The Use of the Lead-Field Concept in the Development of Leads Satisfactory for Vectorcardiography. I. The Sagittal Lead

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After a brief discussion of the lead field concept and an illustration of its application using a Teledeltos paper model, studies carried out on patients, employing multiple electrode or grid arrangements located over the precordium and the left posterior chest, to obtain the sagittal component of cardiac electromotive forces (e.m.f.'s), are described. On the basis of these observations, a minimum of 15 properly arranged and connected electrodes should be employed in the anterior electrode system but fewer will be needed posteriorly. A scheme, using 63 electrodes mounted in sponge rubber, has been devised to simplify the grid arrangement.

Some of the enthusiasm of a few years ago about the value of spatial vectorcardiograms in clinical diagnosis has died down recently and is being replaced by studies being carried out by competent groups or individuals, including both biophysicists and physicians, in an attempt to answer some of the basic questions that must be satisfactorily settled before vectorcardiography can be considered to be much of a science.

Everyone would agree that vectorcardiograms should be taken with leads or lead systems that give good representations of the cardiac electromotive forces (e.m.f.'s) in transverse, vertical, and sagittal directions, but there is no general agreement regarding which, if any, of the several methods proposed for the purpose are satisfactory. The sentiment seems to be increasing that neither the original scheme proposed by Duchosal and Sulzer1 and modified by Grishman and associates2 nor the tetrahedron employed by Burch and associates3 and others give accurate vectorcardiograms. If several experts in the field of vectorcardiography were asked why the systems mentioned are not satisfactory, different answers involving matters like eccentricity of the mean cardiac dipole and unsuitable lead coefficients would be given, and all these replies would be correct and quite logical from the point of view of each of these individuals. Our answer to this query would be a very simple one; namely, that the lead fields associated with most of the leads in question are obviously unsuitable and cannot give good transverse, vertical, or sagittal components of the mean cardiac voltages.

The lead vector proposed by Burger and van Milaan4 several years ago is the basis of many important recent studies on electrocardiographic leads. Because it involves the concept of a single equivalent dipole in the heart, it has naturally led to extensive studies, partly in human beings and partly in models, to prove that portions, at least, of the electrocardiogram can be accurately represented by a single dipole, and further to establish the location of this dipole within the heart. Although much of this work is important and worthwhile, it seems to us that many of the investigators are pursuing their studies without

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full appreciation of the lead-field concept and its advantages in estimating the behavior of leads of any kind and in the design of better ones, especially for vectorcardiography.

This is not the place for a detailed discussion of the lead field and its value, but readers interested in this subject are referred to papers by McFee and Johnston. It should be pointed out, however, that the lead field not only extends the lead-vector concept to the entire heart, thereby eliminating the need to assume the existence of a single dipole, equivalent to all cardiac e.m.f.'s, but provides a method which is simple and easy to use.

In this paper and the ones that follow, leads or lead systems are described that the authors believe to be ideal for vectorcardiography. This first article is devoted to a discussion of a system for the anteroposterior or sagittal component of the cardiac e.m.f.'s. This component is considered first because the arrangement to obtain it illustrates the use of the lead field particularly well and also because most of the leads commonly employed to obtain it are not very good ones. Before the methods used on patients are described, an illustration of the principle employed, using Teledeltos paper,* is presented.

Figure 1 is a model of the sagittal view of the human torso made nonhomogeneous after the method of Brody and Romans. Essentially, it consists of three layers of Teledeltos paper insulated from one another with photographic mounting paper except for a one centimeter margin on the underside of the two top layers. These margins are electrically bonded with a mixture of silver print ink, amyl acetate, and polyester coil dope, so that each layer conducts approximately one third of the current. The second layer contains cutouts for the lungs, and the third layer consists only of the heart and great vessels. By this process the lungs have one third the conductivity of heart and great vessels, and the chest wall has a conductivity halfway between that of lungs and heart. The electrode system to obtain the sagittal component from this model is provided

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*This special paper with a uniformly conducting surface has been available through the courtesy of the Western Union Company.

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FIG. 1. The lead field of the proposed sagittal lead in a two-dimensional nonhomogeneous model. Except for a concentration of the lead-field lines near the apex, the field is nearly uniform and horizontal through all regions of the heart.

by 10 uniformly spaced electrodes on the anterior and posterior surfaces of the chest, each attached by a 50,000 Ω resistance to a common terminal. The resistance from any one electrode to the electrode on the opposite side of the manikin is of the order of 4,500 ± 1000 Ω. Therefore, the 50,000 Ω resistance in each arm of the electrode system is sufficiently large to insure a reasonably uniform current field. To determine this field in the model, a 125-volt battery was attached to electrodes $V_A$ and $V_P$ and isopotential lines were carefully plotted with the two probes of a vacuum-tube voltmeter. After the isopotential lines were
mapped, the current lines were drawn perpendicular to them, and these, of course, constitute the lead field.

