Comparison of the Vectorcardiogram with the Electrocardiogram in the Prediction of Left Ventricular Size

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SUMMARY

The vectorcardiogram has been suggested as an alternative to the electrocardiogram in the diagnosis of left ventricular enlargement. In 107 patients, precordial QRS voltage measurements were compared with vectorcardiographic spatial magnitude measurements in their relationship to angiocardiographically determined left ventricular mass and volume.

Sensitivity, specificity, and linear correlations obtained with instantaneous spatial QRS magnitude measurements were similar to those obtained with selected precordial voltage measurements suggested by Sokolow and Grant. Multiple regression analysis incorporating time-strength integrals of the spatial QRS correlated more closely with left ventricular mass (R = 0.75) and total volume (R = 0.80) than did similar analysis using precordial voltages (R = 0.71). These differences are statistically significant (P < 0.01) but reduce the remaining variability of the electromotive-left ventricular size relationship by only 7 to 14% and leave 30 to 40% of the total variability unexplained. These findings do not support a large practical advantage for the vectorcardiogram over the electrocardiogram in the prediction of left ventricular size.

Additional Indexing Words:
Left ventricular mass  Left ventricular enlargement  Left ventricular volume
Multiple regression

It has been appreciated for many years that a relationship exists between the muscle mass of the left ventricle and the magnitude of the QRS generated during its activation. Both the vectorcardiogram1-10 and conventional electrocardiogram6-22 have been used to demonstrate this relationship, but neither has emerged as a significantly superior measurement of left ventricular size. Simonson,23 for instance, found the literature to support the superiority of the vectorcardiogram, but when he gave unknown tracings to 10 different observers, the electrocardiographic interpretation was most often correct. More recent workers have compared vectorcardiographic vector magnitude with electrocardiographic QRS voltage in the prediction of left ventricular enlargement, and they report no significant difference3,4,9 or superiority of the electrocardiogram.1,10

The purpose of this study was to compare the relationship between precordial voltage
measurements and measurements taken from the Frank vectorcardiogram with left ventricular mass and volume. QRS magnitude measurements were compared with respect to their linear correlation with left ventricular size as determined from biplane angiocardiograms. The sensitivity and specificity of these measurements were compared with respect to their relative ability to predict the presence or absence of left ventricular enlargement. Finally, multiple regression analysis was employed in an attempt to improve the correlation between electromotive measurements and left ventricular size and to provide a sound basis of statistical comparison between the ability of the electrocardiogram and vectorcardiogram to predict left ventricular enlargement.

**Materials and Methods**

Subjects were selected from a group of 130 patients who had had adequate rapid sequence left heart angiocardiograms and Frank vectorcardiograms recorded on tape during the admission for catheterization. Patients were excluded if there was convincing clinical evidence of a past myocardial infarction (11 patients), but neither the electrocardiogram nor the vectorcardiogram was used in making this exclusion. The single remaining criterion for exclusion was the presence of prolonged intraventricular conduction with a QRS duration of 0.125 sec or longer and the pattern of left bundle-branch block (12 patients).

These conditions were met by 107 patients. There were 71 males and 36 females, aged 16 to 75, with a mean age of 45 (±13) years. All but 22 were Caucasian. Most of these patients had valvular heart disease (table 1), but primary myocardial disease (six patients), congenital lesions (three patients), and hypertensive cardiovascular disease (three patients) were also represented.

Electrocardiographic measurements were taken from the tracings of a Sanborn direct writing instrument recorded at the time of the vectorcardiogram. The depth of the S wave in V1 and V2 and the height of the R wave in V5 and V6 were measured for each patient. Vectorcardiograms were recorded without filtration on an Ampex tape transport. They were then digitized for subsequent analysis.

Analysis of the vectorcardiographic data was

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Number</th>
<th>LV mass</th>
<th>Total LV volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valvular heart disease</td>
<td>93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pure aortic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aortic stenosis</td>
<td>7</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Aortic insufficiency</td>
<td>13</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mixed</td>
<td>15</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Pure mitral</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mitral stenosis</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Mitral insufficiency</td>
<td>9</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Mixed</td>
<td>16</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td>Aortic and mitral</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predominant AS, AI, or MI</td>
<td>15</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Predominant MS</td>
<td>17</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>Myocardial disease (cardiomyopathy)</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>8</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Hypertension</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patent ductus arteriosus</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventricular septal defect with AI</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hypertrophic subaortic stenosis</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chronic lung disease</td>
<td>1</td>
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<td></td>
</tr>
<tr>
<td>Normal</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>107</td>
<td>45</td>
<td>37</td>
</tr>
</tbody>
</table>

