a$ and $c_b$ would vary differently with time and prevent $V_a - V_b$ from being zero during the heart complex under study.

**Appendix 11**

**Cancellation Coefficient**

As a result of a variety of factors previously mentioned, the minimum potential difference between the potentiometer taps $a$ and $b$, $V_a - V_b$, when the best cancellation is obtained experimentally will generally be small but not exactly zero. Hence, it is desirable to define a quantity which is a meaningful measure of the degree of cancellation, and which also can be interpreted as a measure of the nondipolar content of the potentials being measured.

An approach to a suitable definition may be found by first referring to a bridge circuit simpler than the four-electrode system; namely, the Wheatstone bridge of figure 8. The degree of cancellation in such a bridge, more commonly called the bridge null, is defined by the quantity $2r/E$ where $r$ is the residual (or null) voltage equal to the magnitude of the potential difference $V_a - V_b$ and $E$ is the magnitude of the potential difference applied to the bridge. The factor of 2 used in this definition arises from the desire to define a quantity having an average maximum possible value equal to 1.9. Thus, for a given setting of tap $a$ with $b$ considered variable, extreme values of the magnitude of $V_a - V_b$ are $mE$ when $n = 0$ and $(1 - m)E$ when $n = 1$, the average magnitude being $E/2$. Hence, for random initial settings of tap $a$, the worse possible null will be, on the average, $2(E/2)/E = 1.0$.

Turning to the equivalent bridge circuit of figure 1, also shown in figure 8, it may be seen that the potential difference between points 1 and 2 is not necessarily the same as that between points 3 and 4, which differs from the case of the Wheatstone bridge. It is plausible to extend the Wheatstone bridge definition to this case by using the average magnitude of the potential differences $V_1 - V_2$ and $V_3 - V_4$ in place of $E$. Hence, the cancellation coefficient $c$ given in figure 8 is seen to be a natural outgrowth of a definition used in a simpler case. The residual voltage $r$ and the magnitudes of $V_1 - V_2$ and $V_3 - V_4$ are directly measurable quantities; and hence $c$ may be calculated directly from raw data. As an illustrative example, consider the peak-to-peak potentials illustrated in figure 2; $V_3 - V_4 = 3.6$ mv and $r = 0.05$ mv. Also, $V_1 - V_2$ (not shown) was in this case equal to 2.9 mv. Therefore,

$$c = 2 \cdot \frac{0.05}{2.9 + 3.6} = 0.031$$

**Fig. 8.** A Wheatstone bridge and the equivalent bridge circuit of the four-electrode system of figure 1 are compared for the purpose of defining the cancellation coefficient $c$ which is a quantitative measure of the nondipolar content of body-surface potentials. In both cases the internal generator resistance is assumed to be negligible in comparison with the potentiometer resistance, $R$. 

---

**WHEATSTONE BRIDGE**

```
1
\|---\|
| \|---\|
2 \|---\| 3
| \|---\|
| \|---\|
4
```

**FOUR-ELECTRODE SYSTEM**

```
1
\|---\|
| \|---\|
2 \|---\| 3
| \|---\|
| \|---\|
4
```

**HUMAN SUBJECT EQUIVALENT CIRCUIT**

```
1
\|---\|
| \|---\|
2 \|---\| 3
| \|---\|
| \|---\|
4
```

**BRIDGE NULL**

$$2 \cdot \frac{r}{E}$$

**C**

$$c = 2 \cdot \frac{|V_1 - V_2| + |V_3 - V_4|}{2}$$
The definition of cancellation coefficient employed by Schmitt\(^3\) is different from the type given here. When the method of definition presented here is applied to Schmitt’s system, assuming that the Wilson central terminal is perfect, the cancellation coefficients calculated will be slightly smaller than Schmitt’s coefficients. For potentiometer settings near the mid-position the coefficients agree exactly, but for settings over the range \(\frac{1}{2}\) to \(\frac{3}{2}\) the coefficients calculated by the definition presented here are as much as 15 per cent lower than Schmitt’s; that is, Schmitt’s coefficient of 0.05 would be calculated as 0.04, in an extreme case. For all practical purposes, however, results calculated from either definition may be compared directly.

