Aimed Electrocardiography with Simple Bipolar Leads

EXPERIMENTAL STUDY OF A NEW CONCEPT: SURFACE SEARCH FOR UNWEIGHTED LEADS WHICH RECORD THE ECG FROM LIMITED CARDIAC AREAS

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ABSTRACT

All currently employed ECG and VCG leads vectorially record added contributions from all cardiac regions. Aimed leads, if feasible, would yield information cancelled during addition.

Three artificial dipoles (μ₁, μ₂, μ₃) are placed within a torso model in the approximate right ventricular free wall, posterobasal wall of left ventricle, and inferior cardiac surface, respectively. Dipoles are excited in turn and torso surface potential fields are mapped for each dipole. A bipolar lead connecting any pair of points on the same equipotential of the field produced by μ₁ does not show a deflection when μ₁ is excited, but responds to μ₂ and μ₃. If this lead is now so placed that its two electrodes, while remaining on the μ₁ equipotential, are on the same equipotential of the μ₂ field as well, then it will respond to μ₂ alone; it is aimed at the latter.

Superimposing the three field maps and searching for those equipotential lines of one map which cross the same equipotential line of another map twice, provides a large number of suitable leads, each aimed at one of the three dipoles. Five leads are described and tested in detail.

ADDITIONAL KEY WORDS ECG leads electrolytic tank torso model equivalent cardiac generator balance waveform cardiac EMF cancellation dipole localized myocardial lesions surface potential maps

Conventional ECG leads and most orthogonal systems record unknown mixtures of contributions from all areas of the heart. Selective recording from limited myocardial areas, if feasible, would improve discrimination among a number of clinical states. Thus, with present techniques, one cause of poor discrimination between anterior infarct and left ventricular hypertrophy is the inability of leads, recording lumped opposing forces, to distinguish between anterior loss and posterior gain in EMF. Also, poor recognition rate in biventricular hypertrophy (only 8 to 26% correlation between ECG and autopsy diagnosis) is due to inability to assess opposing right and left ventricular forces independently. The low rate of recognition of hypertrophy in the presence of a ventricular conduction defect is partly caused by the difficulty of deciding whether the increase in backward or forward forces is due to decancellation alone or to decancellation with added increase in ventricular force. It would help if it were possible to recognize the magnitudes and relative timing of the opposing left and right ventricular forces by synchronous recording of the two.

Leads, using weighted resistor networks to
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Achieve selective sensitivity to dipoles in limited myocardial regions and insensitivity to other cardiac areas,4-8 are relatively complex in design and give small signals with a low signal-to-noise ratio. We described an "aimed" lead system of this type in a previous communication.6 A new approach to this problem, using simple unweighted high-signal networks, is proposed here.

The heart equivalent consists of three myocardial areas, each represented by one of three separate dipoles. The concept is introduced that some points on the body surface reject voltages from two dipoles but respond selectively to one of the three cardiac areas, and a method of detecting these points is described. The existence of such selective points on the surface of an electrolytic tank model is experimentally demonstrated.

Rationale of the Method

The aim of the present phase of this work is to explore, in electrolytic tank analogue experiments, a system of leads selectively sensitive to one dipole and insensitive to other dipoles, when the cardiac generator is represented by two to four dipoles of fixed location and direction. The approach is characterized by the following points. (1) Lead selectivity is achieved not by network weighting based on slanted transfer factors, but by systematic search for body surface points where selective sensitivity can be achieved without weighting. (2) As far as we are aware, the principle which forms the basis of the point-by-point search, has, in this form, not been previously employed in ECG lead theory. (3) If the heart is represented by three mutually perpendicular dipoles of fixed location, the technique will also yield several orthogonal lead systems.

