# An Accurate, Clinically Practical System For Spatial Vectorcardiography

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This paper describes a new improved system of spatial vectorcardiography that is practical for clinical use. It represents an optimum compromise among such factors as soundness of theoretic basis, accuracy, reproducibility, signal-to-noise ratio, and speed of application. Some of its advantages over currently employed systems include a rational physical basis, corrections for torso shape, avoidance of left arm, insensitivity to individual variability of ventricle location, and accuracy comparable to applicability of 3-dimensional torso-model data to the human subject. Detailed description of electrode placement, practical procedures, and useful technics is included.

A N accurate method for determining three orthogonal components of the human equivalent heart dipole has been the objective of an international search for many years. A clinically practical answer to this problem is presented here and represents the product of five years of intensive theoretic and experimental investigations.

All systems of spatial vectorcardiography now in general use suffer from a variety of substantial quantitative defects that are described conveniently in terms of image vectors associated with each lead. Image vectors (sometimes called lead vectors) are related to the equivalent heart dipole in such a manner that the projection of the heart dipole onto the image vector times its length yields potential difference of the lead.[1, 2] An ideal system of vectorcardiography would have 3 equal-length, orthogonal image vectors for all subjects. Experiments with accurate 3-dimensional homogeneous torso models, which apply with surprising accuracy to the human subject,[3-5] reveal that image vectors utilized in most systems[6-8] are not parallel to anatomic body axes, are not mutually perpendicular, are unequal in length (and improperly corrected by standardization factors employed), and, most seriously, are susceptible to variations traceable to change in anatomic location of the equivalent dipole from one subject to another.[9] Standard limb and precordial leads of clinical electrocardiography have similar defects,[10] but have been found useful nevertheless on an empiric basis for diagnosis of many heart disorders. Vectorcardiography appears to have resulted in little new information[11] despite its emphasis on relative timing of various leads. This is not too surprising in view of the errors mentioned above, and especially since limb and precordial leads, which have been studied exhaustively for many years, give the essence of most of the qualitative information available on the body surface. Moreover, vectorcardiography has not been fully exploited because projections of vector loops onto anatomic body axes have been commonly used rather than studying loops in their own frame of reference.

Further strides in electrocardiography are most likely to be made in the quantitative area. Before quantitative analysis may be made meaningful, however, it is essential to correct for many known errors in present methods, especially those arising from torso shape and individual variability in dipole location, left arm characteristics and anatomic orientation of the heart. The system of vectorcardiography proposed here has the express purpose of enabling quantitative studies by suitable correction of these known errors. It will produce vectorcardiograms of far greater accuracy than any system in current use.

Whether or not this improved accuracy will enhance clinical diagnosis of heart disease remains to be demonstrated.

This system of vectorcardiography represents an optimum compromise among many conflicting factors, such as soundness of theoretic basis, accuracy, vulnerability to dipole location, ease and speed of application, reproducibility, signal-to-noise ratio, and cost. Its advantages over currently used methods are believed to outweigh by far its disadvantages.

## GENERAL DESCRIPTION

Four electrodes are the minimum number required theoretically in any system of vectorcardiography, since three independent potential differences are necessary to determine the heart vector in three dimensions.[2, 6] From the standpoint of ease and speed of application and reproducibility, the 3 standard limb positions (right and left arms, left leg) and the back are superior sites. Torso-model data have been applied to these electrode sites as used in the modified Wilson tetrahedron,[6] and to an "average computing" type system[9] that incorporates torso-model corrections for an average ventricle center. Unfortunately major quantitative shortcomings of this most practical arrangement exist. The steep potential gradient at the root of the left arm[4] renders left arm coefficients highly variable from one individual to another, depending in part on left shoulder structure. The situation is similar to that which would be found if a large, variably shaped electrode were placed on an ill-defined region of the precordium. Moreover, changes in dipole location from one individual to another introduce errors of substantial amounts in all electrodes.[9] An improved system may be designed by avoiding the use of the left arm, as is done here. Vulnerability to dipole location errors is not circumvented easily, however, since effects of dipole location on body surface potentials are very pronounced. Furthermore, limb and back electrodes are about as insensitive to dipole location effects as any body surface points. Dipole location effects can be reduced substantially by increasing the number of carefully selected electrodes and interconnecting them in a
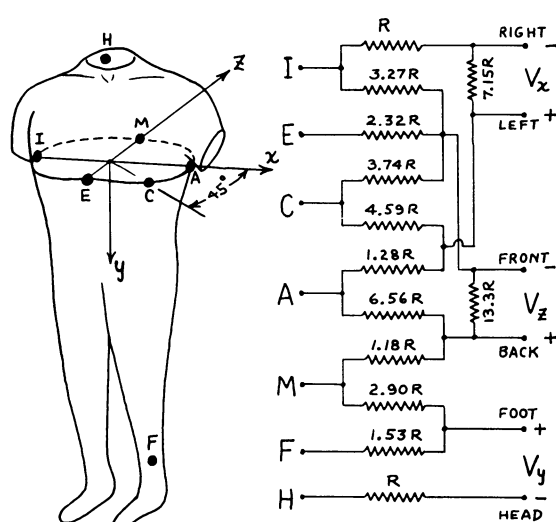


FIG. 1. The seven electrodes of this system of vectorcardiography are shown at the left affixed to a human subject. Five electrodes $A$, $C$, $E$, $I$, $M$ are located at the same transverse level (approximately the fifth interspace), $H$ is on the back of the neck, and $F$ is the standard left leg electrode. Wires joining these electrodes may be connected directly to corresponding points of computing and compensating networks (right), the outputs of which are three potential differences $V_x$, $V_y$, and $V_z$ which are proportional to dipole components $p_x$, $p_y$, and $p_z$, respectively, with equal standardization factors. The entire system may be arranged to feed an ordinary vectorcardiograph but the shunt resistors $7.15\,R$ and $13.3\,R$ might require modification (see text). Effective resistance from any of the six output terminals in any path toward the subject has been designed to be equal to $R$, thus enabling common-mode rejection of 60 cps interference. Lead length from network outputs to vectorcardiograph should be held to a minimum.

fashion suitable to achieve compensation. For example, the SVEC III system of Schmitt and Simonson[7] utilizes this first-derivative compensation principle, but requires 14 electrodes. The system proposed here, shown in figure 1, applies this principle, using a total of 7 electrodes, 3 more than the minimum theoretic number, in order to avoid strong dependence on dipole location.

