Digital Computer Model of a Total Body Electrocardiographic Surface Map
An Adult Male-Torso Simulation with Lungs

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SUMMARY
A 20-dipole digital computer model of the electromotive surface generated by the heart with a simulated human male torso, including lungs, is presented. The simulated torso-surface ECG equipotential maps were compared to those seen in normal human subjects by Taccardi and were found to resemble them to within the resolution of these maps throughout most of ventricular depolarization (QRS). On comparison of the simulated maps to those produced when the heart was considered to be a single equivalent dipole, it was found that normal surface maps contain considerable information not accounted for by an equivalent dipole source during the mid and terminal portions of the QRS. This information occurs in areas not sampled by a standard precordial electrocardiogram. The addition of the lungs did not appear to change the surface ECG map in any important respect.

Additional Indexing Words:
Computer heart model Heart simulation ECG computer simulation ECG equipotential surface maps Equivalent dipole

A MATHEMATICAL MODEL of the vectorcardiogram (VCG) with the heart considered to be a set of 20 distributed dipoles eccentrically placed in a sphere of uniform conductivity was recently reported. Agreement was observed in this model between the simulated data and the clinical, VCG, and electrocardiographic (ECG) data of normal subjects and of patients with varying degrees of right and left ventricular hypertrophy, and large and moderate-sized myocardial infarcts. Simulated total body ECG equipotential maps of a normal heart in a normal homogenous male torso, recently published, were similar to those recorded by Taccardi in normal subjects.

In the present simulation, the set of 20 distributed dipoles which simulates the cardiac generator was placed in a male torso with internal inhomogeneities. The torso is a modification of the Gelernter-Swihart simulation. This is an iterative digital computer solution which allows for a realistic torso-shaped external boundary and internal inhomogeneities. It yields as output the potential distribution to the total body surface. Our modification achieves a convergent solution of surface potentials in a realistic human torso, with internal inhomogeneities, including the shape and resistivity of lungs.

Methods
In this simulation, 20 current dipoles, each representing a segment of heart, were located spatially at the centroid of the myocardial segment which they represented. Each dipole of the cardiac generator had a different time-history of current dipole movement strength based on activation sequences measured in this laboratory in dogs. The timing and geometry were extrapolated to account for human anatomy and the longer ventricular myocardial depolarization and were in agreement with those reported by Durrer and associates in a revived, perfused human heart. The direction of each dipole was assigned

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Equipotential maps are plotted on a flat surface obtained by splitting the torso in the midline posteriorly, unrolling, and stretching flat. Note that the surface distribution resembles an equivalent dipole for the first 15 msec, but after this time the surface distribution becomes more complex in nature.

Normal to the average wave front of depolarization as it passed through that segment.

In the data presented, the contributions of this cardiac generator during the 80 msec of ventricular depolarization were computed for the total body surface. Equipotential maps of an
At 45, 55, 65 msec the surface distribution is very complex, multiple satellite minima or maxima come and go and the null line is very complex. The map at the lower left is the same cardiac generator except that all 20 dipoles are located at a point near the center of the ventricular masses, thus representing the heart at that moment as an equivalent dipole. The plot at the lower right is a difference plot at 45 msec and mathematically is the difference between the map at the upper left and the one at the lower left. This gives a visual picture.
unrolled body surface (fig. 1) were plotted at 5-msec intervals on a Stromberg-Carlson cathode-ray plotter. Examples of these plots are shown (figs. 1 and 2) at 10-msec intervals throughout the QRS interval (ventricular depolarization). The 20 dipoles were then coalesced to the center of the ventricular masses to simulate an equivalent dipole generator representation of the whole heart, and the resultant surface maps were subtracted from maps for the distributed dipole generator. An example of this equivalent dipole

of the potentially useful information that must be left behind by an ideal corrected vectorcardiographic lead system.

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Results

With the lungs present, a solution to the boundary value problem was obtained after the sixth iteration. It satisfied the system to within 1.1% of that of the unique solution of the iterative algorithm. Numerical instability resulting from total surface integration error was held to 4.7% of the theoretical value, based on Gauss' theorem.

When the simulated body surface maps with the 20 dipoles representing the heart and with a male torso boundary and lungs were compared to the equipotential map reported by Taccardi3 in a normal male, it was observed that the simulated maps tracked Taccardi's maps to the limit of resolution of these maps through most of ventricular depolarization. When a normal 12-lead ECG, and VCGs representing a Cube, Frank, McFee, and a SVEC III lead system were picked up from this body surface (figs. 3 and 4), they were found to be well within the range of normal as seen with each of those lead systems. This serves to validate the model further. This simulation includes internal inhomogeneities, and comparison with earlier simulation with a homogeneous

Figure 4

Simulated vectorcardiograms with various lead systems. Note the decrease in AP vector magnitude on the Cube lead system as compared to the corrected lead systems.

at 45 msec is seen in the lower left panel of figure 2. The residual nonequivalent-dipole information is shown as a difference map at 45 msec in the lower right panel of figure 2.
torso indicate that these inhomogeneities are not of major importance in influencing the contours of the equipotential maps in normal subjects.

The 20 distributed dipoles of the heart were then coalesced to one location near the center of the ventricular masses, and the entire heart was then represented by a single equivalent dipole generator. When the surface potentials for this equivalent dipole were subtracted mathematically from those generated by the distributed dipole generator, it was found that the simulated normal maps did not differ significantly from those for an equivalent dipole for the first 15 msec of the QRS and for the last 5 to 10 msec. However, from 20 to 70 msec the nondipolar information was considerable and occurred to a significant degree in areas not sampled by current precordial ECG leads. The difference map at 45 msec is shown in figure 2.