1. CASE OF TWO DIPLOLES WITHIN THE ELECTROLYTIC TANK

For each of the dipoles (μ1 and μ2) excited in turn, equipotentials are plotted on the tank surface using an arbitrarily selected surface point as a voltage reference. A lead connecting any two points along a μ1 equipotential line shows no voltage when μ1 is excited and is thus selective for μ2. The lead voltage is the difference between the μ2 equipotential field at the two selected electrode positions. Similarly, by selecting two electrode positions along any μ2 equipotential line, a lead recording μ1 but rejecting μ2 is obtained.

2. CASE OF THREE DIPLOES WITHIN THE ELECTROLYTIC TANK

For each of three dipoles (μ1, μ2, μ3) excited separately in turn, equipotentials are plotted on the tank surface using an arbitrarily selected surface point as a common reference for the three fields. If the three equipotential plots are superimposed, there will be many instances where a given μ1 equipotential line will cross a given μ2 equipotential line twice. Pairs of such crossings are at the same potential with respect to both the μ1 and the μ2 surface fields. Consequently a lead connecting any pair of such crossings shows no deflection when μ1 or μ2 are either separately or simultaneously excited. It will, however, show a deflection proportional to the difference between the μ3 field equipotentials when μ3 is excited either separately or simultaneously with μ1 or μ2 or with both of these dipoles. This is thus a lead "aimed" at μ3. Leads aimed at either of the other two dipoles are similarly obtained.

3. CASE OF FOUR DIPLOES WITHIN THE ELECTROLYTIC TANK

Extension to four dipoles requires a weighted but still simple lead network. It is possible to position three electrodes and one common reference electrode so that mixtures of voltages from dipoles μ1, μ2, and μ3 are recorded but not from μ4. A simple resistor network is now used to eliminate μ4 and leave a voltage proportional to the remaining dipole. This requires four electrodes and approximately nine resistors for each of the four dipoles.

4. MORE THAN FOUR DIPLOES

The method could be extended to five dipoles but rapidly approaches the complexity of our previously described slanted network "aimed" approach,6 of which the present technique is a special case. The present method makes use of the fact that two dipoles...
have zero effectiveness at two points on the body and the method is simple if the total number of dipoles is only three.

5. QUANTITATIVE APPROACH

The technique will give a quantitative estimate of local dipole moments if it is initially calibrated using dipoles of known strength in a tank.

Methods

ELECTROLYTIC TANK MODEL
AND INSTRUMENTATION

The wall of an elliptical cylinder made of insulating plastic material is penetrated by 140 stainless steel pins, arranged in 20 equally spaced columns around the circumference of the cylinder. Each column consists of 7 pins, row 1 formed by the topmost and row 7 formed by the lowermost pins in each column 1 inch from the rim and 1 inch from the bottom of the tank respectively (Fig. 1). The cardiac generator equivalent submerged in tap water, consists of three rigidly fixed pairs of metal spheres, each sphere 5 mm in diameter. Each pair of spheres represents one of three cardiac dipole areas, and can be excited either separately or simultaneously with the others. The three dipoles are in the approximate centers of the right ventricular free wall (direction of dipole anterior with a small superior and rightward component), the posterobasal free wall of the left ventricle (direction strictly posterior), and the inferior cardiac surface (direction inferior). The separation of the metal spheres in each dipole corresponds approximately to the thickness of the ventricular wall. Thus the spheres in the posterobasal and inferior dipoles are 12 mm, in the anterior dipole 5 mm apart. The distances of the three dipoles from the center of the array correspond to the estimated distance of the relevant portions of heart wall from the center of gravity of the ventricles. The anterior dipole is, therefore, in close proximity to the anterior “chest wall,” whereas the other two dipoles are remote from the torso surface.

Each of the three dipoles is now excited in turn. Potentials with respect to an arbitrarily selected common reference at each of the 140 surface points are entered in an orthogonal map projection of the tank surface. The mapping and checking networks are shown in Figure 2.

