Comparison of Four Orthogonal Systems of Vectorcardiography

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Four orthogonal systems of vectorcardiography that are considered to be more accurate than the tetrahedron and cube systems were compared. In a large majority of subjects the records made with each of the 4 systems were similar. However, in 5 of 60 subjects in whom the Z lead was studied, dissimilarities were found that were considered to be significant. The possible reasons for these dissimilarities are discussed. Comparative normalization data for the systems were obtained in the living human subject, based upon comparison of wave forms.

RECENTLY 4 systems of vectorcardiography based on well-established principles of potential theory have been devised by Schmitt and Simonson,1 Frank,2 McFee and Johnston,3 and Helm.4 They each attempt to provide a more orthogonal reference frame than the cube and the tetrahedron systems. It is the purpose of this paper to report the results of a comparative study in the living human subject of these 4 systems. The study was undertaken for 2 reasons, to determine how interchangeable the results of the different systems were and to provide comparative normalization data for each system in the living subject. If the systems yielded similar results, the study would serve as a consistency check on the validity of the separate methods of analysis and synthesis.

Method

The 3 leads of each orthogonal reference frame were compared individually. They were paired with a common lead to produce a loop rather than being recorded as scalar leads. The latter method requires high-speed, dual-channel recording with a common lead for phase relations, and analysis of such records was found to be less obvious and informative.

All studies were performed with the subject recumbent. Loops were observed directly on an oscilloscope and photographed with a Polaroid Land camera. Each comparison of 4 different X, Y, and Z leads required 2 experimental sessions totaling about 4 hours. Experiments were repeated on different days in 10 instances for the Z lead and 3 for the Y. No X lead studies were repeated because of uniformly good agreement among the 4 types.

Z Lead. Since the anteroposterior or Z lead has been the most variable component in existing systems of vectorcardiography, the major portion of this study was devoted to it. The Z lead of each system was paired consecutively with a common X lead (Schmitt system), and the gain of the Z channel controlled so that the peak-to-peak excursion was the same for all loops. The gain was then recorded for normalization information. The Z leads of the Frank and the Schmitt SVEC III systems were employed as described by these authors in their original communications.1 2 The sponge electrode of Helm1 and the multiple bank of electrodes of McFee and Johnston3 are described as follows.

The sponge electrode consisted of a thin plastic sponge moistened with a saturated solution of sodium chloride. Two sizes of sponge were used on the anterior chest wall to record the Z lead. A large sponge 10 inches square was positioned to cover the area from the first to the seventh interspace and from approximately the right midclavicular line to a line between the V4 and V5 positions. A smaller sponge with dimensions of 8½ inches from right to left and 6½ inches from top to bottom was placed on the precordium, extending from the level of the second to the sixth rib and from V1 to a line between the V4 and V5 positions. The sponge electrode was applied first at the beginning of each experiment without skin preparation, such as rubbing or defatting, and secured in place with a flat sandbag. To complete the Z lead a single electrode 1 inch in diameter was paired with either sponge electrode and placed on the back as recommended by Helm.4 Connection was made at the upper outer edge of the sponge by means of an alligator clip insulated from the skin.

The multiple electrode consisted of a 6 by 5 matrix of ½-inch diameter electrodes, spaced 1½

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inches apart in both directions, and set in a sponge rubber mat. Each electrode was connected to a common terminal through a separate 1-megohm resistor. The over-all area spanned by the electrodes was 8½ inches by 6½ inches, the same area as that of the smaller sponge. To record the Z lead the bank of electrodes was placed on the subject with the larger side horizontally, and in the average individual covered an area from the level of the second to the sixth rib and from the V₁ precordial electrode site to a line between the V₄ and V₅ positions. The skin was defatted by rubbing with an alcohol-ether mixture. Then a small amount of jelly was placed on each electrode avoiding spread beyond the electrode surface. After the assembly was secured in place with a sandbag, each electrode circuit was checked for contact resistance with an ohm meter. Good contact was further attested to by the fact that an imprint of each electrode was seen in the skin after the matrix was removed. A smaller multiple electrode, consisting of a 5 by 4 matrix of electrodes covering an area 6½ by 5½ inches, was centered on the back behind the anterior electrode to complete the Z lead.