In applying this system, the transverse level of the ventricles may be taken as the fifth interspace, or it may be determined more precisely for exacting studies by electrical technics described in Appendix I. Electrodes are placed at this transverse level at the front ($E$) and back ($M$) midlines, at right ($I$) and

left ($A$) midaxillary lines, and at an angle of 45 degrees ($C$) between front midline and left midaxillary line. Letter designations of these electrodes conform to those previously published.[8, 12] The remaining two electrodes are placed on the left leg ($F$) and on the back of the neck ($H$). Potential differences among these 7 electrodes do not yield pure dipole components, but suitably weighted combinations produce accurate orthogonal dipole components for a wide range of dipole locations. The simplest networks to accomplish this are shown in figure 1. Three potential differences $V_x$, $V_y$, and $V_z$, very nearly proportional to each of the dipole components $p_x$, $p_y$, and $p_z$, are delivered with equal relative standardization for convenience in subsequent amplification in the vectorcardiograph. A description of each component follows.

*Right-to-left Component, $p_x$.* The potential difference $V_x$, derived from electrodes $A$, $C$, and $I$ as shown in figure 2, appears between electrode $I$ and a junction of 2 resistors joining $A$ and $C$. Representation of electrodes $A$, $C$, and $I$ in image space for a typical dipole location is also shown in figure 2 where the image vector for $V_x$ is displayed in geometric terms. One role of electrode $C$ is to introduce a correction for the backward slant of the image line from $I$ to $A$ by about 13° for this dipole location. Since the $V_x$ image vector is parallel to the $x$-axis, the potential difference $V_x$ is proportional to $p_x$ for this dipole location. The relative amplitude of the $V_x$ image vector is 174 units without the attenuating resistor 7.15 $R$ shown in figure 1. This shunt resistor diminishes the amplitude of $V_x$ by a factor of 1.28, which reduces its image vector to the same length as that for $V_y$, inherently the smallest amplitude lead. This electrode arrangement not only produces an image vector parallel to the $x$-axis for this particular dipole location, but maintains this property with good accuracy in both length and angle for a substantial range of different dipole locations because of the choice of electrode sites and the way in which electrode potentials are combined.

*Front-to-back Component, $p_z$.* The potential difference $V_z$, derived from all five electrodes at the transverse level $A$, $C$, $E$, $I$, and $M$ as
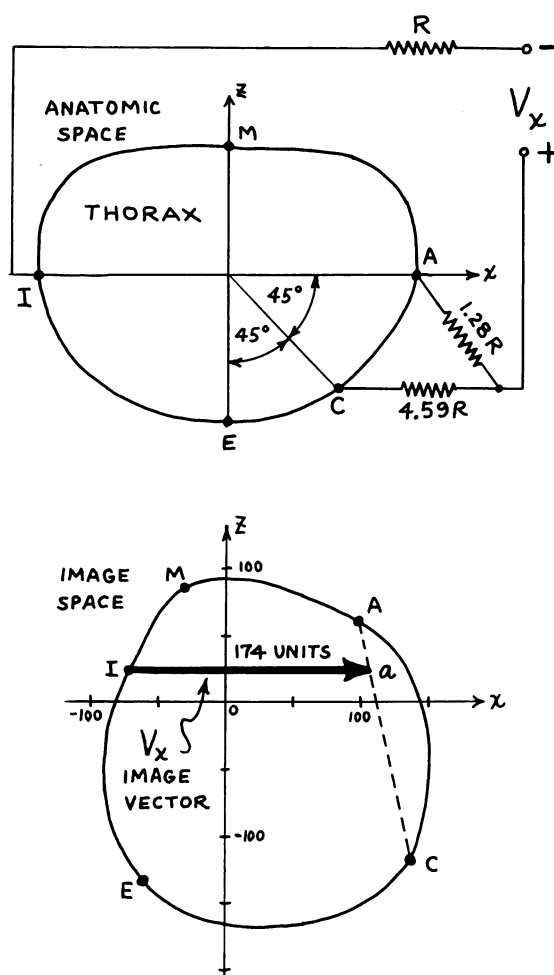


Fig. 2. Details for right-to-left component, $p_x$. Three electrodes, $A$, $C$, and $I$ at the transverse level are utilized to produce $V_x$ whose image vector is parallel to the $x$-axis. It is assumed that the three image points corresponding to anatomic points $A$, $C$, and $I$ lie in the $xz$-plane of image space and hence have negligible contribution from $p_y$. This will be very nearly true if the anatomic transverse level coincides with the equivalent dipole location. The tip $a$ of the image vector divides[17] the dotted line from $A$ to $C$ in image space in accordance with $Aa/Ca = 1.28\ R/4.59\ R$. Normalized data for this image loop may be found elsewhere[12] under dipole location 22. The function of resistance $R$ is to equalize resistance levels for combating 60 cps induced in the subject.