Inspection of figure 1 indicates that the general course of the lead field through the heart is anteroposterior in direction and, except for the apical region where some curvature is present, the electrode system in question would have excellent sensitivity for desired sagittal components and little for vertical components of cardiac voltages. The concentration of lead-field lines near the apex suggests that this electrode system would record an e.m.f. located in this region with somewhat greater amplitude than an equal and similarly oriented e.m.f. located higher in the heart. It must be remembered, however, that curvature and lack of uniformity in the lead field in the model are due entirely to assumed differences in conductivity between areas that represent the heart and great vessels, the lungs, and subcutaneous tissues, and it is likely that such large differences do not exist in living human subjects. Furthermore, studies bearing on this point done with fluid mappers by McFee, Stow, and Johnston suggest that variations in tissue conductivity have only minor effects on the character of the lead field within the heart.

If a model like figure 1 is made, using a horizontal section through the middle of the heart, instead of the sagittal view, and if the lead field is obtained with nine equally spaced and similarly connected electrodes over the anterior and posterior cardiac areas, the field will again be essentially anteroposterior in direction and reasonably uniform.

It is clear that the ideal lead for the sagittal component in human subjects should be some sort of multiple electrode or grid system, and only details remain to be decided. Some of the questions to be settled are: How many electrodes will be required, and how should they be arranged on the precordium and on the left posterior chest? What should be the size of the resistances connected to the individual chest electrodes and to the common anterior and posterior lead terminals? Finally, can some scheme be devised for application of the multiple electrode arrangement that will be simple and quick? The balance of this paper is largely concerned with these matters.

A few words should be said about the use of large, thin, flexible metal plates rather than multiple small electrodes (connected to single terminals through large resistances) for the anterior and posterior electrodes. At first sight this type of arrangement might seem ideal, and something of this kind may be shown to be useful. The big problem is, of course, to be sure whether such electrodes have a uniform contact resistance over their entire surface. Even with careful preparation of the skin over which the electrode is placed, there is no certainty that even approximately uniform resistance is obtained, and there is no direct way to test

Fig. 2. The placement of electrodes on the front and back of the chest in the 15 point grid system is accomplished so that the grid overlaps the projection of the heart on the chest wall.
this. We have tried such electrodes on a few occasions, and the records obtained have been similar but not identical with those secured with multiple electrode grids. We suspect that simple metal plates would give a better anteroposterior component than schemes now in current use, but their value remains to be determined by further comparisons with results obtained with multiple electrode systems.

**Method**

Electrocardiographic studies using two different schemes for application of multiple electrodes for obtaining the sagittal component of cardiac voltages were done on 39 individuals, some with normal and some abnormal hearts. In the first group 15 small (flat buttons of solder about 5 mm. in diameter) electrodes were placed over the precordial area and on the left posterior chest wall as shown in figure 2. Each of these electrodes was carefully applied with electrode paste, fastened securely in position with Scotch tape, and connected through large resistances to single anterior and posterior terminals. Since the resistance measured between corresponding single anterior and posterior electrodes was found to be approximately 22,000 Ω, but varied considerably, 50,000 Ω resistances originally employed were replaced by resistances of 1,000,000 Ω, to be sure that variations in skin resistance at individual electrodes would not disturb the lead field of the electrode system. After an electrocardiogram had been recorded with all of the electrodes in the circuit, additional tracings were taken following progressive reduction in the number of electrodes in use. This procedure was carried out for both the anterior and posterior grids, and as the electrodes were reduced in number, they were kept as well distributed as possible over the area covered by the original 15.

