A Lead System Designed to Record Proximity Effects on the Præcordial Electrocardiogram*

RAUL GAMBOA†

From the Sharon Cardiovascular Unit of the Children's Hospital Medical Center, and the Department of Pediatrics, Harvard Medical School, Boston, Massachusetts, U.S.A.

When the præcordial leads were incorporated into clinical cardiology (Wilson *et al.*, 1944) they were considered to be influenced primarily by the "potential variations" of the myocardium nearest the exploring electrode. The term "potential variations" has been frequently misunderstood (Milnor, Talbot, and Newman, 1953; Sodi-Pallares *et al.*, 1959). "Wilson *et al.* (1944) stated that the potential variations of a præcordial point must represent a mixture of many different components. The extent to which the potential variations of the nearest parts of the ventricular surface dominate this mixture depends upon their relative magnitude and size of the area over which similar oscillations in potential take place simultaneously. The interpretation of the deflections of unipolar leads from the body surface according to the principles that apply to the interpretation of the ventricular complexes of unipolar direct leads may thus give rise to erroneous conclusions. . . ."

Although there is strong evidence in the published work (McFee and Johnston, 1953, 1954a, b; Burger and van Milaan, 1946, 1947, 1948; den Boer, 1952) that the præcordial leads indeed are often predominantly influenced by the myocardium nearest the exploring electrode, it is also recognized that their power of discrimination is not as high as that desired by clinicians.

On the other hand, it has been postulated (Milnor *et al.*, 1953; Pipberger and Lilienfeld, 1958) that, with very few exceptions, the same clinically useful information can be obtained from three orthogonal leads (x, y, z), and that, in addition, the standard præcordial leads are only recording the dipolar behaviour of the electrical forces of the heart. This

assumes that the heart acts as a simple dipole generator. In fact, however, the heart is not so simple: electrical fields generated in one portion of the heart may oppose those in another part, and, therefore, much "potential" information is lost in a single dipole representation. The "ideal" orthogonal lead system, designed to obtain a true weighted integration of all heart sources free of proximity effects will be excellent for the achievement of the "equivalent heart dipole," but poor, certainly, from the viewpoint of localization.

It is the purpose of the present study to show that, by applying the lead-field theory of McFee and Johnston (1953, 1954a, b), it is possible to design a præcordial lead with higher non-uniform sensitivity of recording than present standard leads, which will emphasize the electromotive forces in the myocardial area proximal to the exploring electrode, while being relatively insensitive to forces in other regions of the heart. This lead system, then, represents an attempt to "move closer" to the heart, and "away" from the equivalent dipole concept.

METHODS AND MATERIAL

This type of præcordial lead (hereafter referred to as proximity lead) is illustrated in Fig. 1. It consists of an exploring central electrode surrounded by a network of 6 electrodes mounted on a rubber disk 7.0 cm. diameter. The central electrode is connected to the positive terminal of a lead, and each of the outer electrodes is connected, through 200K resistors, to the negative terminal of the lead (Fig. 2).

Two-dimensional Lead-field Analysis. Two dimensional models of human form were made of conducting paper.* On these models, tacks were applied to the sites of the electrodes simulating both a proximity lead and a standard præcordial lead system.

The proximity lead and the standard præcordial lead were energized with DC current, individually, and the

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† Present address: The University of Texas, Southwestern Medical School, Department of Pediatrics, Dallas, Texas.

* Teledeltos. General Electric Co.

FIG. 1.—The proximity lead. Each electrode is 1 cm. diameter, and the distance between them is also 1 cm. (see text).

resulting isopotential lines were established by a high-sensitivity voltmeter. The flow-lines were then drawn perpendicularly to the isopotential lines (Fig. 3).

Three-dimensional Analysis. A plastic model was used, moulded from a cast of a human body (Fig. 4). Considering that the human body is not a homogeneous volume conductor, the lungs, the spinal column, and the liver were simulated, following Burger and van Milaan's technique (1946, 1947, 1948). Brass screws representing electrodes penetrated the walls of the torso

model in the desired positions for the proximity lead, and for the standard præcordial lead.

Two sizes of energizing dipoles were used: disk electrodes cut both 1 cm. and 2 cm. in diameter. These were stimulated intermittently with a 1.5 volt battery through a 500 series resistor. Both types of præcordial lead systems were connected in parallel with a 9.25 mfd capacitance to a DC input of a Sanborn 350-1600 ECG pre-amplifier.