The cancellation coefficient defined in figure 8 may be regarded as a measure of the approximate average non-dipolar content of the potentials at electrodes 1, 2, 3 and 4. To show the basis for this it is necessary to formulate a theoretical expression for \(V_a - V_b\), which can only be done approximately when conditions are not ideal. One approach is to regard each of the unipolar voltages \(V_1, V_2, V_3\) and \(V_4\) as consisting of a dipolar portion plus a small nondipolar component, and to assume that the residual arises solely from the nondipolar portion which is a conservative basis since other effects also contribute to the residual. For simplicity of illustration, suppose the nondipolar portion is proportional to the magnitude of the unipolar voltage. This of course is not necessarily exactly true, but it will serve to show the way in which \(c\) can be a measure of the nondipolar portion. It was shown in appendix I that \(V_a = V_1(l - m) + mV_2\) and in similar fashion it follows that \(V_b = V_4(l - n) + nV_4\). Now if the unipolar voltages are expressed as \(V_a = V_{ad}(l \pm \delta)\) where \(\delta = 1, 2, 3, 4\) and \(\delta\) is the nondipolar fraction of \(V_a\), then \(V_a - V_b\) may be written as

\[
V_a - V_b = V_{ad}(l - m) + mV_2 + [V_{ad}(l - n) + nV_4] + r
\]

where the sum of all terms except \(r\) represent the cancelling portion of \(V_a - V_b\) and is zero. It is reasonable to express the noncancelling portion of \(V_a - V_b\) as the root-mean-square of the nondipolar portions, in case the residual voltage is given approximately by

\[
r = [V_{ad}^2 \delta^2(l - m)^2 + V_{ad}^2 \delta^2 m^2 + V_{ad}^2 (l - n)^2 + V_{ad}^2 \delta^2 n^2]^{1/2}
\]

Since the dipole contributions to the unipolar voltages usually constitute over 90 per cent of the total, it is a good conservative approximation to use the total unipolar voltages in this expression for \(r\); thus,

\[
r = \delta[V_1^2(l - m)^2 + V_2^2 m^2 + V_3^2(l - n)^2 + V_4^2 n^2]^{1/2}
\]

Hence, a theoretic expression for the cancellation coefficient in terms of the nondipolar fraction \(\delta\) of the unipolar voltages is

\[
c = \delta^2[V_1^2(l - m)^2 + V_2^2 m^2 + V_3^2(l - n)^2 + V_4^2 n^2]^{1/2}
\]

For the ranges of voltages and potentiometer settings encountered in practice this last expression is very nearly equal to \(\delta\); and hence the cancellation coefficient is interpretable as an approximate measure of the fractional nondipolar voltage. As a numerical illustration, suppose \(V_1 = -V_2 = V\) and \(V_3 = -2V, V_4 = 2V\) and \(m = \frac{1}{2}\). Then \(n\) may be calculated approximately from \(V_3(l - n) + nV_4 = V_1(l - m) + mV_2\) whence \(n = \frac{\delta}{2}\). Substituting into the equation for \(c\) results in \(c = 0.94\delta\) for this case. Other examples may be applied with similar results. For instance, with \(V_1 = -V_2 = V, V_3 = -V_4 = 2V\) and \(m = \frac{1}{4}\), \(n\) is calculated to be \(\frac{\delta}{4}\) and the calculated value of \(c\) is 1.18.

If the nondipolar content is not assumed proportional to the magnitude of the unipolar potential, the quantitative interpretation of \(c\) becomes modified somewhat. For an extreme illustration, suppose in the last numerical example that \(V_1\) only contains nondipolar potentials and that \(V_2, V_3, V_4\) are perfectly dipolar. Placing these last three potentials equal to zero in the numerator of the expression for \(c\) results in \(c = \delta/2\). Thus, \(c\) indicates one half the nondipolar content of \(V_1\) in this case. Although \(c\) tends to be a somewhat optimistic measure of dipole action in this instance, it should be noted that \(c\) is still twice the average, \(\delta/4\).

**APPENDIX III**

**Cancellation Preamplifier**

The residual voltage \(r = V_a - V_b\) is ordinarily too small to be measured accurately by a standard electrocardiograph, as illustrated in figure 2, usually being in the vicinity of 50 microvolts peak-to-peak. However, a battery-operated preamplifier with good common-mode rejection characteristics may be constructed from parts costing about $90 (the two micro-pots cost about $50) which not only provides the requisite additional amplification (about 15 times in voltage) but also contains other provisions such as a special lead selector switch and a 0.2 mv. standardization pulse which makes it convenient for the pursuit of cancellations on the human subject. The preamplifier is connected ahead of a standard single-channel electrocardiograph such as an Sanborn Visko Cardieter and when used in this manner enables the cancellation search to be carried out conveniently since the residual voltage can be recorded and studied immediately. A complete schematic of a suitable preamplifier is given in figure 9.

**Power Switch.** In the OFF position, filament (A) and plate (B) supply batteries are disconnected from
the circuit and the neon tube pilot circuit is shunted by a 10K resistor for rapid extinction. In the ON position, both A and B supplies are connected and the 0.1 ma. meter is inserted in the standardization circuit. The meter reading may be adjusted to 0.5 ma. by the 1K STD. ADJ. control, in which case the standardizing pulse in series with the 12AY7 grid is either 1.0 mv. or 0.2 mv. depending upon the position of the STD. SELECT switch. In the A and B positions of the POWER SWITCH the meter is switched so as to check the 6-volt filament battery and the 135-volt plate battery, respectively, the 7.5K and 180K resistors serving to convert the milliammeter to a voltimeter. In normal use the POWER SWITCH is in the ON position.