EXPERIMENTAL HOOKUP AND CALIBRATION

The mapping is accomplished using the circuit shown in Figure 2 (top). The dipole in question is connected to a 1200 cycle per sec square-wave generator of 50 ohms output impedance which produces a voltage of about 0.1 volt peak to peak. In order to form the potential map, each surface electrode is grounded in turn and a reading is obtained from the 4-decade voltage divider

![Diagram of mapping and checking networks](http://circres.ahajournals.org/)

**FIGURE 1**

Distribution of 140 electrodes on surface of elliptical electrolytic tank. Columns are numbered commencing in the left midaxilla (1), through anterior midline (6), right midaxilla (11), and spine (16). Rows are numbered (1-7) from top to bottom. In the subsequent Figures 3 to 7 the lateral surface of the cylinder is “unrolled” into an orthogonal map. Electrode positions in the maps are defined by two-number sets, where first number of set = column; second number = row.

**FIGURE 2**

Mapping and checking networks are shown. (See text.)
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Lead aimed at anterior dipole, with both electrodes distant at the right and left midaxillary lines respectively. Inferior dipole equipotential (light continuous line) and posterior dipole equipotential (heavy line). The interrupted lines are the anterior dipole equipotentials. LM = left midaxillary line, S = spine, RM = right midaxillary line, M = midsternum. (Equipotentials in millivolts.) The lower part shows oscilloscope tracings.

when the scope shows a balance waveform of the type illustrated in the center of Figure 3 (lower). The voltage divider readings are entered in the orthogonal map.

In order to check that a pair of surface electrodes $P_1$, $P_2$ are truly insensitive to a particular dipole, the circuit of Figure 2 (bottom) is used. Once again the scope should show a balance waveform when connected between 1 and 2. In this case the voltage divider provides a "Wagner ground" and is adjusted to minimize spikes on the waveform.

SEARCH FOR PAIRS OF IDENTICAL EQUIPOTENTIAL CROSSINGS

The three sets of 140 voltage readings obtained by exciting the three dipoles sequentially are superimposed on a single rectangular map projection of the tank surface. To design leads which are selectively sensitive to voltages caused by the excitation of the anterior dipole but reject voltages caused by excitation of the posterior or inferior dipoles, a search is made in the map for pairs of points $A$ and $B$ which fulfill the following requirements. (1) The two voltages induced at points $A$ and $B$ by the posterior dipole are approximately identical. (2) The two voltages induced at $A$ and $B$ by the inferior dipole are also approximately identical but not necessarily the same as the voltages caused by the posterior dipole. (3) The voltage caused at point $A$ by excitation of the anterior dipole should differ as much as possible from the voltage caused at point $B$ by the same dipole. Leads aimed at the posterior or inferior dipoles are similarly detected.

A search for a complete array of surface points which reject $\mu_1$ and $\mu_2$ thus consists of observing the $\mu_2$ field at each point of a $\mu_1$ equipotential, and listing all point-pairs with nearly identical values of $\mu_2$. The search is repeated to obtain arrays of points which reject $\mu_2$, $\mu_3$ and $\mu_1$, $\mu_3$ respectively.

Results

Using point 7, 7 near the foot of the anterior midline of the electrolytic tank as the common voltage reference when mapping the three sets of 140 surface voltages, a number of equipotential lines reconstructed at random by inspection of the map gave among others the five suitable pairs of crossings shown in Figures 3 to 7. In Figure 3, posterior and inferior dipole equipotentials cross twice, first in the vicinity of point 9,2 and again at point 19,2. The oscilloscope tracings shown in Fig-
FIGURE 4

Lead aimed at anterior dipole with both electrodes distant, on the dorsal surface of the model. Posterior dipole equipotential (heavy line) and inferior dipole equipotential (light continuous line). The interrupted lines are the anterior dipole equipotentials. LM = left midaxillary line, S = spine, RM = right midaxillary line, M = midsternum. (Equipotentials in millivolts.) The lower part shows oscilloscope tracings.