Because application of 30 individual electrodes is time consuming and would not be a practical method for routine vectorcardiographic work, a simpler and probably better method for obtaining the sagittal component was devised. In the second group of patients studied, the arrangement illustrated in figure 3 was employed. The anterior and posterior electrode systems were alike; each consisted of a rectangular piece of sponge rubber measuring 10 by 12 inches, in which nine rows of brass machine screws were mounted with the heads (the contact electrodes) 1 inch apart. Seven screws were used in each row, so that a total of 63 electrodes were available for both anterior and posterior grid arrangements. Each electrode was connected through a resistance of 1,000,000 Ω to a common terminal. A second piece of sponge rubber of the same size was fastened to the first to protect the wires soldered to the shanks of the machine screws and provide a certain amount of "give" when the electrodes were placed on the chest. Before the electrodes were applied, the skin was prepared by rubbing with alcohol, followed by ether. After electrode paste was applied to the head of each machine screw, the entire unit was placed on the left anterior and posterior chest with the electrodes centered as well as possible over the cardiac areas. Good contact with the posterior electrodes was assured by having the patient lie on them. Several strips of wide gauze wrapped around the subject and electrode assemblies and sand bags over the anterior unit provided good approximation between the anterior electrodes and the precordium. Impressions of each electrode in the skin after removal of the assemblies were evidence of good contact. Although we anticipated some difficulty with this electrode arrangement, none occurred in any of the 18 subjects on whom it was used. The resistance measured between two corresponding individual electrodes was quite variable but averaged around 50,000 Ω, and the resistance of the full grid (including the 1 meg.ohm resistances) was around 100,000 Ω.

In the second group of subjects, like the first, electrocardiograms were taken with all electrodes in the circuit, and then tracings were taken as the number of active electrodes was decreased in both anterior and posterior grids.

All electrocardiograms were taken with a Sanborn Twin-Beam Electrocardiograph, and a simultaneous limb lead, usually lead II, was recorded with each sagittal lead. The effect of reducing the number of active electrodes from the full grids could have been studied in each group of patients by recording vectorcardiograms in the horizontal and sagittal planes, and a few such records were taken. It was thought, however, that the simplest way to find out how many electrodes must be used in both anterior and posterior grids was to study the changes in conventional electrocardiograms representing the sagit-

![Fig. 3. Sixty-three electrodes mounted in rectangular pieces of foam rubber comprise the anterior and posterior grid electrodes for the second group of patients. The switch arrangement permits uniform reduction in the number of electrodes used in the circuit.](image-url)
LEAD-FIELD CONCEPT AND VECTORCARDIOGRAPHY

**Fig. 4.** A. An example of the tracings taken using the 15 point sagittal lead illustrated in figure 2. Reduction of the number of electrodes in successive tracings as shown in table 1 caused erratic changes in phase, voltage and appearance of the Q and R waves. Lead I, recorded simultaneously, is the lower tracing in this figure. B. An example of the tracings taken with the 63 point grid electrode. Reduction in the number of electrodes (table 2) results in only minor changes. Lead II, recorded simultaneously, is the upper tracing in this figure.

**Table 1.—Fifteen Point Grid Electrode System**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description of Lead (Fig. 2)</th>
<th>Fig. 4A</th>
<th>PR (sec.)</th>
<th>QRS (sec.)</th>
<th>Peak Q (sec.)</th>
<th>Peak R (sec.)</th>
<th>Height of Q (mm.)</th>
<th>Height of R (mm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES-10</td>
<td>Full grid (not including electrodes 1, 2, 3 posteriorly)</td>
<td>A</td>
<td>1.500</td>
<td>.0916</td>
<td>.0328</td>
<td>.0638</td>
<td>3.75</td>
<td>15.75</td>
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<tr>
<td></td>
<td>Vp (Solid plate)—Va (Solid plate)</td>
<td></td>
<td>1.567</td>
<td>.0883</td>
<td>.0208</td>
<td>.0583</td>
<td>4.00</td>
<td>18.50</td>
</tr>
<tr>
<td></td>
<td>Posterior electrodes being removed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>electrodes 7, 11, 15 removed</td>
<td>B</td>
<td>1.595</td>
<td>.0867</td>
<td>.0235</td>
<td>.0473</td>
<td>3.75</td>
<td>16.50</td>
</tr>
<tr>
<td></td>
<td>electrodes 6, 10, 14, 18 removed</td>
<td>C</td>
<td>1.510</td>
<td>.0844</td>
<td>.0264</td>
<td>.0542</td>
<td>2.90</td>
<td>16.00</td>
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<td>electrodes 5, 9, 13, 17 remain</td>
<td>D</td>
<td>1.468</td>
<td>.0827</td>
<td>.0290</td>
<td>.0571</td>
<td>3.90</td>
<td>16.20</td>
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<td></td>
<td>electrode 9 remains</td>
<td></td>
<td>1.590</td>
<td>.0846</td>
<td>.0318</td>
<td>.0631</td>
<td>3.75</td>
<td>16.10</td>
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<tr>
<td></td>
<td>Anterior electrodes being removed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>electrodes 1, 4, 8 removed</td>
<td>E</td>
<td>1.720</td>
<td>.0716</td>
<td>.0340</td>
<td>.0654</td>
<td>5.00</td>
<td>16.00</td>
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<td>electrodes 3, 6, 10, 14 removed</td>
<td>F</td>
<td>1.751</td>
<td>.0691</td>
<td>.0219</td>
<td>.0494</td>
<td>2.60</td>
<td>16.00</td>
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<td></td>
<td>electrodes 7, 9, 11, 15 remain</td>
<td></td>
<td>1.560</td>
<td>.0874</td>
<td>.0318</td>
<td>.0655</td>
<td>3.00</td>
<td>18.80</td>
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<td></td>
<td>electrode 9 remains</td>
<td></td>
<td>1.640</td>
<td>.0746</td>
<td>.0394</td>
<td>.0542</td>
<td>10.00</td>
<td>12.40</td>
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Diagnosis: Diabetes with Kimmelstiel-Wilson disease; aortic stenosis with left ventricular hypertrophy. Postmortem, left ventricle 17 mm., weight 460 Gm.