Two types of observations were made. First, iso-response lines were determined using the 2 cm. dipole stimulator, with the axis of the dipole perpendicular to the plane of the proximity or standard præcordial leads. Similarly, such lines were determined when the axis of the dipole was co-directional with, and at 30° and 60° to the plane of the axis of the proximity lead (Fig. 5 and 6); and second, proximity effects were studied by placing two sets of dipoles in the model, simultaneously. The larger dipole, with 2 cm. disks, was placed at a mean of 65 mm. from the anterior chest wall, with the small dipole at a variable but closer distance. The polarities were in opposition to one another (Fig. 7).

Clinical Observations. Tracings were obtained using the proximity lead in 20 human subjects: 10 from normal children, ranging from 5 to 10 years of age; and 10 from patients with different degrees of right ventricular hypertension. Some examples of these are shown in Fig. 8 and 9.

RESULTS

Two-dimensional Field Analysis. Fig. 3A shows a lead field of a standard præcordial lead. The flow

FIG. 2.—Diagram of the proximity lead, electrodes, and resistor arrangements.

FIG. 3.—Lead field patterns of a standard præcordial lead (A), and proximity lead (B).

FIG. 4.—Plastic torso model used experimentally. The energizing dipoles could be introduced through the opening at the neck. This model could be separated at the level of the waist in order to place the simulated lungs, spinal column, and liver (see text).

FIG. 5.—Isoresponse lines of the proximity lead when a current dipole is introduced in the torso model.

lines appear to radiate from the exploring electrode in “straight lines” covering the entire heart area, with “crowding” on the side of the “heart” toward the exploring electrode. Fig. 3B shows a lead field pattern of the proximity lead. The flow lines in this lead appear to radiate from the exploring electrode like a “fountain”, sparsely covering the posterior surface of the heart, and with greater crowding of the flow lines on the heart surface closest to the exploring electrode.

Three-dimensional Analysis. The results of introducing one dipole into the torso-shaped model are seen in Fig. 5 and 6, and the Table. As the distance between the dipole and chest wall is increased, the fall in the voltage recorded with the proximity lead is much greater than that observed with the standard præcordial lead. The Table shows absolute values as well as the ratios between voltages of different distances for the proximity lead and the standard præcordial lead. For example, for a dipole located first at 25 and then at 55 mm. from the body surface, the ratios are 10.7 and 4.8 for the proximity lead and standard præcordial lead, respectively, showing the stronger influence on the proximity lead of dipoles closer to the surface. Analysis of Fig. 6 shows the effect on the proximity lead of changing the angle of the dipole. This demonstrates that the effect is maximal when the dipole and proximity lead are co-directional.

Figure 7 demonstrates the proximity effects on both the proximity lead and the standard præcordial lead. When the smaller dipole was at 25 mm. and the larger at 65 mm. (Fig. 7A), a positive response was obtained in both the standard and proximity

FIG. 6.—Effects of changing the dipole angle on the proximity lead. At 25 mm. distance, these effects are maximal. As the separation between the dipole and the body surface is increased, the changes in dipole angle become less critical.

FIG. 7.—(A) When the smaller dipole is 25 mm. from the surface, both proximity and standard leads give proximity effects, though there is a stronger dipole with opposed polarity. (B) If the smaller dipole is 45 mm. from the surface, the proximity lead still records a positive response, whereas the standard præcordial lead gives a negative response as a result of the stronger second dipole. PL=proximity lead. V=standard præcordial lead.

leads, whereas when the smaller dipole was at 45 mm. (Fig. 7B), the standard præcordial lead gave a negative response, while the proximity lead still gave a positive response.

Clinical Results. The tracings obtained in normal children demonstrate that there are no morphological differences from the standard præcordial leads under normal circumstances (Fig. 8). On the other hand, in patients with biventricular overloading in whom the standard præcordial leads show only left ventricular hypertrophy, the proximity lead demonstrates the presence of right ventricular hypertrophy also (Fig. 9).

DISCUSSION

The clear demonstration by Taccardi (1963), Horan, Flowers, and Brody (1963), Rijlant (1933), and Nelson (1957), of the non-dipolar distribution of potential on the chest surface encourages further interest in the exploration of current sources of higher singularity such as quadrupoles or octopoles, therefore, by procedures other than vectorcardiography. As previously pointed out by Schmitt (1957), it is possible, by inverting the procedure by which orthogonal uniform leads are designed, to achieve leads with high non-uniform sensitivity of recording. In this regard, Schmitt (1964), Stallmann (1957), and Fischmann and Barber (1963) have proposed local leads. These systems, however, have not yet been sufficiently developed for

clinical use. It is evident that these two types of information, either a "total-heart equivalent dipole", or localized dipolar content from a limited proximal myocardial area, are not in opposition, but rather are complementary to each other.