Abbreviations: AS = aortic stenosis; AI = aortic insufficiency; MI = mitral insufficiency; MS = mitral stenosis.
VCG, ECG, AND PREDICTION OF LV SIZE

The cartesian reference system for spatial magnitude data. The magnitude of each 0.8-msec instantaneous spatial QRS vector is calculated according to the formula: $SV_i = \sqrt{x^2 + y^2 + z^2}$, where $x$, $y$, and $z$ are the vector magnitudes along their respective lead axes of the Frank vectorcardiographic lead system.

Carried out with a computer program similar to that of Pipberger and associates,24–26 designed to calculate the instantaneous spatial QRS vector magnitude (SV) at each 0.8 msec according to the Pythagorean formula:

$SV_1 = \sqrt{x^2 + y^2 + z^2}$

The 0.8-msec instantaneous spatial vectors thus obtained were further analyzed to determine the magnitude of the maximum spatial vector (Max SV),4, 24, 25 and the sum of the instantaneous spatial vectors or time-strength integral of the spatial QRS (Sum SV). In addition, the vectors of the left posterior inferior octant of the cartesian coordinate system28 were examined because of a recent suggestion by Hugenholtz and associates8 that these leftward, posterior, and inferior forces might be closely related to left ventricular size. The instantaneous spatial vectors were analyzed for determination of: (1) the maximum leftward posterior inferior vector (Max LSV), (2) the sum of this vector plus the magnitude of the vectors occurring immediately before and after it (Sum 3LSV), and (3) the time-strength integral of all of the QRS activity occurring between azimuth 0° to +90° and elevation 0° to +90° (Sum LSV).

The vectorcardiographic and electrocardiographic measurements used in this study are summarized in figure 1 and table 2.

Angiocardiographic measurements were taken from full-frame biplane retrograde or transseptal left heart studies exposed at six or 12 frames per sec, and analyzed by the methods of Dodge26 and Rackley and associates.90 For each patient, the following values were determined: left ventricular peak systolic pressure, left ventricular end-diastolic wall thickness (LVWath), left ventricular end-diastolic volume (LVEDV), left ventricular mass (LV Mass), and the total left ventricular volume (TLVV), which is end-diastolic volume plus the volume of the myocardium (LVEDV + Mass/1.050, where 1.050 is the specific gravity of cardiac muscle).

Vectorcardiographic and electrocardiographic data were correlated with left ventricular pressure and angiocardiographic measurements by a standard computer program designed to determine the coefficient of linear correlation.

Sensitivity and specificity were determined as previously defined.31 Specificity refers to the ability of a test to give a negative result when the condition under consideration is absent: specificity = number of subjects without the condition who are also negative to the test (number of true negatives) divided by the number of subjects

Table 2

<table>
<thead>
<tr>
<th>Description</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum instantaneous spatial vector</td>
<td>$SV_1 = \sqrt{x^2 + y^2 + z^2}$</td>
</tr>
<tr>
<td>Time-strength integral of all instantaneous spatial vectors</td>
<td>$Max SV (\mu v)$</td>
</tr>
<tr>
<td>Maximum instantaneous spatial vector occurring within the leftward, posterior, inferior octant of the cartesian coordinate system (azimuth 0° to +90° and elevation 0° to + 90°)</td>
<td>$Max LSV (\mu v)$</td>
</tr>
<tr>
<td>Sum of Max LSV plus the instantaneous vector occurring 0.8 msec before and after</td>
<td>$3LSV (\mu v)$</td>
</tr>
<tr>
<td>Sum of all instantaneous spatial vectors occurring within the leftward, posterior, inferior octant.</td>
<td>$LSV (\mu v)$</td>
</tr>
<tr>
<td>Sokolow's precordial voltage criterion</td>
<td>$Sum SV_1 + RV_6 or 4 (\mu v)$</td>
</tr>
<tr>
<td>Grant's precordial voltage criterion</td>
<td>$Sum SV_1 + RV_1 or 2 + RV_4 (\mu v)$</td>
</tr>
<tr>
<td>Largest R in either lead V_3 or V_6</td>
<td>$RV_6 (\mu v)$</td>
</tr>
</tbody>
</table>

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without the condition. The sensitivity of a test reflects its ability to give a positive result when the condition or disease is indeed present: sensitivity = number of subjects with disease and positive test (number of true positives) divided by the number of subjects with the condition under consideration.