X Lead. For study of the X lead, either a constant Z or Y lead was paired consecutively with different X leads. The X leads of the Frank and Schmitt systems were employed as described by the authors in their original publications, with the one exception that the Frank electrodes were placed at the fourth interspace. The X lead originally suggested by McFie and Johnston was omitted because it was so similar to the Schmitt X lead. Instead, the smaller multiple type electrode was placed in the left axilla, extending from a line between the V₄ and V₅ positions to approximately the posterior axillary line and from armpit to the sixth or seventh rib. This was paired with a single electrode 1 inch in diameter, placed at the right anterior axillary line in the fourth interspace. The sponge type X lead consisted of a sheet of plastic sponge 8½ by 6½ inches, similarly positioned in the left axilla, paired with a single electrode on the right. In the 24 studies of the X lead only 10 experiments with the sponge electrode were done because the results were so similar to those using the multiple electrode.

Y Lead. The Y leads of Schmitt, Frank, and Helm were used as originally described. It was our interpretation of recommendations by McFie and Johnston that an average Burger triangle could be used for the derivation of the Y lead. Inspection of image space diagrams reveals that the orientation of lead aVF derived from an average Burger triangle is so similar to the conventional aVF with equal resistors that we used the latter as a matter of convenience.

Material

For comparison of the Z leads, transverse plane vectorcardiograms of 60 subjects were recorded. Twenty-seven subjects were considered normal, being free from symptoms, signs, or history of cardiovascular disease and having normal electrocardiograms and chest x-rays. Of 33 abnormal subjects there were 13 with right bundle-branch block, 4 with left bundle-branch block, 8 with the electrocardiographic pattern of myocardial ischemia, 3 with healed myocardial infarction and residual Q waves, 3 with the pattern of left ventricular hypertrophy, and 2 with abnormal P-R intervals. Sixteen subjects with bundle-branch block were asymptomatic and without other evidence of heart disease. The heart size was well within limits of normal variation in all but 6 of the abnormal group. In 3 the cardiothoracic ratio was just 50 per cent and in 3 more it was approximately 55 per cent. One subject in this latter group showed poor matching as illustrated in figure 4.

In the X-lead study 11 subjects were normal and 13 had various electrocardiographic abnormalities, including 5 with right bundle-branch block, 3 with left bundle-branch block, and 5 with the pattern of myocardial ischemia.

In the Y-lead study 10 subjects were normal, 1 had right bundle-branch block, and 2 had the pattern of myocardial ischemia.

Results

In a large majority of subjects, the X, Y, and Z leads of the 4 systems were similar in contour. Since comparison of loops has thus far defied precise quantitative analysis, results were graded subjectively in 3 classes according to their degree of similarity. Examples of each class are shown in figures 1 through 4. Classification of the records derived for the Z lead is shown in tables 1 and 2. Only in group III were the differences considered of possible diagnostic significance, as interpretable by present methods. In all subjects the direction of rotation of the loops was the same in all 4 systems.

For the 60 subjects in whom the Z leads of the 4 systems were compared the results were as follows. In all 27 normal subjects the QRS loop comparison was classified as group I or II, and the T as group I or II in 25 cases and group I-II in 2 cases. In the abnormal group of
33 subjects the QRS was classified as group I or II in 28 cases and group III in 5 cases. The T wave in the abnormal group was group I or II in 30 subjects and group III in 3 subjects (table 2).

Right bundle-branch block was the pattern that gave the poorest matching of loops, (figs. 3 and 4). Four subjects with this pattern were classified as group III. However, in 9 other subjects with right bundle-branch block the loops were similar. In the records with dissimilar loops the diagnosis of right bundle-branch block can be made. However, if the vectorcardiogram becomes a truly quantitative diagnostic procedure so that right bundle-branch block can be subdivided regarding type or degree, and the interrelationship of the QRS and T loops becomes more meaningful, the variation among these loops as illustrated in figures 3 and 4 could be of significance.

The 10 by 10-inch and the 8½ by 6½-inch sponges were compared in 33 of the 60 Z-lead studies. Occasional moderate differences were encountered. In 8 subjects the large sponge was in better agreement with the other 3 systems.

With regard to the Frank system, electrodes were placed at both the fourth and fifth interspaces in 53 subjects. In 7 instances records taken at the fifth interspace differed significantly from those taken at the fourth, while the latter were in good agreement with the other 3 systems.

X leads were compared in 24 subjects. The results were all group I or II. Figure 5 shows a comparison of 4 different X leads. The similarity of the loops in this instance is very good and this was considered a group I result.