indicated in figure 3, appears between a junction of two resistors joining $M$ and $A$, and a junction of 3 resistors joining $I$, $E$ and $C$. Five electrodes were found essential to obtain an anteroposterior lead of comparable reliability
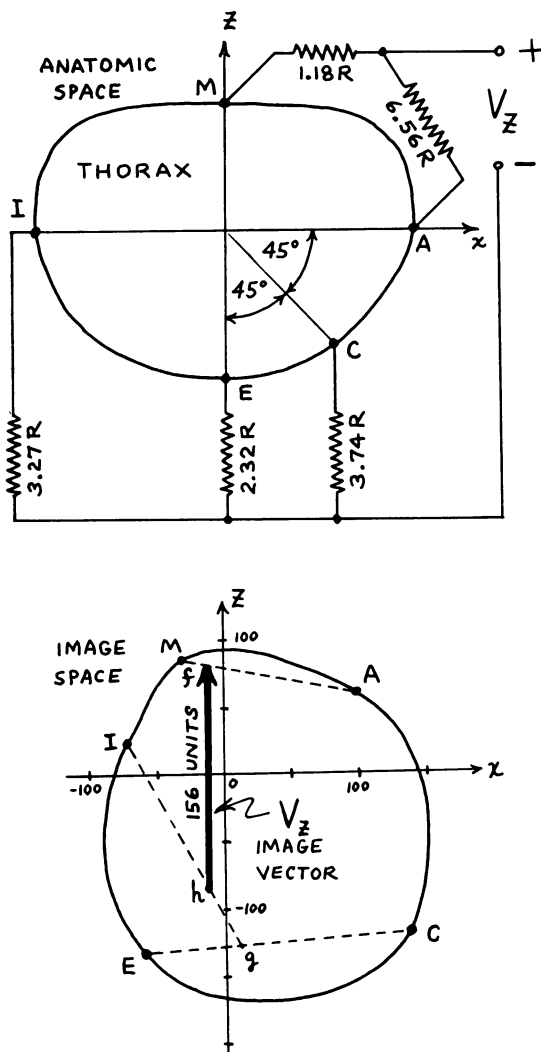
FIG. 3. Details for front-to-back component, $p_z$. Five electrodes $A$, $C$, $E$, $I$, $M$ at the transverse level are utilized to produce $V_z$ whose image vector is parallel to the $z$-axis. It is assumed that the 5 image points lie in the $xz$-plane of image space. The tip $f$ of the image vector divides[17] the dotted line from $M$ to $C$ in image space in accordance with $Mf/Af = 1.18$ $R/6.56\ R$. The tail $h$ of the image vector is at a point within the triangle formed by image points $I$, $E$, $C$, which may be obtained as follows: join $I$ with point $g$ which is located along the $EC$ line in accordance with $Eg/Cg = 2.32\ R/3.74\ R$. Point $h$ is found along the line $Ig$ in accordance with $gh/Ih = 3.74\ R$ $(2.32\ R)/3.22\ R\ (2.32\ R + 3.74\ R)$. Proof of this construction is available on request from the author. Image loop and dipole location are the same as in figure 2. Resistance levels of the 2- and 3-resistor junctions (as seen from $V_z$) have been designed to be each equal to $R$ to counteract 60 cps interference.

and quality to the other 2 leads of this system. Omission of any one of these electrodes (with suitable redesign of the networks to give a pure lead for a typical dipole location) results in significant impairment of performance in terms of vulnerability to dipole-location changes. Representation of these 5 electrodes in image space for a typical dipole location is also given in figure 3, where the image vector for $V_z$ is shown in geometric terms. Clearly, the influence of electrode $A$ is slight, since it is weighted by only 18 per cent of the contribution of electrode $M$ to the 2-resistor junction, and again electrode $C$ serves in part as a correction electrode (though more influential than in the $p_x$ lead), since it is weighted least of the 3 electrodes feeding the 3-resistor junction. The $V_z$ image vector being parallel to the $z$-axis indicates that potential difference $V_z$ is proportional to $p_z$ for this dipole location. The relative length of the $V_z$ image vector is 156 units, without the attenuating resistor $13.3\ R$ shown in figure 1. This shunt resistor effectively reduces the length of the $V_z$ image vector by a factor 1.15, which equalizes it to the $V_y$ image vector.

*Head-to-foot Component,* $p_y$. The potential difference $V_y$, derived from electrodes $H$, $M$, and $F$ (fig. 4), appears between electrode $H$ and a junction of two resistors joining $M$ and $F$. Since the ratio of resistances joining $M$ and $F$ is 1.9 to 1.0, $M$ may be looked upon as introducing a backward correction to the $H$ to $F$ potential difference. Representation of these three electrodes in image space for a typical dipole location is also shown in figure 4 in frontal and left sagittal views, where the image vector for $V_y$ may be seen in geometric terms. The role of electrode $M$ is clearly displayed in the sagittal view, where it can be seen to correct for the more forward location of electrode $F$, the angle of correction being 8° for this dipole location. Since the $V_y$ image vector is parallel to the $y$-axis, the potential difference $V_y$ is proportional to $p_y$ for this dipole location. The relative length of the $V_y$ image vector is 136 units, the smallest of the three, and is therefore unattenuated (fig. 1). This lead determines the amplitude level of the system
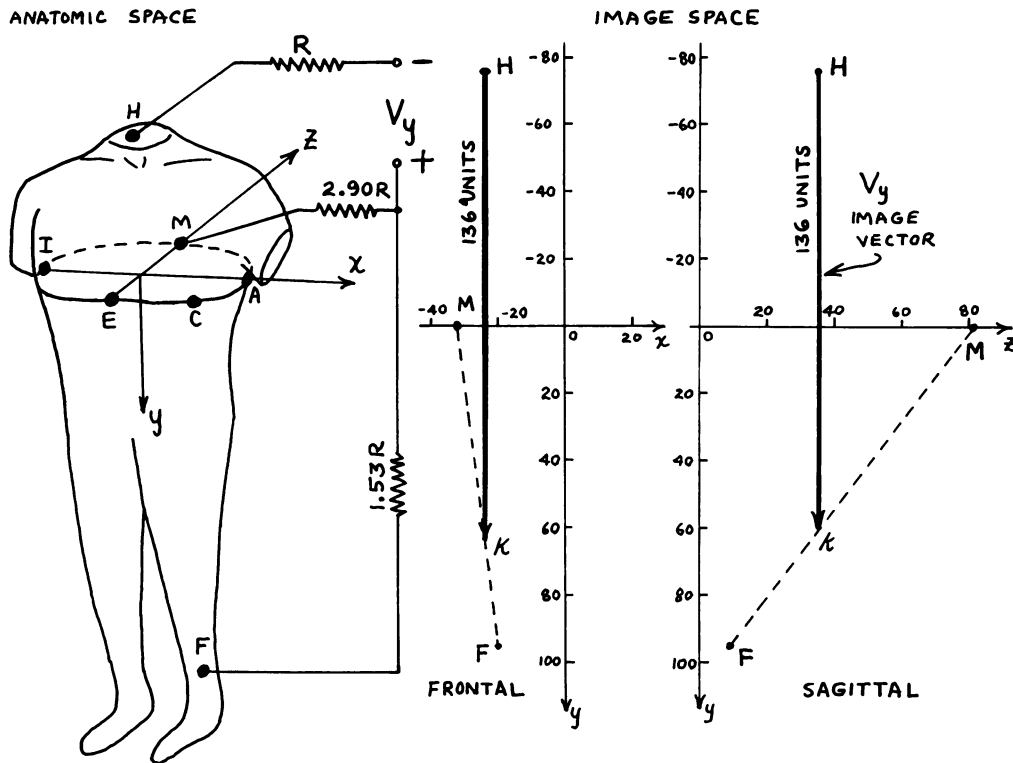
ANATOMIC SPACE                                          IMAGE SPACE