In general, sensitivity decreases as specificity is increased, and for this reason it is convenient to have a measure of comparison between studies that does not tend to maximize one of these measures at the expense of the other. "Performance" has been defined as the sum of sensitivity and specificity divided by 2, and approaches 1.0 as a test maximizes diagnostic accuracy.32

Normal vectorcardiographic limits for the determination of sensitivity, specificity, and performance were obtained from the computerized records of 187 Caucasian men and five Caucasian women, aged 18 to 74 years, with a mean age of 45 (±13) years and without historical, physical, or roentgenologic evidence of cardiovascular disease. Neither the vectorcardiogram nor the electrocardiogram was used in the selection of this "normal" population. The mean value for the Maximum SV was 1.44 mv (±0.38 SEM), with a separately determined 96% range of 0.82–2.26. These values are slightly lower than the normal limits reported by others.3,4,24,25,27 and this may be due in part to the fact that our control group was limited to Caucasians.24 The mean normal value for the time-strength integral of the spatial QRS was 47.9 µv-sec (±10.6 SEM), with a 96% range of 28–70.2.

Sensitivity, specificity, and performance were then determined in the 107 patients studied, with the mean ± 2 standard deviations from the control population as the upper limit of normal for the vectorcardiographic measurements (Max SV and Sum SV) and 3.5 mv as the upper limit of normal for Sokolow's precordial voltage criterion (SV1 + RV5 or 6).33 Normal values for the angiocardiographic measurements were obtained from the work of Kennedy and associates.4 Ventricular enlargement was considered present when the observed measurement exceeded the mean ± 2 standard deviations for their normal subjects. Of the 107 patients studied, there were 45, 42, and 37 with normal mass, end-diastolic volume, and total left ventricular volume, respectively.

Multiple regression analysis35 was chosen as a means of determining whether or not there was a statistically significant difference between the electrocardiographic and vectorcardiographic predictions of left ventricular size. The multiple correlation coefficient (R) was determined by a combination of constitutional variables (age, sex, and body surface area), electrocardiographic measurements, and vectorcardiographic measurements as a function, respectively, of left ventricular end-diastolic volume, left ventricular mass, and total left ventricular volume. Subsequent multiple regressions were then determined after the elimination of either the electrocardiographic measurements or the vectorcardiographic measurements summarized in Table 2. In each case, a new multiple correlation coefficient (R2 and R3) resulted, which could be compared with the multiple correlation coefficient of the initial population of measurements (R1). The statistical significance of any reduction in the strength of multiple correlation after elimination of either the vectorcardiographic or the electrocardiographic measurements was determined by use of the F ratio,25 and was not considered significant unless P was less than 0.01.

Multiple regression analysis was used in this study primarily for the purpose of statistical comparison of dissimilar methods of predicting left heart size. Other investigators have suggested that the technique of multiple regression analysis, which frequently yields higher correlations between electrocardiographic measurements and heart size than does simple linear correlation, might provide a more accurate prediction of left ventricular enlargement.9,36 The acid test of this suggestion would be to derive a multiple regression equation from the measurements taken from one group of patients and to apply that equation to the prediction of left heart size in a second, similar population, using only the appropriately weighted electrocardiographic and vectorcardiographic measurements. Accordingly the original group of 107 patients was divided by a table of random numbers into two subgroups of 54 and 53 patients. The first subgroup contained 31 males and 23 females, with an age range of 16 to 75 and a mean age of 46 (±15) years. In the second subgroup there were 40 males and 13 females, with an age range of 16 to 61 and a mean age of 43 (±13) years. The electrocardiographic and vectorcardiographic measurements and constitutional variables from the first group were correlated by multiple regression to derive an equation that best predicted left ventricular size. The derived equation was then substituted with the appropriate electrocardiographic, vectorcardiographic, and constitutional values for each individual in the second subgroup. Finally, the strength of linear correlations (r) between the observed and predicted values for the second subgroup was compared with the expected correlations (R) derived from the first subgroup.

