Synthesis of Precordial Potentials from the SVEC III Vectorcardiographic System

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Precordial potentials were synthesized from the components of the SVEC III vectorcardiographic system as an application of the Becking-Burger technic for testing the validity of the single dipole concept. The data was further utilized to construct Burger image loops from living subjects. Discrepancies from pure dipole theory and from the applicability of the SVEC III system are quantified. Limitations of even a perfect vectorcardiographic lead system are defined and discussed.

VECTORCARDIOGRAPHY is a method by which one attempts to diagnose the physical state of the heart by a vector representation of the electrical activity associated with the heart. Since the vectorcardiogram is only a vector quantity, it is self evident that its usefulness is limited to the accuracy with which a single vector can describe this electrical activity. By nature the heart is a distributed current source, having dimensions comparable to distances from it to measuring electrodes. In order that body surface potential measurements be correlated with the actual generator it is convenient (if not necessary) to consider equivalent generators, especially since it is not possible to determine uniquely the actual generator from surface measurements. An infinite number of possible equivalent generators would satisfy the requirement of exactly duplicating the surface potentials produced by the actual heart generator. The purpose of this study is to investigate how well an equivalent generator describable by a single vector quantity can account for all of the information available at the body surface due to the heart's electrical activity.

Since a current dipole is a generator having vector properties it can be equated to the vector quantity measured by the vectorcardiogram. Obviously the physical heart is not a dipole, but the problem now reduces to how well a mathematical point singularity,* such as a dipole, can reproduce the actual surface potentials over the entire surface of a torso-shaped medium. An exact equivalent generator would undoubtedly consist of more than a single dipole. For convenience, the torso is taken as homogeneous, but it is, of course, possible to attempt to solve the problem by considering an inhomogeneous medium.

The infinite number of possible equivalent generators can be divided into two categories, distributed type and discrete type. In the latter classification two seem useful. The first is the multiple dipole equivalent generator of Gabor and Nelson.1 This has the advantage of utilizing only dipoles, which are vector quantities, but in order to describe the generator completely the individual dipole locations as well as their magnitudes and directions must be determined. This means, for example, that a Burger image surface2 is associated with each dipole, and the number of dipoles necessary to make an exact equivalent generator depends upon the complexity of the actual generator. If linearity of the medium is assumed, the effects of individual dipoles can be superposed to determine the net effect. If the properties of the equivalent generator are to be preserved this superposition is to be

* A mathematical point singularity is a point at which the potential has an infinite value. This corresponds to the location of point sources and sinks, or combinations of sources and sinks (such as a dipole). Such singular points are necessary to introduce generators into the mathematics of a physical problem.
FIG. 1. Block diagram of experimental set-up. The X and Z lead networks are from the SVEC III system and contain the required standardization. Only two of the three resolver inputs are used and only one angle control is required (azimuthal). The calibrated attenuators are precision 10 turn potentiometers. See text for references to SVEC III lead system and resolver.

easily distinguished from the erroneous concept of superposing the location of multiple dipoles.

The second discrete-type source is the multipole equivalent generator which consists of a dipole and higher order poles, such as the quadrupole and octupole, all of which are located at a point. Terms of order higher than the dipole are tensor rather than vector quantities, but the point location is a desirable feature. Another advantage of the multipole equivalent generator is that the "nondipole" content of the generator is precisely describable as the sum of all higher order terms. Either of these discrete-type generators can exactly produce the required surface potentials, but they reduce to each other only when they both represent only a single dipole. However, given either of these equivalent generators, the other may, at least in principle, be determined from surface measurements of potential. Although distributed-type equivalent generators appear to offer promise as a means of correlating body surface potentials with heart surface potentials, their solutions represent a higher degree of complexity.

Becking and Burger have pointed out that a necessary condition for surface potentials to be attributed to only a single dipole is that an arbitrary surface potential difference can be synthesized by a linear combination of any other three independent surface potential differences. This is shown in Appendix I to be a more general condition than the cancellation conditions used by Schmitt and Frank. The departure from exact synthesis is used as a measure of "nondipole" generator content. However, quantitative correlation of synthesis coefficient and nondipole content must be made with great care.