**Table 2.—Sixty-Three Point Grid Electrode System**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description of Lead (Fig. 3)</th>
<th>Fig. 4B</th>
<th>PR (sec.)</th>
<th>QRS (sec.)</th>
<th>Peak Q (sec.)</th>
<th>Peak R (sec.)</th>
<th>Height of Q (mm.)</th>
<th>Height of R (mm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF-37</td>
<td>Full grid 63-63 electrodes</td>
<td>A</td>
<td>.168</td>
<td>.112</td>
<td>.0208</td>
<td>.0602</td>
<td>4.72</td>
<td>27.50</td>
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<tr>
<td></td>
<td>Posterior electrodes being removed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>63-35 electrodes</td>
<td>B</td>
<td>.170</td>
<td>.108</td>
<td>.0218</td>
<td>.0626</td>
<td>4.23</td>
<td>26.62</td>
</tr>
<tr>
<td></td>
<td>63-16 electrodes</td>
<td>C</td>
<td>.175</td>
<td>.110</td>
<td>.0192</td>
<td>.0610</td>
<td>4.27</td>
<td>26.54</td>
</tr>
<tr>
<td></td>
<td>Anterior electrodes being removed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>35-63 electrodes</td>
<td>D</td>
<td>.165</td>
<td>.108</td>
<td>.0202</td>
<td>.0610</td>
<td>4.95</td>
<td>27.30</td>
</tr>
<tr>
<td></td>
<td>16-63 electrodes</td>
<td>E</td>
<td>.168</td>
<td>.110</td>
<td>.0243</td>
<td>.0653</td>
<td>4.75</td>
<td>27.27</td>
</tr>
<tr>
<td></td>
<td>Anterior and posterior grid reduced</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>35-35 electrodes</td>
<td>F</td>
<td>.168</td>
<td>.110</td>
<td>.0210</td>
<td>.0598</td>
<td>4.70</td>
<td>27.50</td>
</tr>
<tr>
<td></td>
<td>16-16 electrodes</td>
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<td></td>
</tr>
</tbody>
</table>

Diagnosis: Hypertension with left ventricular hypertrophy.
Fig. 5. Sagittal vectorcardiograms using the grid type electrodes. A. All 63 points are used. B. The number of active electrodes is reduced anteriorly and posteriorly to 16.

tal component as the number of active electrodes was progressively decreased.

A number of measurements of the tracings were made, including estimation of the P-R and QRS intervals, the size of the waves in the QRS complexes, and the time intervals between peaks of Q, R, and S in the sagittal lead and the beginning of the QRS complex in the simultaneously recorded limb lead. Amplitude measurements were, of course, corrected for errors in standardization, and most of the time intervals were measured with a Lucas comparator. Figure 4 shows records taken from a patient in each group illustrating the effect of decreasing the number of electrodes in the anterior grids. In figure 4A changes in form and amplitude are obvious on inspection, as the number of electrodes was decreased from the full grid of 15. On the other hand, in figure 4B there is little change in the sagittal electrocardiogram when the full grid of 63 electrodes was reduced to 16, the smallest number employed in this group.