The principle of reciprocity, applied by Helmholtz to electrophysiology (1853), provides the foundation of the lead field theory (McFee and Johnston, 1953, 1954a, b). This theory serves as an ideal basis for testing as well as for designing electrocardiographic lead systems. In essence, the "lead field" is the field of current which is produced in the body when a unit of current enters the negative terminal of a lead and leaves its positive terminal. Applying this concept to electrocardiography, it has been established that an electromotive surface within the heart will produce a voltage in a given lead, proportional to the potential generated across the surface, multiplied by the current which passes through it as the result of connecting the lead to a unit source of current (McFee and Johnston, 1953, 1954a, b).

Two-dimensional Observations. The lead field patterns observed in Fig. 3 explain the higher non-uniform sensitivity of the proximity lead over the standard præcordial lead. In accordance with the lead field theory, the electrocardiographic output of these models will be directly proportional to the number of isoflow line intervals that the depolarization front would occupy. From Fig. 3, it is evident

FIG. 8.—(A) Electrocardiograms obtained with standard præcordial leads (V) and proximity lead (P) in a normal 5-year-old child. There are no significant differences between V and P leads except in voltage. (B) Patient with patent ductus arteriosus and pulmonary hypertension. The standard præcordial leads show left ventricular hypertrophy. The proximity lead shows right ventricular hypertrophy as well.

FIG. 9.—(A) Patient with valvar pulmonary stenosis. The standard electrocardiogram is normal. The proximity lead shows right ventricular hypertrophy. (B) Patient with pulmonary atresia and ventricular septal defect. Severe right ventricular hypertrophy pattern is present in both leads.

that the proximity lead is much more sensitive to dipoles facing, and close to, the central electrode (where there is crowding of the isoflow lines), than to more distant dipoles, or to those perpendicularly oriented to the isoflow lines.

The validity of two-dimensional experiments, as a precise source of information about a three-dimensional body, has been demonstrated by Nelson (1957). This investigator has shown that if the vertical angle of a dipole in a volume conductor is not greater than 30°, the distribution of potential at the boundary of such a conductor will be similar in shape, for the same horizontal dipole angles, as the potential distribution around the boundary of a two-dimensional conductor having the shape of a cross-section of the volume conductor.

Three-dimensional Observations. Since Rush, Abildskov, and McFee (1963) have demonstrated existing differences of resistivity of body tissues, the use of a non-homogeneous torso model makes our experimental observations acceptable.

The three-dimensional observations (Fig. 5-7) are in agreement with the two-dimensional studies demonstrating the high sensitivity of the proximity lead for dipoles facing and closer to the exploring electrode. With the standard *præcordial* lead, our results are in concurrence with previous observations (McFee and Johnston, 1953, 1954a, b). The potential variations registered by means of this lead (Table) are essentially inversely proportional to the square of the distance of the electrode from the exciting dipole (modified by angle dependent factors). On the other hand, the proximity lead is a system in which the difference of potential between the central electrode (ϕa) and the average of the outer electrode potentials (ϕb) is measured. This difference of potential, for optimal separation of the electrodes, is proportional to the field intensity. The field intensity, or gradient of potential field, is inversely proportional to the third power of the distance between the electrodes and the current dipole (also modified by angle dependent factors).

It is possible to derive a formula which expresses

the relation between the potential recorded by the proximity lead and the current source. According to Hamer, Boyle, and Sowton (1965) the potential at the surface of a non-homogeneous volume conductor, derived from an eccentric current dipole will be:

$$\phi = \left(2 + \frac{c}{r}\right) K \cos w c^{-2}, \text{ where } K = \frac{3p}{4\pi} M \quad (1)$$

where c = distance to the source; r = radius of the thorax section; M = dipole moment; w = angle between the source and the surface electrode; p = tissue resistivity; $\frac{3}{4\pi}$ = geometric constant. Since the proximity lead is a "bipolar lead", with both terminals in the field of interest, the total output (V) of this lead will be:

$$V = \phi a - \phi b \quad (2)$$

$$V = \phi a - \frac{\phi 1 + \phi 2 + \dots + \phi 6}{6} \quad (3)$$

$$V = \phi a - \frac{\sum_{i=1}^6 \phi_i}{6} \quad (4)$$

Where V is the potential recorded by the proximity lead, ϕa represents the potential at the central electrode, and the integral of the second term represents the sum of potentials of the outer electrodes divided by the number of these electrodes.