FIG. 4. Details for head-to-foot component, $p_y$. Three electrodes $H$, $F$, $M$ are utilized to produce $V_y$ whose image vector is parallel to the $y$-axis. The tip $k$ of the image vector divides[17] the dotted line $F$ to $M$ in image space in accordance with $Fk/Mk = 1.53\,R/2.90\,R$. Data for these image points may be found in a previous publication[8] which is very nearly the same dipole location as in figures 2 and 3. The scale of the image coordinates is different from that in figures 2 and 3. The function of resistor $R$ is to equalize the resistance level with that of the positive side of $V_y$, a necessary practical condition to achieve adequate 60 cps rejection.

that provides larger potential differences than obtained in most other systems of vector-cardiography.

## ELECTRODE PLACEMENT

Great care must be exercised in electrode placement to take full advantage of the accuracy capabilities of the system and its invulnerability to dipole location.

*Ventricle Level.* For ordinary clinical routine use the transverse level of the ventricles may be taken as the fifth interspace (at the sternum). Some error may be introduced using this level, but it is usually within 1 inch of the correct level. For precise determination of the electrical level of the ventricles, the technic given in Appendix I may be employed. Fluoroscopic estimate of the anatomic center of the

ventricular mass is often too high because the diaphragm obscures an uncertain portion of the ventricles. Electrodes $A$, $C$, $E$, $I$ and $M$ are all located at precisely the same anatomic level. When the subject is capable of standing, the level may be marked around the chest by the use of a string with a weight on the end (plumb bob) adjusted in length so that the weight just touches the floor at various points around the steady subject.

*Angular Locations of Chest Electrodes.* Electrodes $E$ and $M$ are placed exactly on the front and back midlines, respectively. Electrodes $A$ and $I$ are placed on the left and right midaxillary lines, respectively. The meaning of midaxillary line, as used here, is a line passing exactly through the axilla and parallel to the central axis of the trunk. The vertical

plane containing $A$ and $I$ is typically closer to the back than to the precordium, often cutting the thorax in the ratio 1.2:1.

Various types of chest protractors may be devised that permit the location of electrode $C$ to be established at an angle of 45 degrees between electrodes $E$ and $A$. This location is often deceptive because of precordial contour, and anatomic distances on the body surface from $A$ to $C$ and from $C$ to $E$ are usually unequal.

*Head and Foot Electrodes.* Electrode $H$ is placed on the back of the neck 1 cm. to the right of the back midline at a level corresponding to the extension of the top shoulder line across the back. Its location is not especially critical. Electrode $F$, least critical of all, is at the standard location of currently used $LL$ electrode, on the left leg, between the knee and ankle.

## Theoretic Performance

Basic assumptions underlying this system of vectorcardiography are: (1) ventricular depolarization may be represented at each instant of time by an equivalent dipole that is variable in strength and orientation but is fixed at a single (but generally different) anatomic point for each individual, and (2) the medium in which heart currents are produced is homogeneous, resistive, and linear for all individuals with boundaries the same as that of the individual torso shape. These assumptions have been discussed in detail[3] and tested experimentally.[3-5, 12] As a result of this and other unpublished work, it is expected that a theory based on these assumptions will be accurate to about ±15 per cent.

With these assumptions, the relationship between the potential at any boundary point and an internal dipole of any location may be determined experimentally by homogeneous, three dimensional torso models. Such data have been published elsewhere[2, 9, 10] including complete results for the entire torso surface.[8] The influence of torso shape has been found to be less than 10 per cent for most subjects, including male and female, except for absolute amplitude.[2, 8, 9, 10] A typical dipole location for ventricular depolarization is 9.4 per cent

of the thorax width to the left of the vertical plane containing electrodes $E$ and $M$, 14.8 per cent of the thorax depth forward of the vertical plane containing electrodes $A$ and $I$, and at the level of the fifth interspace. This is very close to a dipole location designated as 22 in a previous publication,[12] for which complete model data have been presented.[8] Because this location is nearly at the center of results obtained in both normal persons[13] and patients[5] whose electrical ventricle locations have been determined by actual experiment, it is taken as the design center for this system of vectorcardiography. For this typical dipole location, unipolar potentials[2, 8, 12] at the seven electrodes of this system and rectangular components of the internal dipole are related by:

$$\begin{aligned} V_A &= 95\ p_x + 58\ p_z \\ V_C &= 131\ p_x - 113\ p_z \\ V_E &= -60\ p_x - 130\ p_z \\ V_M &= -32\ p_x + 80\ p_z \\ V_I &= -71\ p_x + 21\ p_z \\ V_H &= -24\ p_x - 76\ p_y + 35\ p_z \\ V_F &= -21\ p_x + 91\ p_y + 11\ p_z \end{aligned} \tag{1}$$

where coefficients are given in the same relative units defined elsewhere.[12] It is assumed here that the transverse level is correct and, therefore, that coefficients of $p_y$ are small compared with those of $p_x$ and $p_z$ for the 5 transverse level electrodes. With these relationships it is possible to demonstrate that the networks of figure 1 result in the production of 3 essentially pure dipole components with equal standardization factors. Circuit equations for the 3 output voltages applied to the vectorcardiograph are, in general, for any $R$

$$\begin{aligned} V_x &= 0.610\ V_A + 0.171\ V_C - 0.781\ V_I \\ V_y &= 0.655\ V_F + 0.345\ V_M - 1.000\ V_H \\ V_z &= 0.133\ V_A + 0.736\ V_M - 0.264\ V_I \\ &\quad - 0.374\ V_E - 0.231\ V_C \end{aligned} \tag{2}$$

and are most conveniently obtained by node analysis[14] of the networks of figure 1. Inserting the potentials of Equation (1) into Equation (2) results in

$$\begin{aligned} V_x &= 136\ p_x - 0.2\ p_z \\ V_y &= 136\ p_y - 0.8\ p_x - 0.2\ p_z \\ V_z &= 136\ p_z \end{aligned} \tag{3}$$

Thus it can be seen in mathematical terms that each of the 3 potential differences for this dipole location is essentially proportional to only 1 of each of the 3 dipole components, and that the proportionality factors are the same for each lead.