Results

Simple Linear Correlations

The coefficients of simple linear correlation

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Results of Simple Linear Correlation

<table>
<thead>
<tr>
<th></th>
<th>TLVV</th>
<th>LVEDV</th>
<th>LV Mass</th>
<th>LVWaTh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constitutional correlations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>-0.03</td>
<td>-0.12</td>
<td>0.06</td>
<td>0.20</td>
</tr>
<tr>
<td>Sex (male = + r)</td>
<td>0.34</td>
<td>0.20</td>
<td>0.41</td>
<td>0.33</td>
</tr>
<tr>
<td>Body surface area</td>
<td>0.31</td>
<td>0.25</td>
<td>0.32</td>
<td>0.22</td>
</tr>
<tr>
<td>Electrocardiographic correlations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SV₁ + RV₅ or ₆ (Sokolow)²³</td>
<td>0.58</td>
<td>0.50</td>
<td>0.57</td>
<td>0.37</td>
</tr>
<tr>
<td>SV₁ or ₂ + RV₄ (Grant)³⁷</td>
<td>0.57</td>
<td>0.53</td>
<td>0.50</td>
<td>0.24</td>
</tr>
<tr>
<td>RV₄,₆</td>
<td>0.52</td>
<td>0.49</td>
<td>0.45</td>
<td>0.19</td>
</tr>
<tr>
<td>Vectocardiographic correlations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum SV</td>
<td>0.67</td>
<td>0.59</td>
<td>0.63</td>
<td>0.35</td>
</tr>
<tr>
<td>Max SV</td>
<td>0.54</td>
<td>0.46</td>
<td>0.53</td>
<td>0.32</td>
</tr>
<tr>
<td>Sum LSV</td>
<td>0.63</td>
<td>0.56</td>
<td>0.59</td>
<td>0.30</td>
</tr>
<tr>
<td>Sum 3LSV</td>
<td>0.59</td>
<td>0.51</td>
<td>0.57</td>
<td>0.35</td>
</tr>
<tr>
<td>Max LSV</td>
<td>0.58</td>
<td>0.51</td>
<td>0.55</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Simple linear correlations are significant (P < 0.01) if r is greater than 0.24.

are given in Table 3. Pressure measurements did not reach statistically significant levels in any correlation and are omitted. Vectorcardiographic measurements were significantly (P < 0.01) correlated with left ventricular end-diastolic wall thickness (LVWaTh) (r = 0.29–0.35), LV Mass (r = 0.53–0.63), LVEDV (r = 0.46–0.59), and TLVV (r = 0.54–0.67).

Electrocardiographic measurements were significantly related to LVWaTh only in the case of Sokolow's precordial voltage criterion (r = 0.37). Each of the electrocardiographic measurements was significantly related to LV Mass (r = 0.45–0.57), LVEDV (r = 0.49–0.53), and TLVV (r = 0.52–0.58).

Comparison of the vectorcardiographic measurements with those taken from the electrocardiogram shows that the sum of the instantaneous spatial voltages (Sum SV) and the sum of the leftward, inferior, posterior spatial voltages (Sum LSV) are more closely related to left ventricular mass and volume measurements than are the precordial voltages. The differences are not large, however, and none of the remaining vectorcardiographic measurements are consistently superior to the precordial voltage criteria proposed by Sokolow²³ or Grant.³⁷

Sensitivity, Specificity, and Performance

The results of the linear correlations suggested that the time-strength integral of the spatial QRS (Sum SV), the maximum spatial vector (Max SV), and Sokolow's precordial voltage criterion would be most useful for analysis in terms of sensitivity, specificity, and performance: the sum, SV₁ + RV₅ or ₆, because it was as closely related to left ventricular size as any other precordial voltage measurement made, the Max SV because it was the easiest spatial vector to measure, and, finally, the time-strength integral of the spatial QRS because it was the computer measurement most closely related to left ventricular size. The results of this analysis are given in Table 4.

The sensitivity, specificity, and performance of the time-strength integral were, in each case, superior to either the maximum spatial vector or to Sokolow's precordial voltage criterion in the prediction of left ventricular enlargement. Once again, the differences were not large, and the performance scores of Sokolow's precordial voltage criterion were comparable to those of the maximum spatial vector in making this prediction.

Multiple Regression Analysis

The results of the multiple regression analysis are given in Table 5. The combination of constitutional, electrocardiographic, and vectorcardiographic measurements increased...
the strength of correlations with left ventricular size measurements over that achieved with any of the electrocardiographic or vectorcardiographic measurements alone. The multiple correlation coefficient was highest in the prediction of total left ventricular volume \( (R = 0.81) \), and less high in the prediction of left ventricular mass \( (R = 0.77) \) and of left ventricular end-diastolic volume \( (R = 0.76) \).

