Reliability of Individual Frontal Plane Axis Determination

By Noboru Okamoto, M.D., Katsumi Kaneko, M.D., Ernst Simonson, M.D., and O. H. Schmitt, Ph.D.

SUMMARY
In a sample of 649 healthy men, the QRS and T amplitude frontal plane QRS and T axes and mean vectors were determined from leads I and III (standard reference), II and III, I and II, I and aVF, aVL, and aVF, and from a vectorial combination of leads I, II, and III. The group means were similar, but there were large intrindividual differences of the QRS axis (up to ±35°) and, to a somewhat lesser degree, of the T axis between the different lead combinations. Hypothetically, the axes from different lead combinations should be identical. The intrindividual discrepancies of the mean frontal plane vectors were also large (about 20%). In a smaller sample of 50 healthy men the axis was also determined from Frank X, Y leads, and the QRS and T axes were determined from both amplitudes (as in the larger sample) and areas. The results were similar to those obtained in the larger sample: no significant differences in the group means, but large intrindividual discrepancies between the various lead combinations both for amplitude and area axes. It is concluded that the normal standards obtained for the axis determined from leads I and III are also valid for the other lead combinations, but that for the individual patient there is no assurance that the axis determined from any one lead combination will be the true axis, even with a liberal range of error. The major part of the variation in axis as measured from various lead combinations is attributable in this study to time disparity between components measured in the individual leads, but skin impedance contributes substantially in many conventional measurements. For a patient in whom the axis is considered to be of diagnostic importance, it is probably worth averaging axes determined by several different lead combinations.

Additional Indexing Words:
Electrocardiogram  Area method  Amplitude method  QRS axis  T axis

Although the electrical frontal plane QRS and T axes can theoretically be determined from any two limb leads (standard or “unipolar”), they are nearly exclusively measured from leads I and III in electrocardiographic routine. In the textbook by Graybiel and White, determination of the “electrical axis” from the net amplitude (algebraic sum) in leads I and III is recommended as the “commonly used method” in 1946. Ashman and Hull also state that the mean or average electrical axis of the QRS complex is “ordinarily determined” by the algebraic sum of the amplitudes of the R and S waves in leads I and III, but for the correct determination the net area (algebraic sum of the areas of upward and downward deflections) should be used. Determination from areas of QRS and T wave is recommended also by Wolf, Wood, and Kossmann. Kossmann states, “The planimetric area method . . . is the most precise, but also the most laborious and time consuming.” Therefore, in clinical routine, axis

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Supported by Grants HE 05491 and HE 11325 from the National Institutes of Health.

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Received February 1, 1971; revision accepted for publication April 1, 1971.

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determination from amplitudes is more commonly used. In fact, if there are no conduction defects, the correlations between axes determined from amplitudes and axes determined from areas in electrocardiograms is quite high (for QRS, \( r = 0.82 \); for T, \( r = 0.88 \)).\(^6\) While the QRS axis is usually determined from leads I and III, Goldberger\(^7\) utilizes \( aV_L \) and \( aV_F \) leads. However, the variability of the augmentation ratio\(^8\) is a limitation for the use of augmented unipolar limb leads. Wolf\(^9\) uses Wilson's original \( V_R \), \( V_L \), and \( V_F \) leads as part of the reference frame.

That, in principle, the frontal plane QRS and T axes can be determined from any two limb leads has been generally recognized. Pipberger states, "Construction of a frontal plane QRS axis in the Einthoven triangle makes it very obvious that only two leads are necessary to obtain this axis. Additional leads cannot contribute any new information and are, therefore redundant."\(^10\) This statement, while strictly true for noiseless leads ideally measured at identical instants, not at maximum times for individual leads, is subject to considerable amendment in the case of real typical measurement. The generally accepted equivalence of any two limb leads for axis determination may explain why there does not seem to be any published experimental investigation of actual discrepancies in the electrical axis as determined from different lead combinations, such as leads I and II, II and III, \( aV_L \) and \( aV_F \), as compared to leads I and III, which may be considered as standard. The axes, determined from any two lead combinations, should in the absence of differentiating factors be assigned the same validity, so that it is difficult, in case of differences, to decide which one is to be considered the "true" axis for a given patient. Yet most statistical information regarding electrical axes in healthy populations or in abnormal conditions refers to determination of the frontal plane axes from leads I and III.