A fundamental advantage of this system is revealed when data for a variety of different dipole locations are applied. Indeed, the system has been deliberately devised to be relatively insensitive to dipole location and, as such, surmounts a major defect of most systems. To illustrate, consider the influence on $V_x$ of shifting the dipole to location 04, which is 2 cm. forward and 2 cm. rightward of the design-center location 22, a total shift of 2.8 cm. Electrode $A$, $C$, and $I$ potentials are then given by[12]

$$V_A = 71\ p_x + 68\ p_z$$
$$V_C = 161\ p_x - 57\ p_z \qquad (4)$$
$$V_I = -74\ p_x + 43\ p_z$$

which differ considerably from those in Equation (1). Yet the $V_x$ expression of Equation (2) still yields a faithful result: $V_x = 129\ p_x - 1.9 p_z$. The relative amplitude has been reduced by about 5 per cent from 136, and the angle error is $\tan^{-1}\ (1.9/129)\ =\ 0.8°$. In similar fashion, dependence on dipole location can be calculated for the other potential differences $V_y$ and $V_z$. For dipole locations within a cube 4 cm. on a side that is centered on location 22, it is found that image vectors associated with $V_x$, $V_y$, and $V_z$ undergo length changes of about ±9 per cent and angle shifts of ±2°. For a cube 5 cm. on a side, length variations are ±20 per cent and angle shifts are ±5°. The latter volume was found to encompass 90 per cent of 40 patients with assorted heart disease whose ventricle centers were determined precisely by experiment.[5] Thus, deviations owing to individual location of dipole are usually comparable to the accuracy with which model data apply to the human subject. Deterioration in accuracy with commonly used systems of vectorcardiography when dipole location is shifted is very substantial in the range for which this system shows good performance.[9] Although this system does tend to become less accurate outside the specified

5 by 5 by 5 cubic centimeter volume, other systems become far worse.

It is of course tacitly assumed in these calculations that the transverse level at which electrodes $A$, $C$, $E$, $I$, and $M$ are located on the subject is not seriously in error. It is noteworthy in Equation (2) that coefficients in each equation add up to zero. This is a network property resulting from equalizing resistance levels, but also indicates that if each chest electrode has about the same amount of potential traceable to $p_y$, a condition which is approximated if *all* chest electrodes are at a slightly incorrect level, then $p_y$ tends to cancel out of $V_x$ and $V_z$.

PRACTICAL CONSIDERATIONS

Several practical points based on experience with hospital patients deserve mention.

1. *Electrode Attachment.* It has been found most convenient to use a standard perforated rubber belt to hold the 5 chest electrodes. Commercially available precordial electrodes may be inserted under the belt at locations $A$, $C$, and $I$. Modified precordial electrodes with a straight rod perpendicular to the disk slide through an appropriate hole in the belt for locations $E$ and $M$. The rod is long enough so that spacers can be slipped onto the rod and under the belt to hold electrodes firmly against the skin despite hollows in body contour frequently encountered. Electrode $H$ consists of a flat precordial type electrode disk; it is affixed with adhesive tape. As is true in all systems, a ground electrode is required. This may be attached to any of the 3 unused limbs, such as the right leg.

2. *Female Subjects.* In female subjects, electrode $C$ has some unavoidable error when the transverse level of the ventricles does not fall above or below the left breast. This error is not acute because electrode $C$ serves as a correction for $V_x$, is weighted by about 27 per cent in its contribution to the three resistor junction of $V_z$, and does not affect $V_y$ at all.

3. *Subject Posture.* Because amplitudes of potential differences $V_x$, $V_y$, and $V_z$ are larger than those obtained in presently used systems of vectorcardiography, it has been possible

to study subjects of all ages in the sitting position with little disturbance from muscle tremor.

4. *Skin Treatment.* The network of resistors (fig. 1) may be connected directly to the subject, but it is necessary to rub the skin, so that resistance beneath the electrode is small compared with the input resistance to the network. Otherwise electrical errors are encountered. This problem is similar to the skin resistance problem[15] recognized in connection with the Wilson central terminal, and is present in any system that employs resistance networks. Hence, the choice of $R$ (which sets the entire impedance level of the networks) is important. The value of $R$ should be as high as is consistent with 60 cps. disturbances, desirably 100,000 ohms and not less than 25,000 ohms. The skin should be rubbed under each electrode until a resistance less than $R/10$ is achieved between any two electrodes (this may be measured roughly by using a common ohmmeter). If $R = 50,000$ ohms, the $R/10$ result (5000 ohms) is easily achieved with moderate rubbing which typically gives 3000-ohms resistance. If $R$ is too small, extremely brisk rubbing is required, which is quite inconvenient, time consuming and uncomfortable.*

5. *Vectorcardiograph Input Resistance.* The input grid resistors (if any) of the amplifiers to which $V_x$, $V_y$, and $V_z$ are delivered must be taken into account if standardization factors are to be precisely equalized. Figure 1 portrays conditions for an infinite input resistance, often approached in practice. If amplifier input resistances are each equal to $KR$, where $K$ is any constant, then the shunt resistance required across $V_x$ is given by $7.15\,KR/(K + 2)$. The shunt required for $V_z$ is 1.86 times this value. For example, suppose the amplifier input resistance is 15 times $R$. Then with $K = 15$ a shunt value of 6.31 $R$ is calculated for $V_x$

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* The problem of skin resistance may be circumvented by feeding electrode potentials directly into cathode followers and applying their outputs to the resistance networks. It is necessary to use direct current for the filaments, and coupling capacitors (with suitable discharge provisions) should be incorporated to block the unequal direct voltages of $V_x$, $V_y$, and $V_z$ from the vectorcardiograph input circuits.