METHODS

The Becking and Burger technic is used in this experiment. Precordial potentials (with respect to a midback electrode site at the same height) were synthesized from the X and Z components derived from Schmitt's SVEC system. Figure 1 is a block diagram of the experimental system. A coordinate resolver similar to the one described by Schmitt was used for adding the X and Z components, and the output of this resolver was fed to the vertical plates of an oscilloscope. The direct precordial potential was fed to the horizontal plates of the oscilloscope and the resolver azimuthal control was varied until the resulting Lissajou pattern was as straight a line as could be made. This is a method of shape comparison independent of amplitude. Both signals go through calibrated attenuators and are subtracted by the difference amplifier. The attenuators were adjusted for minimum peak-to-peak value of difference signals on a second oscilloscope, and both wave shapes and differences were then recorded (fig. 2). Relative readings of the attenuators were used to give the amplitude, and the azimuthal control of the resolver the angle, with which a Burger image surface locus was constructed. Y component potentials in the direct precordial lead were minimized by a vertical search on the body.

Precordial potentials were synthesized for seven locations, starting at the left mid-axillary line, and spaced 22.5 degrees apart in azimuth at a level midway between the SVEC III system Z leads. This is approximately the zone covered by the standard leads V_{1} to V_{6}.

Twenty normal subjects ranging in age from 18 to 70 were studied. They were free from cardiac abnormalities as judged by negative histories, normal physical examinations, chest x-rays, and electrocardiograms. The abnormal group consisted of 8 patients with clinically documented episodes of myocardial infarction and abnormal electrocardiograms.

* A visual comparison of synthetic leads with direct precordial leads has been made by Milnor et al. The technic is limited, since good visual comparisons often result in very poor cancellations because of phase differences.
RESULTS

Peak-to-peak values of the residual signal were taken as a percentage of the average of the direct and synthesized precordial signals (these latter signals were approximately equal as a consequence of adjusting the attenuators for minimum residual) and were designated the "synthesis coefficient." The average synthesis coefficient of 7 measurements on each of 19 normals was 23 per cent with a standard deviation of 11 per cent. The synthesis coefficients are respectively 9, 22, and 60 per cent for figures 2A, B, and C. Figures 2A and B are from normal subjects, and 2C from a patient with a well healed infarction.
deviation of ± 7 per cent. The average coefficient of the same number of measurements on six patients (with healed infarctions) was 29 per cent. One out of 20 normal subjects, and 2 out of 8 patients, yielded synthesis coefficients of greater than 60 per cent on two or more precordial sites and were not included in these calculations.

**DISCUSSION**

Results of the experiment can be interpreted from the following standpoints: (1) synthesis coefficient as a measure of nondipole content of surface potentials; (2) synthesis coefficient as a measure of the ability of the SVEC III system to account for precordial potentials; (3) construction of Burger image locus from potential measurements on human beings; and (4) quantitative extension of Milnor’s visual comparison between synthesized and direct leads, including the effects of phase differences.

Interpretation of the synthesis coefficient must be made with caution. If it is assumed that the SVEC III system yields the true dipole component and only the dipole component, then the coefficient can be interpreted as the percent nondipole potentials in a particular lead. However, this assumption is not completely valid, since Schmitt’s own homogeneous model studies have revealed departures from orthogonality and normality in the SVEC III system. Indeed, it is necessary to integrate potentials vectorially over the entire body surface to obtain accurate dipole components.

The synthesis coefficient gives the percentage of precordial potential which is not recorded by the given lead system, in this case the SVEC III system. The large average val-
The degree to which even a very carefully designed lead system falls short of its goal. The necessary condition test for the single dipole equivalent generator is independent of the accuracy of the lead system, since these leads simply provide the equivalent of two independent body surface potentials. The accuracy of the Burger image surface, however, depends on the lead system as well as the magnitude of the residual.