Elimination of the precordial voltage measurements from these multiple regressions reduced the strength of correlation to an insignificant degree, whereas elimination of the vectorcardiographic measurements was followed by highly significant reductions in the strength of multiple correlations \( (P < 0.001 \) for TLVV and LVEDV; \( P < 0.01 \) for LV Mass). In the prediction of total left ventricular volume, for instance, elimination of the vectorcardiographic measurements was followed by a fall in \( R \) from 0.81 to 0.71, whereas elimination of electrocardiographic measurements caused \( R \) to fall to only 0.80.

Multiple regression analysis of the measurements from the randomly selected subgroup of 54 patients yielded \( R \) of 0.86 in the prediction of left ventricular end-diastolic volume and total left ventricular volume and of 0.79 in the prediction of left ventricular mass.

When the multiple regression equations derived from the first subgroup were substituted with the electrocardiographic and vectorcardiographic measurements from the second subgroup, the strength of correlation between the observed and predicted values for left ventricular size suffered a striking
reduction. As shown in table 6, the predicted values correlated modestly with the observed values for TLVV (r = 0.71) and even less closely with the observed values for LV Mass (r = 0.68) and LVEDV (r = 0.52). The strength of these correlations is not superior to that of many of the simple linear correlations in this study.

Discussion

The demonstration of a relationship between left heart size and the magnitude of surface potentials has stimulated attempts to predict the degree of left ventricular enlargement from QRS measurements and has generated controversy over the relative advantages of vectorcardiographic and electrocardiographic measurements in making this prediction. Studies that compare the vectorcardiogram with the electrocardiogram1, 3, 4, 10, 12, 23 do not consistently favor either one, and it is uncommon to find apparent superiority of one or the other supported by firm statistical analysis.5

Studies of Linear Correlation

Carter and Estes18 reported the presence of significant linear correlations between electrocardiographic measurements and the deviation of heart weight from normal, but did not comment on the strength of the relationship. More recently, Baxley and associates11 reported significant correlations between angiocardiographic measurements of left ventricular size and QRS voltage measurements taken from the electrocardiogram. The highest correlations they could demonstrate were in the range of r = 0.50 to 0.58. Similarly, Dower and Horn4 found that selected vectorcardiographic measurements were only modestly correlated with heart weight at autopsy (r = 0.40–0.50).

In the present study, we were able to demonstrate significant, but again modest, correlations between electrocardiographic voltage measurements or QRS magnitude measurements from the Frank vectorcardiogram and left ventricular wall thickness, mass, and volume measurements. The strength of these relationships ranged from r = 0.19 to 0.37 in the prediction of left ventricular wall thickness, and r = 0.45 to 0.67 in the prediction of left ventricular mass and volume.

Of the vectorcardiographic measurements, only the time-strength integrals of major portions of the spatial QRS (Sum SV and Sum LSV) seemed clearly superior to the more conventional, and far less expensive, measurements of precordial voltage suggested by Grant37 or Sokolow.33 This superiority, while apparently significant, offered small practical advantage over the conventional electrocardiogram. When Sokolow’s precordial voltage criterion, for instance, was correlated with the total left ventricular volume, a coefficient of r = 0.58 was obtained. This means that 34% (r² = 0.34) of the variability in the relationship could be accounted for with a standard electrocardiographic tracing and a ruler. In contrast, the computerized time-strength integral of the vectorcardiogram generated an r²

Table 6

<table>
<thead>
<tr>
<th>Angiographic measurement</th>
<th>Coefficient of multiple regression* (R)</th>
<th>Correlation between predicted and observed values† (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVEDV</td>
<td>0.8617</td>
<td>0.5199</td>
</tr>
<tr>
<td>LV Mass</td>
<td>0.7864</td>
<td>0.6819</td>
</tr>
<tr>
<td>TLVV</td>
<td>0.8616</td>
<td>0.7102</td>
</tr>
</tbody>
</table>

*Coefficient of multiple correlation obtained when all constitutional, ECG, and VCG measurements were correlated with left ventricular size measurements in a randomly selected subgroup of 53 patients.