We decided, therefore, to test experimentally the validity of the general concept of axis equivalence as determined from any two limb leads by comparison of various lead combinations both for amplitude and area axes. In addition, the axes, as well as mean frontal plane vector magnitude, were also determined from X and Y leads of the Frank lead system in order that we might evaluate the effect of interlead electrical distortion on axis differences between the various lead combinations.

**Material**

Two groups of clinically healthy men were investigated. Group 1 consisted of 649 railroad employees for whom data were available from Dr. H. Taylor's investigations. This group was described in detail previously and was used for obtaining ECG normal limits corrected for age, sex, and weight.\(^11\) Group 2 consisted of 50 employees from the Veterans Administration Hospital in Minneapolis. All subjects were carefully screened by medical examination and history to insure absence of manifest cardiovascular disease or other disease that might affect the ECG. In view of the age trend in QRS and T axes and amplitudes,\(^11\) group 1 was subdivided into four age groups: 20–29, 30–39, 40–49, and 50–59 years. The age range in group 2 extended from 20 to 75 years, with the majority (45 subjects) over 40 years.

**Methods**

In group 1 (649 subjects), the QRS and T axes were determined from peak amplitudes in the following lead combinations: I and III, I and II, II and III, I and \( aV_F \), \( aV_L \), and \( aV_F \), and a vectorial combination of I, II, and III.

In group 2 (50 men) the mean axes were also determined from the Frank X and Y leads by both amplitudes and areas in addition to the lead combinations used for group 1. The amplitudes were measured manually from a direct written electrocardiogram, but the axis and mean frontal plane vector magnitude were determined with the aid of a cursor program developed by the Biophysics Group, using the PDP 8 computer and a special alphagraphic display system. This computer was also used for the statistical evaluation. The areas were measured with a planimeter on a projection of the ECG on a screen (10 times enlargement) following the original procedure of Wilson et al.\(^12\) This procedure is more accurate, but also more time-consuming, than the simplified method of Ashman et al.\(^13\) The areas were expressed in time integral \( \mu \text{v-sec} \). The amplitude and area values in leads \( aV_L \) and \( aV_F \) were multiplied by 1.15 for correction of the augmentation ratio in unipolar limb leads, since this correction\(^7\) has been generally accepted. In view...
of beat-to-beat variation, which was quantitative-
ly studied in a separate investigation, we selected for measurement by inspection beats representative of the average amplitudes, following the clinical routine.

We calculated the group means and standard deviations (SDS) for axes and mean frontal plane vectors, and the intraindividual differences between the different lead combinations (means with SDS). The main emphasis was placed on the intraindividual standard deviations, i.e., the size of the discrepancies that may occur in the same subject between the values obtained with different lead combinations. We also calculated simple correlation coefficients of frontal plane QRS and T axes between the various lead combinations.

Results

Group 1

The means and standard deviations (SDS) for the QRS axis and the T axis were calculated for the four age subgroups and the total group. The means and SDS were quite similar for all lead combinations in the four age subgroups, and the age trend of the QRS axis was not statistically different for the various lead combinations. The SDS are significantly smaller for the T axis than for the QRS axis in all lead combinations, in agreement, for the combination of leads I and III, with previous information. For the total group of 649 men, the mean QRS axis was within the narrow limits from 41.4 to 43.7° and the mean T axis, from 38.6 to 40.5°. The SDS were 33.1 to 35.1 for the QRS axis and 18.8 to 19.9 for the T axis. These slight differences between the different lead combinations were not significant.