A further difficulty (see Appendix II) in the interpretation of the synthesis coefficient arises from the possibility that the equivalent dipole source location may not be fixed as the direct precordial lead is moved from point to point across the chest. The image surface locus was constructed to explore this source of error. Most of the normal subject image surfaces were roughly similar in shape to those determined by homogeneous torso model studies with the exception that one point was often located so that an irregular shape resulted. This indicates further departure from the single fixed location dipole theory other than the existence of finite synthesis coefficients. Some patient image surfaces were as regular as those of normal subjects, but others (fig. 3) were extremely irregular. There is an ambiguity in this irregularity since the points of these latter curves correspond to very high synthesis coefficients, and therefore their exact location was not sharply defined by the experiment. The high values of the coefficients, however, are significant in themselves.

Some lead systems for vectorcardiography have been devised to obtain normalized orthogonal leads which remain so if the equivalent dipole location is anywhere within a prescribed volume inside the body. An equivalent lead system results when equal weight is given to multiple dipoles located within the prescribed volume. If the perfect lead system is defined as one which accomplishes these objectives exactly, then by definition it can respond only to the dipole component of an exact equivalent generator.

In a specific case, the exact equivalent generator might consist of multiple dipoles located within the prescribed volume. Since the perfect system gives equal weight to all dipoles, the potentials measured by the system would be the same as if the generator were placed in an infinite medium and the measuring points were very far from the source compared to its dimensions. As far as this distant point is concerned, individual dipoles could be superposed at any point in the volume and a potential identical with that induced by the original multiple dipole generator would be measured. This potential is due to the dipole component. If now the multiple dipoles were replaced by their equivalent multipole generator, located at a point, the potential could be expanded as

\[ V = V_{\text{dipole}} + V_{\text{quadrupole}} + \text{higher order terms} \]

where the terms are distinguished by their dependence on \( r \), the distance from generator to measuring point (e.g., \( V_{\text{dipole}} \) is proportional to \( 1/r^2 \), \( V_{\text{quadrupole}} \) is proportional to \( 1/r^3 \), etc.). Thus, if \( r \) is very large, only the dipole term is present. This potential will agree with the potential obtained by superposing the multiple dipoles, and illustrates why the perfect lead system responds to only the dipole term of the multipole expansion.

The higher order terms represent nondipole components of the equivalent generator and it can be seen that the perfect lead system does not respond to them at all. Note that the potential due to the dipole term can be expressed as \( \mathbf{V} = \mathbf{C} \cdot \mathbf{P} \), where \( \mathbf{P} \) is the vector corresponding to the dipole source and \( \mathbf{C} \) is the Burger image vector. This can not be done as simply for the higher order terms, since they are not vectors, but rather tensors (see, for example, reference 3). If the multiple dipole equivalent generator is used and linearity is valid, the complete description requires a different image surface for each dipole. This means a vector loop for each dipole and information concerning its location in space.

**Summary**

The degree to which precordial potentials can be synthesized from the SVEC III vectorcardiographic lead system was measured on 20 normal subjects and 8 patients, and expressed
as a synthesis coefficient. The synthesis of any surface potential from any other three independent surface potentials is a necessary condition for a single dipole equivalent generator. The discrepancies are of the order of 20 to 30 per cent on a peak-to-peak basis in most of the subjects studied with much higher values on 3 subjects. The quantification of nondipole content from these figures requires assumptions and must be interpreted with caution. The synthesis experiment yielded data for construction of the Burger image surface subject to the accuracy of the SVEC III system and the nondipole content of surface potentials. A perfect vectorcardiographic lead system is defined, and its limitations pointed out with respect to equivalent generators representing heart action. A single vector loop by itself can completely describe the electric activity of the heart only if the heart can be represented exactly by a single equivalent dipole.

Although the possibility of considerable nondipole content of surface potentials exists, the synthesized wave shapes are roughly equivalent to direct precordial potentials when examined visually on a time base. The dipole generator by itself can produce time patterns that are identical to actual surface potentials in a majority of individuals as far as most clinical observations are concerned. There is a distinct possibility that nondipole potentials are large enough to be of clinical value in some patients if techniques can be developed to measure them simply and accurately.