†Coefficient of linear correlation between the left ventricular size measurements of a second group of 53 patients and the size predicted from the multiple regression equation derived from the first group.
of 0.45 in the prediction of total left ventricular volume and increased the strength of the relationship by only 11%. Similar analysis of the remaining vectorcardiographic measurements suggests much less, if any, superiority over the precordial voltage measurements, and supports the conclusion that selected instantaneous spatial voltages are no more closely related to left ventricular size than are selected precordial voltage measurements. Summation of spatial voltages strengthens this relationship to a modest degree.

**Studies of Sensitivity, Specificity, and Performance**

When a test measurement, such as QRS voltage, does not bear a progressive incremental relation to the degree of involvement by an independently determined disease process, such as left ventricular enlargement, but where enlarged hearts do tend to have increased QRS magnitude, sensitivity may be relatively high in the face of poor coefficients of correlation. Unfortunately, those studies that maximize specificity usually do so at considerable cost to sensitivity and vice versa. This reciprocal relationship between sensitivity and specificity makes it difficult to compare the ability of different measurements to predict the presence or absence of left ventricular enlargement. The sum of sensitivity and specificity divided by 2 has been suggested as a comparative measurement of the ability of a set of criteria to determine the presence or absence of left ventricular enlargement. As the “performance” of a test, thus defined, approaches 1.0, its ability to recognize a condition when present and to exclude it when absent is improved.

For comparative purposes, then, the performance score has the advantage of being relatively insensitive to small differences in the upper normal limit chosen for a particular test. In the present study, for instance, when the upper normal limit of Sokolow’s precordial voltage criterion in the prediction of total left ventricular volume was increased from 3.5 to 4.0 mv, specificity increased from 0.70 to 0.81 and sensitivity fell from 0.63 to 0.51, but performance remained at 0.68. This relative stability breaks down at the extremes of sensitivity and specificity, but it is useful when attempting to compare studies using different criteria for the prediction of left ventricular enlargement.

The best performance scores we could calculate from the literature for the prediction of left ventricular enlargement from QRS magnitude measurements were in the low 0.80’s. Borun and associates reported data that generated a performance score of 0.81 for the relation between precordial voltage measurements and the clinical assessment of left ventricular enlargement. In their hands, vectorcardiographic measurements did not yield performance scores above 0.70 and were considered less adequate. In contrast, Romhilt and associates and Wolff and associates reported performance scores of 0.80 to 0.81 in the prediction of left ventricular enlargement at autopsy; the latter group favored the vectorcardiogram in making this prediction. These performance scores, derived from QRS magnitude measurements alone, are not exceeded by the performance scores obtainable by any combination of vectorcardiographic or electrocardiographic or vectorcardiographic or electrocardiographic measurements reported in the recent literature, and are probably unduly elevated by the elimination of patients responsible for false negative results. In the study by Borun, for example, the measurements were made on separate “normal” and “diseased” populations, which would have the effect of increasing specificity by elimination of patients with slight degrees of cardiac enlargement but with normal electrocardiograms.

The study by Romhilt and associates excluded cases with autopsy evidence of marked right ventricular hypertrophy, which has been shown to interfere with the electrocardiographic manifestations of left ventricular hypertrophy. The study by Wolff and associates is the single unselected autopsy series that generates a performance score in the 0.80’s (0.81), and no other unselected clinical or autopsy series reviewed approaches this value. To the extent that these points are valid, the maximal performance scores obtain-
able from conventional electrocardiographic or vectorcardiographic measurements would seem to fall into the mid-to-high 0.70's, without clearly favoring either method of making this measurement.

The present study supports this conclusion because the performance scores for the vectorcardiographic measurements (0.63-0.78) are not appreciably different from those obtained using Sokolow’s precordial voltage criterion (0.67-0.76). Individual comparisons, however, suggest a small increase in sensitivity, specificity, and performance of the time-strength integral of the spatial vectors in comparison with the precordial voltage measurement or the maximum spatial vector magnitude.

It was a disappointment to find that no combination of conventional electrocardiographic1, 11-17, 19, 21, 22 or vectorcardiographic1-5, 10 measurements reported in the recent literature generated performance scores greater than 0.70 to 0.80, because tests within this range may incorrectly diagnose more than a third of the subjects under consideration. Consider, for example, an older population in which the prevalence of left ventricular enlargement may be in excess of 5%. It can be shown31 that a test with a sensitivity of 0.90 and a specificity of 0.60 will be incorrect 39% of the time when applied to the detection of a disease with a prevalence of 5%. Similarly, a test with a sensitivity of 0.60 and a specificity of 0.90 will be incorrect only 12% of the time when applied to the same population, but 40% of the subjects with the condition under consideration will be misdiagnosed. In each example, the performance score is 0.75, but no matter how the sensitivity and specificity scores are set within these limits, one has to choose between maximization of disease identification, in which case more than a third of the total population is incorrectly identified, or maximization of correct identification of normal subjects, in which case almost 50% of the diseased may not be identified.