(instead of 7.15 $R$) and a shunt of value 1.86 (6.31 $R$) = 11.8 $R$ is needed across $V_z$ (instead of 13.3 $R$).

## DISCUSSION

Perhaps the most striking gross feature of the system proposed here is the use of 3 precordial electrodes. This is justified by numerous experiments on many normal[13, 16, 17] and abnormal[5, 16] subjects who have given consistent and precise evidence that the dipole representation is applicable to an accuracy of 85 to 95 per cent for the precordium. The use of precordial electrodes for spatial vectorcardiography is not new. Precordial leads $V_2$ and $V_6$ have been advocated,[18, 19] a group of 4 electrodes on the precordium has been proposed,[7] and other investigators[20] have used precordial electrodes of different kinds in their systems.

Advantages and disadvantages of this system of vectorcardiography are summarized below. The basic theory underlying this system is soundly supported by experiment for the QRS complex to an accuracy of about ±15 per cent, while other systems in current use are subject to sizable known errors in both principle and practice. Torso-shape influence is corrected by model coefficients that vary by less than 10 per cent for a wide range of body builds. Effects of individual variations in left arm coefficients are avoided by excluding the left arm. Insensitivity to individual variability in dipole location is accomplished by choice of electrode sites and processing of electrode potentials in compensating and computing networks. Thus, a major shortcoming of common systems of vectorcardiography is overcome, without the need of determining the actual location of the dipole. For dipole locations within a cube 5 cm. on each side centered on a typical dipole location, image vectors remain accurate within ±5° in angle and ±20 per cent in length. Individual variability of anatomic heart orientation may be overcome, as in all systems, by studying the spatial loop in its own frame of reference rather than in terms of projections on fixed anatomic axes. The number of electrodes, while three more than the minimum theoretic requirement, is

not excessive and is less than the total number of electrode sites used in routine clinical electrocardiography. Yet just as much and even more information may be expected. Procedures involved in applying this system can be reduced to a routine requiring about 15 to 20 minutes per subject. Potential differences derived from the body surface sometimes approach twice the size of systems that employ "remote" electrodes, and represent a marked advantage in combating muscle tremor and 60-cps interference. Moreover, subjects may be studied in the sitting position, which is often a convenience impossible in other systems because of excessive muscle tremor. Electrode sites should be rubbed adequately in this system to avoid electrical errors. This disadvantage, which is minor if $R$ is 50,000 ohms or greater, may be overcome by use of cathode followers, which have been found to be practical in this application. Cost of equipment to implement this system is not substantially different from any other system of vectorcardiography. Input leads and networks, which can be adapted to existing equipment, constitute a small percentage of total equipment cost. Potential differences representing 3 orthogonal components are produced with equal standardization factors for convenience in amplification. While electrode location is critical in this system, this is partially offset by pooling various electrode combinations. Moreover, electrode placement is critical in many other systems of vectorcardiography, and is not so precisely specified. Preliminary studies indicate that reproducibility comparable to beat-to-beat variations can be achieved, provided care is exercised in electrode placement.

A system whose stated performance compares closely to that described here is the SVEC III system.[7] The system proposed here appears to have a basic advantage over SVEC III because the left arm is not employed and, perhaps of most practical significance, the SVEC III system uses a total of 14 electrodes, twice the number required here.

Results obtained from the proposed system should not be expected to differ qualitatively in many cases from those obtained with standard electrocardiographic or other vectorcardiographic systems. For example, leads I and $V_5$ or $V_6$ are usually qualitatively similar to $V_x$, $V_F$ (or $aV_F$) is often similar to $V_y$, and either $V_1$, $V_2$ or $V_3$ usually resembles $-V_z$. However, the main purpose of devising a more accurate system is to enable quantitative explorations; and quantitative differences between results of this system and those of other methods are enormous, amounting to several hundred per cent in amplitude and drastic differences in shape, timing and angle. An example is given in figure 5. It is believed that a more accurate system such as the one described will reveal new invariants not heretofore discernible, if indeed they are there to be found.