Figure 6 shows a comparison of Y leads of 4 types, those recommended by Schmitt, Frank, and Helm, and aVF. This phase of the study was limited to 13 experiments because of the similarity of the results and because it was believed that the Y lead was a comparatively simple problem, being a head-to-foot lead with refinements that would not be expected to have any profound influence. Figure 6 is an example of the poorest result. In 3 of 13 instances, aVF showed this degree of dissimilarity while the other systems were in good agreement.

Results of comparative lead magnitudes were available for 47 subjects for the Z lead, 24
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**Fig. 2.** Good similarity in matching of loops for the Z lead. Except for the Schmitt lead which shows moderate deviation, the other loops are similar. This subject had right bundle-branch block. An example of a group II classification. Directions of X and Z leads are the same as in figure 1.

for the X, and 10 for the Y. Only group I and II results were used for this calculation.

With the Schmitt system as a reference, the relative magnitudes of all lead vectors are listed in table 3. The Schmitt system requires normalization external to the electrode system to equalize the lead vectors. The Frank system has normalization built into its resistor network and the results indicate excellent consistency with the Schmitt system for X and Z and a difference in Y leads of 13 per cent of the mean. The results for the Helm system show excellent agreement with the Schmitt system for Z and Y and a difference in the X lead of 17 per cent of the mean.

**Discussion**

An important problem in vectorcardiography is the choice of a practical system of electrode placement that will provide a frame of reference consisting of 3 mutually perpendicular lead vectors of equal length. It has been demonstrated that there may be considerable variation in the same individual between vectorcardiograms made with the cube and the tetrahedral method of electrode placement and this would be expected on the basis of model studies. Recently, 4 systems of electrode placement based on more accurate theoretical and experimental grounds have been devised. The systems employ multiple
Fig. 3. Poor matching of the loops in a subject with right bundle-branch block. There is considerable variation in the terminal appendage of the loop. The rest of the loop is fairly similar in the sponge, multiple, and Schmitt systems. There is greater variation in the Frank Z recorded in the fourth interspace and poor correspondence in the case of the Frank Z recorded at the fifth interspace. An example of a group III classification. Direction of X and Z leads is the same as in figure 1.

electrode sites and computing networks, which either compensate for variations in heart dipole location within a given region or give equal weighting to any dipoles located in this given region. These statements are equivalent. However, it is fundamental to recognize that because of this compensating and weighting these systems attempt to yield information only about the dipole component of the actual heart generator. Indeed, if the heart’s electric activity cannot be completely accounted for by the action of an equivalent dipole in a homogeneous medium, these systems cannot by themselves yield all the available information. When the dipole component does not represent the total heart activity, these systems suppress the nondipole information. In this case additional information is available, for example, in precordial scalar leads.

The 4 systems are quite different, and each was arrived at through a somewhat different theoretical approach. All are based on results of model studies. Frank’s and Schmitt’s studies were performed on 3-dimensional homogeneous torso models whereas McFee and Johnston used only 2-dimensional models.
Helm derived his system from the model data published by Frank. The theoretical basis for each system is as follows. Frank used image surface representation to derive his system, which is reasonably accurate for a dipole located within a 5- by 5- by 5-cm. volume, provided the electrode level is placed in the plane of possible dipole location. Schmitt used transfer impedance representation to derive his system, which is reasonably accurate for one or more dipoles located within a 5- by 5- by 5-cm. volume in the anatomic region of the heart. McFee and Johnston used the lead field or reciprocal field concept to derive their system. Normalization figures and limits of accuracy of the latter system have not been stated. Helm used Frank’s model results to derive his system by mathematical analyses. Using any of these 3 tools of analysis and synthesis, namely, image surface, transfer impedance, or reciprocal field, one can explain equally well each of these systems. For linear resistive media there is a one-to-one correspondence between these tools and no one is fundamentally more general than the others.