For clinical application, concerned with individual patients, intraindividual variation of the axes is more pertinent than group means and SDS. Table 1 shows the differences for the total group between axes determined for each subject from leads I and III as standard and five other lead combinations for the QRS axis (D1–D5), and four lead combinations for the T axis (D1–D4). The SDS in Table 1 refer to intraindividual variation, which are, of course, smaller than the interindividual (group) SDS mentioned earlier, reflecting the total distribution range. The mean differences are small but statistically significant from zero for D2 (P = 0.01) and D4 (P = 0.05) of the T axis and for D3 of the QRS axis (P = 0.05). The intraindividual SDS of the differences between the axis from leads I and III and the other lead combinations are extremely high. Differences between different lead combinations (D1–D4) of up to approximately 35° in the QRS axis and about 20° in the T axis may be expected in the large majority of individual patients. Such large variations were actually seen in several subjects. There was no significant age trend.

D5 (vectorial combination) for the QRS axis and D2 (leads II and III) for the T axis are closest to the axis determined from leads I and III. The SDS for all differences (D1–D4) are significantly smaller (P < 0.01) for the T axis than for the QRS axis. The correlations between the QRS and T axes as determined with the different lead combinations were quite high, varying between r = 0.82 and r = 0.91, in spite of the large variation of differences in Table 1.

Table 2 shows the mean frontal plane QRS vector (Einthoven's manifest potential) determined with different lead combinations for the total group of 649 men: group means and SD (right) and mean differences and their intraindividual SDS (left). The decrease of QRS amplitude with age was nearly identical for all five combinations (not shown in Table 2). The

<table>
<thead>
<tr>
<th>Difference†</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>D5</th>
</tr>
</thead>
<tbody>
<tr>
<td>QRS axis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>-1.7</td>
<td>-0.1</td>
<td>0.1</td>
<td>0.6</td>
<td>-0.6</td>
</tr>
<tr>
<td>SD</td>
<td>18.1</td>
<td>13.9</td>
<td>17.0</td>
<td>19.3</td>
<td>9.8</td>
</tr>
<tr>
<td>T axis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.0</td>
<td>-0.9</td>
<td>-0.5</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>10.2</td>
<td>5.1</td>
<td>10.8</td>
<td>11.5</td>
<td></td>
</tr>
</tbody>
</table>

*N = 649.
†D1 = Ang (I, III) − Ang (I, II)
D2 = Ang (I, III) − Ang (II, III)
D3 = Ang (I, III) − Ang (I, aVF)
D4 = Ang (I, III) − Ang (aVL, aVF)
D5 = Ang (I, III) − Ang (I, II, III)
group means and sds are quite similar for the different combinations. Like those of the QRS axis, the mean differences are quite small but their sds are large. For individual patients, the mean frontal plane QRS vector may be expected to vary between the different lead combinations up to approximately 0.3 mv (95% expectancy limits). There was no significant age trend for the mean differences and their sds. The intr-individual sds (right) are significantly smaller than the group sds (left), as expected. Determination from leads I and aVF (D₃) comes closest to the standard procedure (leads I and III). The correlations of the mean frontal plane QRS vector amplitude between the different lead combinations are high, varying from r = 0.86 to r = 0.95. It should be noted, however, that these correlations were obtained in a large sample and refer to group correlation. They cannot be used for prediction in single subjects. The small, not significant differences between the means show that the large variation of QRS axis and mean frontal plane QRS vector between the different lead combinations is random. The situation is similar for the mean frontal T vector: small or absent differences for the means but large intr-individual sds.

**Group 2**

Since the group means and absolute values of the axes were irrelevant for our present problem, we limited ourselves to the intr-individual differences between the various lead combinations. In addition to the five combinations in tables 1 and 2, the axis was measured also from the Frank X and Y leads. The axis determined from leads I and III again served as reference. The axes were determined both from amplitudes and areas.