Tables 1 and 2 illustrate the type of measurements made in the two groups, where the full grids consisted of 15 and 63 electrodes, respectively. These data support the tentative conclusions suggested by the tracings shown in figure 4. It is unnecessary to discuss these tables in detail, but a few important matters should be pointed out. As might be expected, table 1 shows that the number of electrodes in the posterior system can be considerably reduced without greatly altering the electrocardiogram, while a comparable change in the anterior grid caused definite alteration in the tracing. This situation is, of course, due to the fact that the heart lies much closer to the anterior than to the posterior chest wall, and it would be anticipated that fewer electrodes posteriorly would still give a lead field essentially uniform and of the proper direction through the heart.

RESULTS

Although it may be possible to use as few as nine or even six anterior electrodes and still obtain a fairly accurate sagittal electrocardiogram, it must be remembered that the importance of the location of individual electrodes increases greatly as the number decreases, and the proper location of a small number would vary greatly in different subjects. For this reason alone, we feel that a reasonably large number of electrodes is advisable in the anterior grid.

The results of the studies presented in table 2 supplement those of table 1. They indicate rather clearly that as many as 63 electrodes in the anterior grid are unnecessary and suggest that the minimal number tested, that is 16, may be satisfactory. From the theoretic standpoint, however, the large number should have some advantages, and with the sponge rubber assembly technic, it is not much more difficult to use them.

SUMMARY AND CONCLUSIONS

In a brief discussion of matters relating to electrocardiographic leads, particularly ones suitable for vectorcardiography, advantages inherent in the use of lead-field concept are pointed out. In this connection, it is emphasized that the lead field removes an important limitation imposed by use of the lead vector; namely, that cardiac e.m.f.’s must be assumed to be concentrated in a single equivalent dipole. The lead field within the heart actually gives the direction of lead vectors for e.m.f.’s located anywhere in this organ.

A study made with a model of the human torso in the sagittal plane using Teledelto paper indicates that several uniformly spaced electrodes over the precordium and left posterior chest, each connected through large resistances to two terminals, create a lead system with a lead field of the type necessary for a good sagittal lead.

Results are presented of studies on human subjects using multiple electrodes in a grid arrangement over the precordium and left chest behind the heart as a method for securing the sagittal component of cardiac e.m.f.’s. These studies suggest that approximately 15 electrodes will be required in the anterior group if an accurate lead is to be obtained. The posterior grid may consist of fewer electrodes without seriously affecting the performance of the lead.

Since the application of 15 individual
electrodes is time-consuming and would not be practical for routine vectorcardiography, we have devised a special electrode arrangement consisting of large sheets of sponge rubber in which 63 brass machine screws, which serve as electrodes, are mounted. These electrode assemblies have proved to be quick and easy to use.

**Summario in Interlingua**

Es presentate un breve discussion de derivationes electrocardiographic, specialmente del typo usabile in vectecardiographia, con le objectivo de signalar le avangages inherente in le uso del concepto del campo de derivation. In iste connexion le facto es sublineate que le uso de ille concepto elimina un importante limitation in le application del vector de derivation, i.e. le limitation que on debe supponer que le cardiac fortias electromotive es concentrate in un sol dipolo equivalente. De facto, le campo de derivation intra le corde da le direction de vectores de derivation pro fortias electromotive de non importa qual location in ille organo.

Un studio executate per medio de un modello del torso human in le plano sagittal (usante papiro Teledeltos) indica que plure electrodos, uniformemente spaziate supra le precordio e le thorace sinistro-posterior e omnes conectite via alte resistentias con duo terminales, crea un systema de derivation con un campo de derivation del typo requirite pro un bon derivation sagittal.

Es presentate resultatos de studios in subjectos human, utilisante multiple electrodos de arrangiamento grilliforme supra le precordio e le thorace sinistre a retro del corde como methodo de assecurar le componente sagittal de cardiac fortias electromotive. Iste studios indica que circa 15 electrodos es requirite in le gruppo anterior si un derivation accurate debe esser obtenite. Le grillia posterior pote consiste de minus electrodos sin que le efficacia del derivation es seriemente obstruite.

Considerante que le application de 15 electrodos individual consume multe tempore e es consequentemente impractic in vectecardiographia routinari, nos ha elaborate un special arrangiamento de electrodos consistente de grande placas de cauchu spongia in que es montate 63 vites de laton serviente como electrodos. Iste combinationes de electrodos se ha provate capace de manipulation rapide e facile.

**REFERENCES**

The Use of the Lead-Field Concept in the Development of Leads Satisfactory for Vectorcardiography. I. The Sagittal Lead
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