Briefly, the advantages and disadvantages of each system are as follows. The Frank system is simplest to apply and has the advantage that precordial electrodes are already in place if it is desired to record scalar leads. However, the chief disadvantage of the Frank system is vulnerability in the event that electrodes are not placed at the mean electric heart center level. The sponge electrode is very inexpensive and simple to apply. However, despite the relative agreement between the sponge and the multiple electrode in all but 2 of 60 individuals there is still some reservation about the
TABLE 1.—Results of Z-Lead Shape Comparisons of Four Different Systems in Normal Subjects

<table>
<thead>
<tr>
<th>Loop</th>
<th>Group I</th>
<th>Group II</th>
<th>Group III</th>
<th>Total cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>QRS</td>
<td>13</td>
<td>14</td>
<td>0</td>
<td>27</td>
</tr>
<tr>
<td>T</td>
<td>16</td>
<td>9</td>
<td>2</td>
<td>27</td>
</tr>
</tbody>
</table>

TABLE 2.—Results of Z-Lead Comparisons of Four Different Systems in Abnormal Subjects

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>QRS LOOPS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>III</td>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>13</td>
<td>3</td>
<td>8</td>
<td>2</td>
<td>3</td>
<td>33</td>
</tr>
</tbody>
</table>

| T LOOPS |         |          |         |      |         |        |       |
| I      | 3        | 4        | 2       | 4    | 1       | 1      | 14    |
| II     | 1        | 8        | 3       | 3    | 2       | 2      | 16    |
| III    | 2        | 1        |         |      |         |        | 3     |
|        | 4        | 14       | 3       | 7    | 2       | 3      | 33    |

reliability of uniform skin contact and the short-circuiting effect of the sponge. It is believed that this requires more study in a larger number of individuals. The multiple electrode is fairly simple to apply in the male, despite the 30 or more individual contact points. It is more expensive than the other systems because it requires 30 matched resistors and construction of a durable matrix assembly with internal wiring that will not break with repeated use. The Schmitt system is only slightly more complicated than the Frank system to apply. It has the great advantage of having been evaluated for a 5- by 5- by 5-cm. volume of dipole positions in homogeneous model studies and poses none of the problems presented by the other 3 systems in applying to the female.

A greater portion of our study was concentrated on the Z lead because this has been the most difficult one to devise from both the theoretical and practical standpoints, and has provided the source of greatest variability in earlier systems. Similarity of the loops recorded by all 4 systems suggests that this problem of an accurate Z lead has been solved for a majority of subjects. There are several theoretical explanations for the significant discrepancies that occurred in the 5 Z-lead studies in our series: 1. The heart may be representable by a single equivalent dipole, but its location may be outside the volume within which a given system is accurate. 2. The heart may be representable by a single equivalent dipole at any instant of time but its location may migrate outside the volume covered accurately by a given system. 3. The heart may be representable by a distribution of dipoles occupying a volume larger than that covered accurately by a given system. 4. The limits of accuracy for the systems covering a given region may allow a sufficient degree of latitude that dissimilar loops can still be accounted for. 5. There may be inhomogeneities in the conducting mediums of sufficient magnitude to affect the results. 6. Finally, a factor not encountered in our series, namely, gross distortion of the volume conductor by bizarre thoracic contour, such as pigeon breast, funnel chest, or marked kyphosis.

The results in our X-lead study were remarkably good in all the 22 subjects studied.
In the study of the Y lead we encountered 3 cases of 13 in which aVF was significantly dissimilar to the Frank, Helm, and the Schmitt Y. This could be explained by the variability of the Wilson central terminal position in image space.

In some cases, while the QRS loops compared well, in the same subject the T loops were dissimilar and vice versa. This may also be explained on the theoretical grounds mentioned above.

The fact that loops derived from different systems were dissimilar in 5 individuals for the Z component does not necessarily indicate that any one of the methods is in error. Each system could be fundamentally sound based on what it was designed to do and still produce different loops because of reasons enumerated above. If all loops are the same, then the heart acts either as a single equivalent dipole or a number of dipoles within a 5- by 5- by 5-cm. volume. This is the limit of reasonable accuracy for the Schmitt and Frank systems, provided the latter is centered properly. It is possible that the multiple and sponge electrodes accurately cover a larger volume than the Schmitt system but this point has not been adequately studied in 3-dimensional models.