Discussion

Whereas the introduction of normal lungs in the model did not seriously disrupt or change the surface map, it is clear from examination of the mathematics and physics of this simulation that a significant change in thoracic geometry, such as one sees in children, females, obese males, patients with emphysema and patients with cardiac enlargement, would change the resultant contour maps considerably. Large and significant inhomogeneities, such as pneumothorax and hydrothorax, can be expected to introduce especially significant changes in the surface maps. Brody and Nelson and associates have demonstrated by theoretical and experimental means that the intracardiac blood mass is indeed a significant inhomogeneity and tends to enhance the equivalent dipole nature of the cardiac generator. Studies are under way to examine these factors in more detail. In time, these maps can be examined by contour plots, perspective plots, and motion picture display and by computation techniques to develop a catalog of changes in surface maps that are related to all the significant known changes in the heart and in the body geometry and resistivity.

As can be seen in figures 1 and 2, the contour lines of the surface maps are compound curves with pseudopod formation, and at certain times (55 and 65 msec) multiple maxima or minima or both, occur. The surface map from 25 msec on cannot be produced by a single fixed, location-equivalent dipole. In other words, after about 20 msec, all normal surface maps generated to the present time in persons and in our simulations contain considerable nonequivalent-dipolar information.

When the entire heart in the simulation was represented by a single equivalent dipole by placing all 20 dipoles at one location near the center of the ventricular masses and when body surface equipotential maps were plotted, all contour lines were simple curves with a smooth-contoured, single maxima and minima throughout (fig. 2, lower left). Such a plot is consistent with the observations of Horan and associates, where a dipole placed in a living animal and a cardiac pacemaker placed in human subjects (Brody, Daniel: Personal Communication) produce such simple, smooth contours in spite of complex internal or external geometry. These data suggest that the distributed nature of the sources of electromotor force in the heart and its complex irregular electromotive surface are mainly responsible for the complex irregular contour seen in all body surface equipotential maps. It is becoming increasingly apparent that any lead system designed to contain only equivalent dipole information (and this is the ultimate goal of all corrected VCG lead systems) is deliberately rejecting available information from the surface which is potentially useful in describing the state of local areas of the cardiac generator. The difference map in figure 2 gives a visual picture of the potentially useful information left behind by an ideal corrected lead system.

Further research is needed to record and evaluate the potential usefulness of simultaneous records from a large number of points on the surface. These points should
be chosen to give maximal information about local areas in the heart with minimal sensitivity to inherent errors, such as errors in measurement and differences in geometry of the patients. It is expected that the computer model reported on herein will provide one tool for such investigation.

One of the immediate advantages of this type of model building has now become apparent. The total body ECG in a normal male torso can now be simulated for all manner of changes in the heart the same way that this was done in the analog and digital simulations of the VCG. Furthermore, now that the difficult computational job of finding transfer numbers from each of the 20 dipoles of the heart to the total body surface has been done, the transfer numbers become simple constants that can be put in between our cardiac generator model and any lead system on the surface. Thus, all manner of abnormalities can be simulated on small analog or digital computers that generate as output, for example, a Cube, a McFee or a Frank VCG, or a standard 12-lead ECG, as well as the total body surface-equipotential map.

Collier (Collier, C. B.: Personal Communication) has been studying such simulations at the Computer Facility at Loma Linda University. An IBM 1620 computer has been used extensively in a teaching environment where the student, medical resident, or internist queries the program regarding infarcts in the usual, or in obscure locations with or without associated right or left ventricular hypertrophy, or both. The student receives as output the Cube, McFee or Frank VCG and a 12-lead ECG displayed on an oscilloscope or as hard copy from a Calcomp plotter. Because the computer is small and operates rather inexpensively, it is reasonable to allow for this type of teaching by man-computer interaction. Such interaction is not permissible, however, with larger computers. The development of realistic and practical time sharing in large computer centers will, of course, make this type of man-computer interaction feasible on large computers, as well.

As greater sophistication is achieved, and the significant additional inhomogeneities are identified and included in the simulation, these transfer numbers from all sizes and locations of the heart to all types of torsos with various kinds of inhomogeneities can be updated as indicated. These sets of constants can then be programmed along with the generator model into the computer simulation which will generate total body surface ECGs, VCGs, and conventional 12-lead ECGs for all such cardiac abnormalities and varying body geometries. These would be readily available to the student program.

This anatomically and physiologically based model will, when properly validated, provide a rational basis for a methodical exploration of the parameters in the torso, such as variations in torso shape, inhomogeneities, and heart size and location that might influence surface ECGs. It will allow for the study of complex combinations of myocardial infarctions, chamber dilatation and hypertrophy, abnormalities of myocardial conduction, and these body geometric changes.

Conclusions

The total body surface equipotential maps resemble those seen by Taccardi to within the resolution of these maps through most of ventricular depolarization.

These simulated and presumably real, normal body surface ECG maps contain considerable information not accounted for by an equivalent dipole source, especially in the mid and terminal portions of the QRS. This information occurs in areas not sampled by the standard precordial electrocardiogram.

Simulated 12-lead ECGs and VCGs for any desired lead system can be picked up at will from the surface maps and recorded as conventional scalar plots or X-Y vector plots. Such simulated ECGs and VCGs are well within the range of those recorded in normals with each of these surface lead configurations which further validates this model.

It can be expected that the physiological
and anatomical basis of the simulation will remove much of the empiricism from current ECG and VCG interpretation. The extent will depend on the ability of the model to reflect real conditions.

References


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