Figure 3 demonstrate that a bipolar ECG lead connecting these two points records no deflection when the posterior and inferior dipoles are excited. Since the two lead points are near different equipotential lines of the surface field caused by the anterior dipole, exciting the anterior dipole produces the lead deflection as shown in the record. The two electrodes of this lead are near the upper rim of the tank, the first somewhat anteriorly in relation to the right, the second somewhat behind the left, midaxillary lines. Another aimed lead (Fig. 4) with selective anterior dipole sensitivity is obtained by using point 18,5 which is approximately midway between the upper and lower rims of the tank and halfway between the spine and the left midaxillary line, together with 13,6 which is somewhat lower and halfway between the spine and the right midaxillary line. Since inferior dipole and posterior dipole equipotentials pass through both these points, the lead excludes potentials from these dipoles but records a deflection when the anterior dipole is excited. The lead shown in Figure 5 again aims at the anterior dipole but differs from the two preceding leads insofar as the 6,4 electrode is in close vicinity of the cardiac generator, somewhat off the center of the anterior tank wall. The second electrode is, as in the preceding leads, at a distance from the heart, dorsally from the left midaxillary line, level with 6,4. This lead also differs from the others insofar as the posterior dipole is excluded by the passage of two separate equipotential lines of identical voltage through the two lead points, whereas in the preceding anterior-dipole aimed leads (Fig. 3 and 4), the same equipotential line passes through both electrodes.

Figure 6 shows a lead aimed at the posterior dipole. Of the five leads shown, this is the only one where both electrodes are on the anterior tank wall, fairly close to the cardiac generator. The anterior and inferior dipoles are excluded, since one each of their equipotential lines passed through both the 5,3 and 9,2 electrode positions. The posterior dipole equipotentials passing in the vicinity of the two electrodes are at a different potential, giving an ECG deflection when the posterior dipole is excited.
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FIGURE 5

Lead aimed at anterior dipole. One electrode is near, the other at a distance from the cardiac generator. Two unconnected equipotential lines of equal voltage of the posterior dipole field (heavy lines), and a single inferior dipole equipotential (light line) cross at points 6,4 and 19,4. The lead thus excludes the posterior and inferior dipoles but responds to the activated anterior dipole, the field of which is at different potentials at the two lead points. The lead rejects the inferior and posterior dipoles whether they are separately or simultaneously activated. LM = left midaxillary line, S = spine, RM = right midaxillary line, M = midsternum. (Equipotentials in millivolts.) The lower part shows oscilloscope tracings.

Discussion

The unipolar chest leads of Wilson and associates introduced the concept of limited area recording into clinical electrocardiography and this is so far the only system of this type that has been widely applied. Electrode networks applied to the anterior chest wall with lead fields so designed that maximum sensitivity centered in a limited region within the heart, were described by McFee and Johnston. Schmitt described "high distortion differential leads" obtained by planned selection of lead transfer impedances, in essence a reversal of what is attempted in orthogonal leads which should give uniform sensitivity throughout the heart. Selvester et al. investigated the correlation between a multielement model heart and torso surface potentials. Hor-
an et al.\textsuperscript{9} have shown in animal experiments and Hirsch et al.\textsuperscript{10} in the living human, that artificial dipoles in certain intracardiac positions have characteristic torso surface effects.