Unquestionably, a lead in which the recorded voltage varies inversely with the cube of the distance has a higher non-uniform sensitivity than a standard *præcordial* lead in which the potential varies inversely with the square of the distance. In this difference, theoretically and practically, is expressed the main purpose of the proximity lead, that is, greater power of discrimination between proximal dipoles and more distant dipoles. Because of its extreme sensitivity to changes in distance and position, and to tissue inhomogeneity, however, only waveforms may be studied with this lead, paying little regard to absolute potentials.

Clinical Applications. The reliability of model studies is limited by our relative knowledge of the

TABLE
COMPARISON OF VOLTAGES BETWEEN PROXIMITY LEAD AND STANDARD *PRÆCORDIAL* LEAD (see text)

Lead distance (mm.)	25-35	25-45	25-55	25-65	35-45	35-55	35-65	45-55	45-65
Standard <i>præcordial</i> lead									
Voltage Ratio	3.0 1.6 1.87	3.0 9.0 3.33	3.0 0.6 5.00	3.0 0.4 7.50	1.6 0.9 1.77	1.6 0.6 2.66	1.6 0.4 4.00	0.9 0.6 1.50	0.9 0.4 2.22
Proximity lead									
Voltage Ratio	1.5 0.5 3.00	1.5 0.3 5.00	1.5 0.1 15.00	1.5 0 —	0.5 0.3 1.66	0.5 0.1 5.00	0.5 0 —	0.3 0.1 3.00	0.3 0 —

electrical properties of the human torso and the heart. Therefore, the clinical applicability of the present method, and any other electrocardiographic system, will be affected by *in vivo* variation in the position, shape, volume, and conductivity of the heart as well as the torso, and in the distribution and orientation of the spread of excitation.

One possible shortcoming of the proximity lead lies in the small magnitude of the observed potentials, as compared with those obtained by the standard præcordial lead system. In children, however, as observed in this study, the magnitudes of voltage recorded were sufficient to produce tracings* of a quality comparable to those of the standard lead system (Fig. 8 and 9), even though actual potentials were small.

The similar morphologies obtained from normal children with either the proximity lead or the standard præcordial lead demonstrate that the former does not produce artificial patterns of right ventricular hypertrophy. In fact, the proximity lead closely approaches direct epicardial morphologies, where rS or RS patterns have been described in normal hearts (Barbato *et al.*, 1959; Jouve *et al.*, 1960), during exploration of the central part of the anterior wall of the right ventricle. In cases of right ventricular hypertension, these epicardial morphologies are of Rs or R type (Jouve *et al.*, 1960), similarly to P₁ and P₂ observed in Fig. 8 and 9.

The experimental results, as well as the few examples of electrocardiograms illustrated in this paper, are encouraging enough to suggest that pursuit of the technical development as well as the clinical application of the proximity lead may prove to be profitable. The detection of mild degrees of right ventricular hypertrophy, biventricular hypertrophy in presence of predominant left ventricular forces, or small areas of myocardial infarction may be simplified by this type of lead system.

The spectrum of information obtained through the different electrocardiographic techniques can be illustrated by a statement by Burger (1952): "the vectorcardiogram is of particular importance in order to get a complete idea of the entire building. But I must add that if we want to investigate whether the building is solid and the beams are not decayed, we shall have to look closely. . . ."

SUMMARY

A præcordial lead has been designed (proximity lead), which is highly sensitive to electromotive forces in the myocardial area facing the exploring electrode, while being relatively insensitive to forces

in other regions of the heart. It consists of an exploring electrode surrounded by a network of electrodes, all mounted on a rubber disk with a 7 cm. diameter. The central electrode is connected to the positive terminal of a lead, and each of the outer electrodes is connected through 200K resistors to the negative terminal of the lead.

Two-dimensional analyses were performed using conducting paper. The current field of the proximity lead appears to radiate from the exploring electrode, with considerable crowding of the isoflow lines at the surface of the "heart" nearest the exploring electrode, and wider separation of flow lines at more distant surfaces. Three-dimensional analyses, using a non-homogeneous torso model, where a current dipole was introduced, showed that the voltage recorded by this lead varies inversely with the cube of the distance between the central electrode and the dipole. The simultaneous introduction of two exciting dipoles of different strengths was studied, and the proximity lead continued to detect the weaker more proximal dipole in a situation where a standard præcordial lead only detected the stronger more distant dipole. In patients with biventricular preponderance, while the proximity lead showed evidence of biventricular hypertrophy, the standard electrocardiogram showed only left ventricular preponderance.

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