### Multiple Regression Analysis

The use of multiple regression equations has been suggested as a means of strengthening the relationship between surface potentials
and left ventricular measurements. Our multiple regression coefficients and standard errors of estimate are presented in Table 7 for possible use by other investigators in comparing similar data.

As anticipated, the use of multiple regression analysis improved the strength of correlations in this study over that obtained using simple linear analysis. In the prediction of total left ventricular volume, for example, the combination of constitutional and electrocardiographic measurements increased the strength of the relationship from \( r = 0.58 \), the highest simple linear electrocardiographic left ventricular size correlation, to \( R = 0.71 \) for the multiple regression equation. Similarly, the combination of constitutional and vectorcardiographic measurements increased the strength of correlation from \( r = 0.67 \) to \( R = 0.80 \), a value higher than that obtained from any combination of electrocardiographic precordial voltages.

The statistical significance of a higher correlation between vectorcardiographic measurements and left ventricular size as compared with electrocardiographic measurements was clearly supported. When all of the constitutional, electrocardiographic, and vectorcardiographic measurements were combined into a multiple regression equation, the resultant \( R = 0.81 \) in the estimation of total left ventricular volume was not significantly different from the value obtained using constitutional and vectorcardiographic measurements alone (\( R = 0.80 \)). Elimination of vectorcardiographic measurements, however, caused a reduction in \( R \) to values that were significantly lower at the 0.001% level for total left ventricular volume and left ventricular end-diastolic volume, and at the 0.01% level for left ventricular mass.

Although the strength of correlations between the vectorcardiographic and left ventricular size measurements was statistically superior to the strength of correlations with the precordial voltage measurements used in this study, the practical significance of these differences is less impressive. The coefficient of determination is the square of the appropriate \( r \) or \( R \) value, and is a measure of the percentage of the variability of the dependent variable, left ventricular size in this case, accounted for or "explained" by the independent variables, the selected vectorcardiographic and electrocardiographic measurements. If the \( R^2 \) values from this study are compared, it can be seen that the vectorcardiographic-constitutional measurements "explain" 64% of the variability in the total left ventricular volume measurements. Similarly, the precordial voltage, a simple bedside measurement, accounts for fully 50% of this same variability, and the relationship might be improved if other criteria such as limb lead voltage were added to the regression. When ventricular mass is considered, the vectorcardiogram explains 57% of the relationship as compared to 50% using the electrocardiogram, a difference of only 7%.

In conclusion, it would seem that sophisticated computerized vectorcardiographic measurements of QRS magnitude do not offer the large advantages in the diagnosis of left ventricular size hoped for by workers who have been unable to find adequately close relationships between left ventricular size and standard electrocardiographic measurements. Even the recently proposed use of multiple regression analysis failed to define a relationship strong enough to predict left ventricular size in an independent group of patients or to account for more than one-half to two-thirds of the variability of left ventricular size measurements in our large group of patients with heart disease. The slight superiority of the vectorcardiogram demonstrated in this study is probably biased by the use of only electrocardiographic precordial voltage measurements. Nevertheless, other electrocardiographic criteria were not added when it became apparent that measurement of precordial voltage was as good as any single instantaneous vector magnitude in the prediction of left ventricular size. It would seem that the classic approaches to the electrocardiographic and vectorcardiographic diagnosis of left ventricular enlargement are inadequate for application to individual patient diagnosis.
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except in those instances where one is willing to establish criteria that are either so sensitive that a negative test virtually excludes left ventricular enlargement or so specific that a rarely positive test is “always” diagnostic. No criteria proposed to date have been able to do both well.

An alternative approach, which employs the concept that the diseased heart is not the equivalent of a single dipole within the chest, has recently been reported by Holt and associates32 to yield correlations with left ventricular mass that approach unity in patients with isolated aortic valve disease and give performance scores above 0.90 when applied to a heterogeneous group of patients with heart disease. Their results suggest a very significant improvement over those of previous workers and deserve careful consideration in future study of the relationship between heart size and surface potentials.

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