Vectorcardiograms (fig. 5) obtained in November 1955 enable comparison between results of the proposed system and those of the commonly used Wilson tertrahedron, for a normal subject. Absolute accuracy for the QRS complex may be judged from results of an accurate research determination carried out on the same subject in May 1954.[12] In the research determination, dipole location was established by 11 cancellation experiments[12] after which dipole components were obtained using 18 different leads dictated from torso-model results as previously described in detail.[3] Total time required for a research determination of this kind is typically 30 hours. Vectorcardiograms obtained routinely in 15 minutes by use of the presently described system are seen to agree with the research determination within the stated accuracy of the system, while the Wilson tetrahedron results contain sizable quantitative errors, most glaring of which is in the front-to-back component, $p_z$. This particular defect, often found with the Wilson system, is traceable in part to characteristics of the left arm which, for this subject, are known to contribute substantially to discrepancies between the two systems. The accurate $p_z$ obtained in the proposed system in itself represents a major stride forward. There are many other known causes for disagreement; for example, exaggeration of the head-to-foot component, $p_y$, in the Wilson
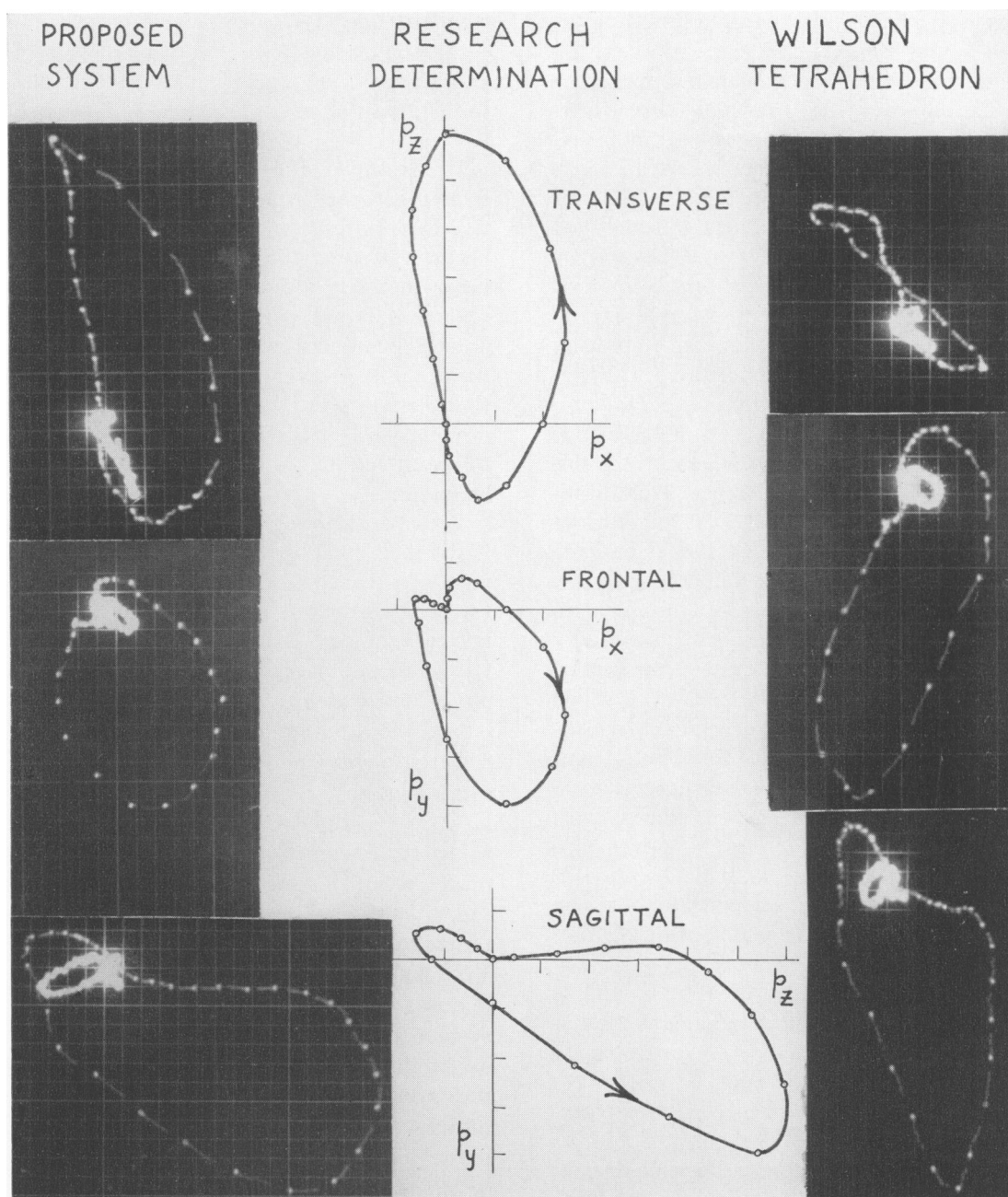
FIG. 5. Shown in the center column are previously published[4] projections of the QRS loop of a normal male subject that were determined by elaborate research technics.[3] Vectorcardiograms of the proposed system (left) are seen to be in close agreement while the Wilson system (right) contains substantial errors. Timing markers in records are spaced 2.5 milliseconds apart; bright spots occur immediately after blanked portions of the trace and reveal direction of inscription. Points on research determination are spaced 5 milliseconds apart. Rectangular grid-line spacing on records is 0.1 inch. Standardization employed in the proposed system was 1.0 in/mv. for all three components. The customary standardization factors for the Wilson tetrahedron system were employed: 1 in/mv for lead I, 1.2 in/mv. for $V_B$ and 1.7 in/mv. for $V_F$. Standard electrocardiograms for this subject may be found elsewhere.[3] Records were obtained through the courtesy of the Provident Mutual Life Insurance Company, with research equipment of Dr. Paul H. Langner, Jr.

system is a characteristic that has been emphasized elsewhere.[6, 10]

While this system is soundly supported by experimental evidence for the QRS loop, there is less evidence concerning its performance with T loops and no evidence regarding P loops. It may be satisfactory for T loops because T waves cancel[21] and ventricular repolarization is representable by a fixed-location dipole. The insensitivity of this system to dipole location would then result in accurate T loops, provided the center of T-wave activity does not differ too much from that of the QRS complex.

For completeness and historic interest it should be mentioned that an accurate central terminal representing the dipole midpotential may be devised using the chest electrodes of this system. However, no such terminal is necessary for vectorcardiography and, furthermore, such a terminal cannot provide basic information not already present in the dipole components. One terminal representing the dipole midpotential more accurately than the Wilson central terminal may be formed as a junction of 3 resistors joining electrodes $E$, $C$, and $M$ with resistance ratios $R_E/R_C = 1.45$ and $R_C/R_M = 2.82$. Another terminal at nearly the same potential may also be formed by the junction of 3 resistors joining electrodes $A$, $C$, and $I$ with resistance ratios $R_C/R_I = 3.08$ and $R_A/R_C = 1.5$. These junctions are somewhat insensitive to dipole location, as can be shown by analysis of published image loops,[12] but they do not shift concordantly with dipole location. Potential difference between the 2 junctions on normal subjects is typically $0.13 \pm 0.08$ mv. provided the electrode level is correct.

### Summary

1. An accurate system of spatial vectorcardiography employing 7 electrodes (3 on the precordium) in combination with computing networks is practical for clinical use, and enables quantitative analysis of electrocardiographic potentials.

2. Advantages of this system include a theoretic basis (tested by experiment) accurate to $\pm 15$ per cent, corrections for torso shape, avoidance of left arm, insensitivity to in-

dividual variability of ventricle location, reduced muscle tremor interference, rapid application, and cost comparable to other systems. Disadvantages are critical electrode placement and requirement of low skin resistance (unless cathode followers are employed).

3. For heart dipole locations within a cube 5 cm. on a side centered on a typical ventricle location, image vectors remain accurate to within $\pm 5°$ in angle and $\pm 20$ per cent in length.

4. Precise designations for electrode locations and many practical considerations are discussed. Theoretic design and performance are also included.