In a previous paper\textsuperscript{6} we reported an "aimed" ECG method based on experiments in a homogeneous torso model containing a solid three-dimensional model of the heart, the conducting surface of which was divided into \( n \) separate cardiac areas. When potentials were measured at \( n \) surface electrodes after exciting each cardiac area in turn and then again after exciting all areas simultaneously to different strengths, it was possible to calculate the strengths of each of the \( n \) area dipoles by solving \( n \) simultaneous linear equations. The coefficients of the equations were obtained from the \( n \times n \) set of potentials. A table of coefficients for a 6-dipole equivalent cardiac generator and a lead system for aimed recording in patients which contained a variable resistance network to introduce the slanting coefficients were also given. These leads as well as the Schmitt differential leads employ numerous surface electrodes and complex weighting networks, and the smallness of the signal and low signal-to-noise ratio and the relative complexity of the leads remain a problem. In our weighted aimed leads, voltages in patients ranged from 0.5 to 1.0 mv. To overcome some of these difficulties a new approach to aimed ECG recording using a small number of unweighted electrodes and giving signal strength in the conventional ECG range was tested in work reported in the present communication.

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It is quite possible that several pairs of surface electrodes will be insensitive to two particular dipoles. A systematic search would involve checking every possible pair and selecting those which give potential differences negligibly small compared to the maximum values. The selected pairs could then be scrutinized to yield those which give large potential differences when the third dipole is activated. At the present time it is not clear how many leads are available for recording each dipole but it is relatively easy to select one or two leads by inspection of the orthogonal potential maps. A comprehensive search for all acceptable points, as described in the present paper, is a relatively simple digital computer task.

It is evident from the leads so far explored that anatomic proximity between the dipole region and the electrodes of a lead is not necessary to make the lead selectively sensitive to changes in a given dipole. This agrees with the surface potential mapping studies of Taccardi,9 Horan et al.,10 and Barr et al.12 who have shown that the nondipolar content of the cardiac generator is often reflected in surface areas remote from the heart. Not one of the six electrode positions employed in the three anterior-dipole aimed leads shown in Figures 3 to 5 is in the quasi-precordial area of the model. Electrode 6,4 (Fig. 5) is the nearest to the precordium, on the right anterior wall. The electrodes of lead 9,2 to 19,2 (Fig. 3) are both distant from the anterior cardiac region on the right lateral and left posterior walls respectively. The 13,6 to 18,5 lead electrodes (Fig. 4) are both on the back, approximately equidistant from the spine and thus remote from the myocardial area represented by the anterior dipole. It is of interest that the 5,3 to 9,2 lead (Fig. 6) with electrode positions nearest to the anterior chest wall shows selective sensitivity to the posterior dipole and is thus again remote from the dipole it selects.

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Since the surface potential map of the human torso in remote areas shows smaller potential gradients than in the vicinity of the precordium, it is expected that aimed leads with electrodes placed in remote areas will be somewhat less vulnerable to positional variables than leads with electrodes near the heart. Whether this reduction in positional vulnerability is sufficient to make these leads clinically useful is a matter for further investigation.

The equivalent cardiac generator postulated in the present work consists of a finite number of fixed-location and fixed-direction dipoles, each dipole having its own independent time-variable dipole moment. The moments of the artificial dipoles used in these experiments are kept constant. They are thus instantaneous models of a time-variable multiple dipole cardiac generator. The direction of each dipole is fixed and approximately perpendicular to the cardiac surface. A lead selectively sensitive to such a dipole, as any of the leads described in the present communication, records that component of the local force which is perpendicular to the wall. This is accurate only if activity in an area of ventricular myocardium can be represented by the activity of a single dipole. However, an extension of the proposed lead concept to include sets of three aimed leads which record three orthogonal components of the local equivalent dipole does not appear to present any difficulty.

It is expected that these leads show to a varying degree the following disadvantages: sensitivity to changes in torso shape, to torso conductivity structure, electrode position and cardiac position, and to the relative position of dipole areas within the heart. Further exploration of this type of lead will, therefore, aim at reducing these shortcomings by (1) selecting from the great number of possible combinations a few leads least affected by these variables and (2) using in each case several independent leads for determining the behavior of each of the 3 dipoles of the composite cardiac generator. The employment of several leads is made possible by the simplicity of this type of aimed lead. From the leads found least sensitive to the enumerated variables, a further selection will be made to obtain those with the largest signal and signal-noise ratio.

References
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