**Lead Selector.** In the GND position of the LEAD SELECTOR switch, the preamplifier input is grounded. In the next two positions $V_1 - V_2$ and $V_3 - V_4$ are presented to the preamplifier; their peak-to-peak values are used in calculating the cancellation coefficient. Following the method of cancellation discussed previously, selector positions $V_a - V_d$ and $V_a - V_b$ may be examined in the next two positions for mirror patterns. For convenience, the $V_a - V_d$ polarity is automatically reversed in the switching circuit so that patterns identical in shape are observed when the mirror condition is satisfied. In the final position of the LEAD SELECTOR switch the residual voltage $V_a - V_1$ is connected to the preamplifier input. Two 10-turn, 100K, 0.1 per cent linearity micropots are contained in the preamplifier and are automatically connected across leads pairs 1-2 and 3-4. A 5-ma. fuse protects the subject.

**Preamplifier.** The preamplifier is a differential amplifier direct-coupled to the electrocardiograph. The high ratio of cathode return to plate load enables considerably more common-mode rejection than found in commercial electrocardiographs; this is necessary to minimize 60 cycles per second interference at the higher amplification provided. The low-frequency response of the preamplifier is down 3 decibels at 0.05 cycles per second, while the high-frequency response is constant to at least several thousand cycles per second. The overall high-frequency response is limited by the electrocardiograph, in particular the galvanometer, which in a Sanborn Visko Cardielle is down 3 decibels at about 60 cycles per second. The 1K BALANCE control is used to equalize the output plate-to-ground voltages, while the 50K LEVEL control is used to set the direct potential of the output. This should be set for ground potential with the GAIN control set at maximum. The BALANCE adjustment is far more critical than the LEVEL, but remains stable over a period of several hours provided the batteries are stable and the 12AY7 is a selected, low-noise tube. The BALANCE and LEVEL adjustments may be made with a direct current vacuum-tube voltmeter connected from outputs to
The operating point of the 12AY7 may be changed if desired by altering the 68K resistor with little influence on the output level. In normal operation the electrocardiograph gain control should be permanently set to its maximum value and the 250K preamplifier GAIN control should be used to set the recording level. This procedure is essential in order to avoid amplitude limiting in the electrocardiograph when signals other than $V_x - V_a$ are being measured. With the LEAD SELECTOR in the GND position and the preamplifier GAIN at maximum, the 0.2 mv. STD. pulse should cover the full width of the recording paper and the baseline should be stable and show only about 5 microvolts of noise.

Micropots. The choice of 100K for the micropots is an optimum value bordered on both sides by two conflicting requirements. On one hand, the micropots must have a resistance large compared with the electrode resistance, which is not negligible when small electrodes are used. On the other hand, the micropots must have a resistance small compared with the preamplifier input resistance in order to minimize 60 cycles per second interference and ground signal imbalance. The impedance of several different types of electrodes was measured with the help of Dr. Herman P. Schwan with the following results: Standard electrocardiograph electrodes (1½ inches × 2 inches) display very small polarization impedance when the skin is rubbed thoroughly, approximately 30 ohms. Circular disc nickel electrodes (½ inch diameter) display a polarization impedance comparable to that of 27 gauge hypodermic needles, about 1500 to 2000 ohms. The ratio of resistance to reactance is about 0.4 at frequencies from 10 to 1000 cycles per second. Thus, it may be seen that the use of 100K micropots leads to errors of less than 2 per cent with these electrodes. The use of 3 megohm resistors in the preamplifier is slightly higher than in conventional design with the result that there are small grid-current effects, which however are not serious. It is necessary to use these large values to minimize 60 cycles per second and ground-signal feed through when the residual is being measured. Suppose the right leg ground-signal voltage with respect to the micropot taps is about 2 mv, and that the micropots are set to the worse possible condition; i.e., one micropot set to zero or maximum and the other micropot set to mid-position. Then there is, in effect, a 50K unbalance in the series resistance feeding the preamplifier. Therefore, one preamplifier grid will receive the 2 mv. ground signal and the other grid will receive 3000/3050 times 2 mv, or 1.97 mv. Thus, there will be a 30 microvolt ground-signal residual under these extreme conditions, even though the potentials of electrodes 1, 2, 3, and 4 cancel perfectly. A typical maximum feed through is about 10 microvolts in practice, and is usually small compared with the residual from the noncancelling portion of the other signals. It is informative to note that excellent cancellations are obtained, as expected theoretically, even though measurements are made with respect to the grounded right leg, and this would also be so for other ground points. This gives further evidence that cancellation existence does not depend upon achieving a reference potential which coincides with the electrical center of the heart.

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