### Table 3.—Relative Size of Lead Vectors

<table>
<thead>
<tr>
<th>Lead</th>
<th>System</th>
<th>Length of lead</th>
<th>No. of cases</th>
<th>Per cent S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>Schmitt</td>
<td>1.00†</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>Frank 5 I.C.S.</td>
<td>1.03</td>
<td>47</td>
<td>32.0</td>
</tr>
<tr>
<td>Z</td>
<td>Frank 4 I.C.S.</td>
<td>1.15</td>
<td>47</td>
<td>21.8</td>
</tr>
<tr>
<td>Z</td>
<td>Multiple</td>
<td>1.31†</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>Large sponge (Helm)</td>
<td>1.33‡</td>
<td>47</td>
<td>17.2</td>
</tr>
<tr>
<td>Z</td>
<td>Small sponge</td>
<td>1.41</td>
<td>47</td>
<td>23.4</td>
</tr>
<tr>
<td>X</td>
<td>Schmitt</td>
<td>1.33†</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>Frank 4 I.C.S.</td>
<td>1.16</td>
<td>24</td>
<td>18.4</td>
</tr>
<tr>
<td>X</td>
<td>Multiple</td>
<td>1.17</td>
<td>24</td>
<td>14.8</td>
</tr>
<tr>
<td>X</td>
<td>Helm</td>
<td>1.09</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>Schmitt</td>
<td>1.40†</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>Frank</td>
<td>.98</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>Helm</td>
<td>1.31†</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>aVF</td>
<td>1.11</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

* The Schmitt Z lead was arbitrarily assigned the value of unity. In all 3 components the Schmitt system, without the required external normalization, was used as a reference for the above table. For example, the ratio of the Frank Y to the Schmitt Y lead vector is given by .98 divided by 1.40.

† Requires external normalization factor of .75.

‡ Requires external normalization factor of .71.

Although Burger's contributions to vectorcardiography are of the greatest importance, his system was not used because it does not compensate for variable dipole locations.

Our present study suggests that the 4 systems used were interchangeable judged by present clinical standards in all normal individuals and in a majority of the abnormal subjects. However, there was a significant difference among the 4 systems in at least 5 individuals. In 5 subjects with significant Z-lead differences among the systems the 2 electrodes of large area, namely, the sponge and multiple, resembled each other but differed considerably from the Schmitt and Frank, which in turn resembled each other. This raises a question as to which type of system is more accurate. The answer to this problem could be determined only by more fundamental studies or judged on an empirical basis of superior diagnostic accuracy and usefulness.

**Summary**

The results of study of the Z leads in 60 subjects indicated that the systems were inter-
changeable in over 90 per cent of the cases for both QRS and T with regard to shape and orientation. Of the X lead studied in 24 subjects the systems were interchangeable for the QRS in all of the cases, and the T in 90 per cent. The evidence suggests that the Y lead is fundamentally a head-to-foot lead as recommended by Schmitt, with refinements introduced by Frank and Helm that produce little or no difference in the shape of the lead and only slight difference in amplitude.

Normalization data for the various systems was obtained, based upon comparison of wave forms.

Similarity of vectorcardiograms derived from 4 different systems in a large majority of subjects supports the validity of the individual methods of analysis. Theoretical possibilities for observed instances of dissimilarity are suggested.

In the recumbent position the Frank system at the fourth interspace gave better similarity with the other systems than when used at the fifth interspace. The Frank system seemed to be significantly influenced by the level at which the electrodes were placed in approximately 10 per cent of the subjects studied.

Results with the 2 electrodes of large area (sponge and multiple) were different from those obtained with the Frank and Schmitt systems in 5 subjects.

**Summario in Interlingua**

Le resultatos del studio del derivationes Z in 60 subjectos indicava que le systemas eseva mutualmente excambiabile in plus que 90 pro cento del casos quanto al configuration e al orientation de QRS etiam de T. Le studio del derivationes X in 24 subjectos indicava exctabiilitate mutual del systemas quanto a QRS in omne casos e quanto a T in 90 pro cento. Le datos indica que le derivation Y es fundamentalmente un derivation capite-a-pede secundo le recommendation de Schmitt, con raffinamenti introduciti per Frank e Helm que produce pauc o nulle differentia in le configuration del derivationes e solmente leve differentias in lor amplitude.

Datos de normalisation pro le varie systemas eseva obtenite super le base de comparationes del configuration del undas.

Le similaritate del vectorcardiogrammas derive ab quatro differente systemas in le grande majoritate del subjectos supporta le validitate del methodos individual de analyse. Es offerite possibile explanationes theoret del observate casos de non-similaritate.

In le position recumbente le systema Frank, usate al quarte interspatio, resultava in un melior similaritate con le alte systemas que le mesme systema usate al quinte interspatio. In circa 10 pro cento del subjectos studiate, le systema Frank pareva esser influentiate significativamente per le nivello a que le electrodos eseva placiate.

Le resultatos obtenite per medio del 2 electrodos de grande areas (typo a spongia e typo multiple) differava in 5 subjectos ab le resultatos obtenite per le systemas Frank e Schmitt.

**References**

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