The results are shown in tables 3 and 4. The mean differences are similar and small for all lead combinations, including the axis determined from Frank X, Y leads, both for amplitude and area axes. There is a tendency for the T axis to have smaller sds, but it is less distinct than in the larger sample (table 1). In general, the large discrepancies between intr-individually determined axes from different lead combinations, as shown by the large sds, agree well with the results from group I. The discrepancies cannot be reduced by axis determination from areas. In fact, the sds of the differences tend to be higher for the axes determined from the areas than for those determined from amplitudes.

Table 4 shows group means and sds of the mean frontal plane QRS and T amplitude and area vectors determined in six lead combination. The amplitude vectors are somewhat higher for the Frank X, Y leads; otherwise, the means are nearly identical and the sds are also similar.

Table 5 shows the mean differences and intr-individual sds between frontal plane vectors (amplitudes and areas) determined from leads I and III and from five other lead combinations, including Frank X and Y leads. The mean differences are small and not statistically significant. The sds are large in relation to the absolute values of the vectors determined in leads I and III, as shown in table 4. For instance, the sd for D₂ is 17.5% for

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**Table 2**

Mean Frontal Plane Magnitudes and Mean Differences of Frontal Plane Magnitudes in Group 1* of QRS Between Different Limb Lead Combinations

<table>
<thead>
<tr>
<th>Mean frontal magnitude (0.1 mv)</th>
<th>Difference of magnitude†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D₁</td>
</tr>
<tr>
<td>Mean</td>
<td>0.86</td>
</tr>
<tr>
<td>sp</td>
<td>0.34</td>
</tr>
</tbody>
</table>

*N = 649.

†D₁ = Mag (I, III) - Mag (I, II)
   D₂ = Mag (I, III) - Mag (II, III)
   D₃ = Mag (I, III) - Mag (I, aVF)
   D₄ = Mag (I, III) - Mag (aVL, aVF)
the QRS amplitude vector and, for D6, 26.0% for the area vector. The discrepancies are largest for the X, Y leads (significantly different from all other lead combinations at the $P<0.01$ level, both for QRS and T amplitudes and areas). This is probably due to the additional factor of varying electrical distortion in the conventional limb leads. Although the means and SDs of amplitude and area vectors are not directly comparable because of different units, it appears that on a relative scale the discrepancies are not reduced by the area method; if anything, they tend to be larger.

**Discussion and Conclusions**

Large discrepancies are encountered when frontal plane QRS and T axes are determined by several presumably equivalent methods utilizing various pairs of conventional frontal plane leads. There is little systematic difference between angles determined by the several methods, so that for statistical studies of moderate size the measures can be considered equivalent with random variation. Therefore, the normal standards for the QRS and T axes determined from leads I and III in large samples are valid for all lead combinations. However for an individual patient, large axis differences up to 35° may be expected occasionally, and were actually observed in several subjects. Such variations can hardly be regarded as negligible and are in excess of the usual variabilities found upon redetermination of axis by any one method. One is tempted to suggest that at least two or three differently calculated axes should be

**Table 3**

*Differences of QRS Axis and T Axis Between Different Lead Combinations in Group 2 (N = 50)*

<table>
<thead>
<tr>
<th></th>
<th>Axis determined from amplitudes (mv)*</th>
<th>Axis determined from areas (mv-sec)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D1</td>
<td>D2</td>
</tr>
<tr>
<td>QRS axis Mean</td>
<td>1.9</td>
<td>0.4</td>
</tr>
<tr>
<td>SD</td>
<td>10.4</td>
<td>8.4</td>
</tr>
<tr>
<td>T axis Mean</td>
<td>2.5</td>
<td>-1.3</td>
</tr>
<tr>
<td>SD</td>
<td>9.3</td>
<td>7.7</td>
</tr>
</tbody>
</table>

*D1 and D2 = (I, III) - (I, II)  
D3 and D4 = (I, III) - (II, III)  
D5 and D6 = (I, III) - (aVL, aVF)  
D7 and D8 = (I, III) - (aVL, aVF)  
D9 and D10 = (I, III) - (X, Y)  