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Summario in Interlingua

Le grado a que potentiates precordial pote esser synthetisate ab le systema vectorcardiographic SVEC III esseva mesurate in 20 subjectos normal e in 8 patientes. Illo esseva exprimite como coefficiente de synthese. Le synthese de non importa qual potential de superficie ab non importa qual grupo de tres independente altere potentials de superficie es un condition necessari pro un generator de equivalente dipolic unic. Le discrepantias es del ordine de 20 a 30 pro cento, super le base de pico a pico, in le majoritate del subjectos studiate. In 3 subjectos le valores esseva mul- to plus alte. Le quantification de contenu non-dipolic ab iste cifras require suppositions additional e debe esser interpretate multo cautamente. Le experimento de synthese produc Caveva datos pro le construction del superficie de imagine de Burger, intra le limites del accuratia del systema SVEC III e del contenu non-dipolic de potentialas de superficie. Un perfecte systema de derivationes vectorcardiographic es definite, e su limitationes es signalate con respecto a generatores de equivalente que representa le action del corde. Un sol spira vectorial per se pote describer complemente le atividade electric del corde sol- mente si le corde pote esser representate exactamente per un dipolo equivalente unic.

Ben que le possibilitate de un considerabile contenuto non-dipolic de potentialas de superficie existe, le synthetisate conformationes de una es grossiermente equivalente a potentia- les precordial quando examinate visualmente super un base de tempore. Le generator dipolic per se pote producir configurationes de tempore que es identic con real potentialas de superficie in le majoritate del subjectos, al minus con respecto al majoritate del observa- tiones clinic. Il existe un forte possibilitate que potentialas non-dipolic es sufficientemente grande pro esser de valor clinic in certe pa- tientes, providite que technicas pote esser dis- veloppate pro mesurar los simple e precisemente.

Appendix I

Burger points out that the method of Becking (i.e., the synthesis of a fourth surface potential from three other independent surface potentials) is a generalization of the mirror pattern technic of Schmitt and Frank. To see this, one writes the fourth potential as a linear combination of the three other potentials as

\[ V_4 = aV_1 + bV_2 + cV_3 + V_R \] (1)

where \( V_R \) is the residual potential. (It is due to the nondipole content of the generator, but is not related to it in a simple manner, since \( V_R \) and \( V_4 \) probably have some nondipole content.) The
expression for residual potential of Frank's four-electrode system is

$$V_R = (1-n) V_1 + n V_2 + (1-m) V_3 + m V_4$$

where $n$ and $m$ are the relative positions of the two potentiometers and $V_k$ ($k = 1, 2, 3, 4$) are body surface potentials. Equation 1 is less restricted, since $a$, $b$, and $c$ are independent and can also take either positive or negative values. The mirror pattern technic requires a body search to make up for its lack of generality, and also requires a more arbitrary definition of "cancellation coefficient."

A. M. Scher points out correctly that equation 1 is a test of how well a fourth potential can be synthesized by three independent sources (which are obviously proportional to $V_1$, $V_2$, and $V_3$ or a linear combination of these) of which a dipole is only a special case (personal communication). Equation 1 with $V_R$ zero, however, remains a necessary (but not sufficient) condition for a single dipole equivalent generator to exactly reproduce body surface potentials over the entire surface. Of course, one must remember that it is not possible to define uniquely the actual generator from body surface potentials alone. To test the necessary condition, then, for a dipole equivalent generator, four surface potentials are required—one more than the number of independent time variations.

**Appendix II**

The method of synthesizing a fourth potential from three other independent ones can lead to almost zero residuals if applied indiscriminately. For instance, if one attempts to synthesize a particular chest potential from three others, one of which is taken close to the original, the residual will be extremely low. If, further, one of the references is moved close to the original point as this point is moved over the whole body, then low residuals will appear over the whole body. This is not interpretable as good dipole evidence, since the error due to assuming a constant location dipole can now be very large. It is significant that the SVEC III system electrodes were not physically close to the precordial points used in this experiment. Further, the SVEC III leads are composed of fixed amounts of their individual components, which reduces the effects noted above.

**References**

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