5. A novel technic for determination of the electrical level of the ventricles is offered as an optional procedure.

6. Two different 3-resistor terminals representing the dipole midpotential are described.

### Appendix I

#### Experimental Technic for Determination of Transverse Level of Equivalent Dipole of the Human Heart

The transverse level of electrodes $A$, $C$, $E$, $I$ and $M$ is important in influencing the accuracy of dipole components derived from this system of vectorcardiography. Although the correct level is usually found within 1 inch of the fifth interspace, there are sometimes individual exceptions. Moreover, for precise research measurements it is desirable to be as certain as possible that the level selected for the chest electrodes is correct.

A novel three-step technic utilizing a triple-electrode assembly may be used to determine this level precisely in a rapid manner. The basis of the method resides in a property of the image surface in the region corresponding to the precordium. Over this region the outward bulge of the image surface is very pronounced because of the leftward and forward anatomic location of most human hearts.[8] The level at which this bulge is greatest corresponds to the desired electrical level and, in a torso model, is the level at which the internal dipole is located.[12] The objective of the method is to determine the level of maximum bulge in image space.

The electrode assembly, shown in figure 6, is utilized in the 3-step procedure below. In all cases the electrodes are always aligned with the intersection on the precordium of a plane containing the vertical central anatomic axis of the subject.

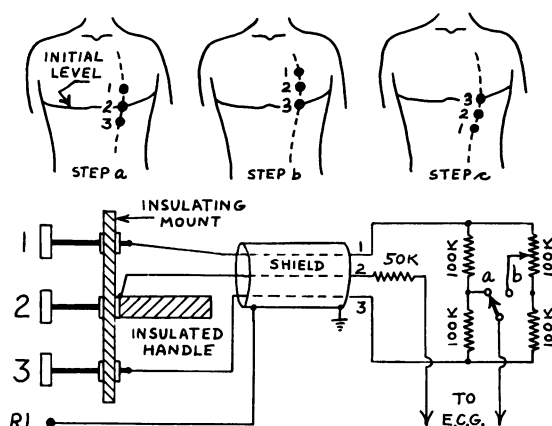*Step a.* Place electrode 2 directly over the heart at the level of the fifth interspace with electrode 1

FIG. 6. The three precordial locations of electrode assembly in steps *a*, *b*, and *c* of heart level determination are shown along with electrode assembly and associated circuit and switching arrangement. Electrode 2 level in step *a* is tested for correctness by this procedure. The line along which electrodes are placed is not exactly vertical (see text). Electrodes are $\frac{1}{2}$-inch diameter disks spaced exactly 1 inch apart. A ground electrode is affixed to the subject's right leg. The function of the 50,000-ohm (50 K) resistor is to equalize resistance levels as seen from the electrocardiograph.

above electrode 2 (Fig. 6, step *a*). (In female subjects a line passing just to the right or left of the left breast may be used.) With switch in position *a*, observe (and record, if desired) the shape of the QRS complex and note its amplitude.

*Step b.* Move the electrode assembly up by exactly 1 inch as shown in figure 6 (Step *b*), so that electrode 3 occupies the spot formerly taken by electrode 2. With switch in position *b*, vary the 100,000-ohm potentiometer until the QRS complex has approximately the same shape as observed in step *a*; note its amplitude.

*Step c.* Rotate the electrode assembly by 180 degrees and replace electrode 3 in the same location as in step *b* (see fig. 6). Observe the shape and amplitude of the QRS complex with switch remaining in position *b* and with no alteration of the potentiometer.

If the waveshape in step *c* is in reasonable agreement with those of steps *a* and *b*, the initial level at which electrode 2 was placed is correct, usually to within $\pm\frac{1}{4}$ inch. If the waveshape shows decidedly poor agreement, repeat the entire 3-step procedure starting at a different initial level. Amplitudes of the complexes often can serve as a guide in selecting a new trial level, since the QRS amplitude is frequently (but not invariably) largest at the level of maximum bulge in image space. Hence, the new level tried should be shifted toward the direction of the larger complexes.

This procedure was developed on a sound theoretic basis in terms of properties of dipole potentials in 3-dimensional torso models. Space does not permit a description of the underlying theory.

Several practical points deserve mention. The person holding the insulated handle of the electrode assembly should be connected to ground by means of a leg electrode to minimize 60 cps interference, if it is encountered. Before electrodes are applied, rub the skin along the line of the electrodes a total distance of 4 inches symmetrically about the initial level. The electrode line on the body should be wiped clean before each trial, and contiguity of electrode paste must be avoided. If complexes are too small in amplitude, the electrode line along which the determination is made may be shifted toward the midline or toward the left side. Because the method is extremely sensitive in most subjects, a small error in initial level results in a pronounced disagreement in step *c*. Therefore, waveform agreement in the 3 steps need not be perfect to obtain good accuracy. Three trials are usually the maximum number required to arrive at a final result, once the technic has been mastered. An ordinary electrocardiograph or one input of the vectorcardiograph may be used to observe complexes. This method has been applied successfully in over 100 hospital patients. A typical time required for each subject is about 5 minutes.

## ACKNOWLEDGMENT

## SUMMARIO IN INTERLINGUA

1. Es presentate un accurate systema de vectocardiographia spatial que es de valor practic in usos clinic. Illo emplea 7 electrodos (3 al precordio) in combination con retes de computation. Illo rende possibile le analyse quantitative de potentiales electrocardiographic.

2. Le avantages del systema include un experimentalmente verificate base theoric con un exactitude de $\pm15$ pro cento, correctiones pro le configuration del torso, evitation del bracio sinistre, non-influentiabilitate per variationes individual del location ventricular, reducite interferentia per tremores muscular, rapide applicabilitate, e un costo comparabile al costo de altere systemas. Le disavantages es le importantia critic del placiamento del electrodos e le necessitate de basse resistentias cutanee (excepte si sequitores cathodic es empleate).

3. Pro locationes de dipolo cardiac intra un

cubo de 5 cm super un latere centrate verso un typic location ventricular, le vectores de imagine remane accurate intra ±5° in angulo e ±20 pro cento in longitude.

4. Es discutite precise designationes pro locationes electrodic e multe considerationes practic. Theoric structura e efficacia es etiam tractate.

5. Un nove technica pro le determination del nivello electric del ventriculos es offerite pro uso optional.

6. Es describite 2 differente terminales a 3 resistentias representante le mediepotential dipolar.

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