**Table 4**

*Frontal Plane Amplitude and Area Vectors for QRS and T Wave in Six Different Lead Combinations*

<table>
<thead>
<tr>
<th>Leads</th>
<th>I, II</th>
<th>II, III</th>
<th>I, III</th>
<th>I, aVF</th>
<th>aVL, aVF</th>
<th>Frank X, Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>QRS amplitude vectors (mv) Mean</td>
<td>0.99</td>
<td>0.99</td>
<td>0.96</td>
<td>0.97</td>
<td>0.96</td>
<td>1.17</td>
</tr>
<tr>
<td>SD</td>
<td>0.42</td>
<td>0.40</td>
<td>0.41</td>
<td>0.43</td>
<td>0.48</td>
<td>0.57</td>
</tr>
<tr>
<td>QRS area vectors (mv-sec) Mean</td>
<td>29.2</td>
<td>28.7</td>
<td>27.0</td>
<td>27.0</td>
<td>28.1</td>
<td>28.8</td>
</tr>
<tr>
<td>SD</td>
<td>18.7</td>
<td>17.6</td>
<td>17.5</td>
<td>17.0</td>
<td>18.2</td>
<td>16.3</td>
</tr>
<tr>
<td>T wave amplitude vectors (mv) Mean</td>
<td>0.21</td>
<td>0.22</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.26</td>
</tr>
<tr>
<td>SD</td>
<td>0.08</td>
<td>0.09</td>
<td>0.08</td>
<td>0.08</td>
<td>0.10</td>
<td>0.11</td>
</tr>
<tr>
<td>T wave area vectors (mv-sec) Mean</td>
<td>21.3</td>
<td>21.2</td>
<td>21.9</td>
<td>21.5</td>
<td>22.3</td>
<td>24.4</td>
</tr>
<tr>
<td>SD</td>
<td>8.3</td>
<td>8.8</td>
<td>7.8</td>
<td>6.9</td>
<td>6.8</td>
<td>8.3</td>
</tr>
</tbody>
</table>

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averaged for a patient where the axis is considered diagnostically important, such as for right or left ventricular hypertrophy or hemiblock and for cor pulmonale. Averaging would be important also when the axes determined from leads I and III are close to the normal limits. The limitations of frontal plane axis determination apply logically also to the P axis, although it was not specifically investigated.

If the "true" axis is taken to be the axis along which the orthogonalized, normalized integral current moment vector projected onto the frontal plane experiences its QRS maximal magnitude, then errors of four kinds can be expected in addition to the inevitable measurement errors and possible failure to compensate for lead sensitivity:

(1) First there is the inescapable fact that the standard leads are not uniform in transfer impedance throughout the heart and do not form an equilateral triangle according to the simplistic Einthoven approximation. This does not constitute a source of variability, however, as the standard frontal leads should lie consistently if perfectly measured.

(2) It is also true that a large and often neglected systematic axis error arises as a result of the very large skin-electrode impedance, which is loaded by the central terminal resistance network often used in recording.15-17

(3) If this resistance network is left fixed for all lead measurements, the resulting axis measurements should all be consistent even though wrong. If the network is switched, however, to generate the augmented limb leads (the precordial leads and the standard limb leads I, II, III in the classical manner) then this impedance becomes a prominent source of variability. A difference must be expected, of course, between even ideally measured limb lead axes, Frank lead axes, SVEC III lead axes, etc., because of the different detailed mixes of transfer impedance that these leads represent.

(4) A different kind of variance between differently determined axes must be expected on the basis of the different instants in time at which axis determining maxima are determined in various leads. The maxima in I, II, III, aV_L, aV_R, aV_F, etc. may all be expected to be reached at slightly different times. It was in recognition of this factor that area maxima as well as magnitude maxima were calculated and used separately to determine axes. This major difference in measurement definitions did not yield any strikingly different results.

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Circulation, Volume XLIV, August 1971
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Circulation. 1971;44:213-219
doi: 10.1161/01.CIR.44.2.213
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

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