Performance of Conventional Orthogonal and Multiple-dipole Electrocardiograms in Estimating Left Ventricular Muscle Mass

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SUMMARY For estimating left ventricular mass (LVM), ECG criteria for left ventricular hypertrophy (LVH) were selected from conventional 12-lead ECGs, orthogonal three-lead ECGs, and multiple-dipole ECGs (MDECG). The three cardiomograms were recorded in 139 patients for whom the degree of LVH was independently determined from biplane ventriculograms.

Tested ECG criteria included Sokolow-Lyon measurements for the 12-lead ECG; for the orthogonal ECG, maximal ORS magnitude in the horizontal plane, R duration in the z-lead and $J_{sys}$ (spatial magnitude of point J); and for the 126 leads of the MDECG, the dipole activity (DA) of the septum and the free left ventricular wall.

Correlation coefficients between LVM and the 12-lead ECG, three-lead ECG and MDECG were 0.61, 0.78 and 0.89, respectively, with corresponding errors of estimated LVM of 103, 82 and 60 g. More complex recording and analytic methods clearly led to increased accuracy in LVM estimates. However, the large error of estimate may limit practical applicability of such correlations. For classification of subjects into normal and above-normal categories, a likelihood ratio was also used and led to a maximum performance index of 86% with MDECG measurements.

RECENT ATTEMPTS to quantitate left ventricular mass (LVM) are part of the trend to refine and improve noninvasive diagnostic techniques. An easily obtained estimate of LVM would be particularly desirable for patients with left ventricular hypertrophy (LVH). The ECG is well recognized as a clinical tool for the diagnosis of hypertrophy and has been used to demonstrate an increase or decrease in the degree of LVH accompanying change in clinical status. However, previous efforts to determine a significant correlation between degree of LVH and ECG measurements have had only limited success. Holt et al. reported a wide range of performance of various ECG criteria for the recognition of LVH. This may be attributed in part to the use of too few or inappropriate ECG leads that may not provide all the electrical information which is obtainable from the body surface. In addition, comparative studies have been inconclusive either because the various lead systems may not have been recorded in the same patients, or because an independent and accurate measure of muscle weight was not available, or because of the lack of uniformity in the statistical methods used.

In this study we compare several lead systems —
TABLE 1. Distribution of Clinical Diagnoses

<table>
<thead>
<tr>
<th>Diagnostic category</th>
<th>No. of subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No heart disease</td>
<td>12</td>
</tr>
<tr>
<td>2. Valve disease only</td>
<td>82</td>
</tr>
<tr>
<td>3. Cardiomyopathy, primary</td>
<td>8</td>
</tr>
<tr>
<td>4. Idiopathic hypertrophic subaortic stenosis</td>
<td>8</td>
</tr>
<tr>
<td>5. Cardiomyopathy with hypertension</td>
<td>1</td>
</tr>
<tr>
<td>6. Cardiomyopathy with valve disease</td>
<td>2</td>
</tr>
<tr>
<td>7. Coronary artery disease only</td>
<td>7</td>
</tr>
<tr>
<td>8. Valve disease + coronary artery disease</td>
<td>3</td>
</tr>
<tr>
<td>9. Hypertension only</td>
<td>1</td>
</tr>
<tr>
<td>10. Hypertension + valve disease</td>
<td>1</td>
</tr>
<tr>
<td>11. Hypertension + coronary artery disease</td>
<td>4</td>
</tr>
<tr>
<td>12. Pericardial disease</td>
<td>2</td>
</tr>
<tr>
<td>13. Congenital (L → R shunt)</td>
<td>7</td>
</tr>
<tr>
<td>14. Chronic obstructive pulmonary disease</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>139</strong></td>
</tr>
</tbody>
</table>

the standard 12-lead ECG, Frank's orthogonal three-lead ECG and the 126-lead ECG — for accuracy in estimating LVM. These systems were chosen as representative of different levels of complexity and completeness with respect to modeling cardiac electrical activity. The 12- and three-lead systems are usually used. The 126-lead ECG is a result of recent research, which allows the electrical activity of the interventricular septum and the free left ventricular wall to be computed using a 12-dipole model of the heart as described by Holt et al.\(^1\)\(^2\) This method is called the multiple-dipole ECG (MDECG).

**Materials and Methods**

Each patient studied had a complete cardiac evaluation, including cardiac catheterization and biplane angiograms. LVM was estimated from the angiograms by the method of Rackley et al.\(^3\) Kennedy and co-workers\(^4\) established the average normal male angiographic LVM as 188 ± 33 g (SD). The upper limit of normal, therefore, is considered 254 g (2 standard deviations above the mean). Using this determination of mass as an indicator independent of ECG measurements, 64 of the 139 subjects were normal and 75 were above normal. The distribution of subjects as to clinical category is given in table 1. Twelve had no evidence of heart disease and the others had valvular heart disease, cardiomyopathy, hypertension, congenital heart disease or coronary artery disease. All but two were male. Subjects were excluded if they had a history of myocardial infarction (MI), because angiographic estimates of LVM are larger than electrical LVM in these patients; and 2) ventricular conduction defects, because the MDECG model is based on normal depolarization.

The standard 12-lead ECG, the Frank orthogonal three-lead ECG, and the 126-lead MDECG were recorded in each of the subjects. The following measurements or calculations were made from each cardiogram:

1) For the standard 12-lead ECG, the criterion proposed by Sokolow and Lyon\(^5\) was selected because it is most widely used. The amplitudes of S\(_{VI}\), R\(_{V5}\) and R\(_{V6}\) were measured by hand from each record.

2) The orthogonal three-lead ECGs were analyzed by computer.\(^6\)\(^7\) From the large number of resulting measurements, a subset was chosen in a stepwise statistical procedure whereby a variable is added to the regression equation only if the variance decreases significantly.\(^8\) The subset that resulted in maximum "goodness of fit" was maximal QRS\(_{xz}\) magnitude, R\(_{V5}\) duration and J\(_{xyz}\)\(^*\).

3) From the 126 leads of the MDECG, the total dipole activity (DA) of the interventricular septum and the free left ventricular wall was computed using a 12-dipole model of the heart situated within an electrically inhomogeneous, realistically-shaped body torso. The transformation of the lead voltages to a set of time-strength curves representing DA has been described by Lynn et al.\(^9\)

To compare the information content of each of the three different ECG lead systems for the estimation of LVM, regression lines, the standard error of estimate and the standard error of prediction were computed.\(^10\) In addition, the diagnostic performance of each of the three systems was tested in terms of separating cases with normal LVM from those with elevated LVM using a likelihood ratio,

\[
l(i | x) = f(x | i) / [f(x | i) + f(x | j)]
\]

where \(l(i | x)\) is the likelihood of group \(i\) given the measurement vector \(x\), \(f(x | i)\) is the Gaussian density function for \(x\) in group \(i\), and \(i, j\) can assume values \(1\) (for normal LVM) and \(2\) (for elevated LVM). The density function was univariate for the Sokolow-Lyon criterion and for DA, but trivariate for three-lead orthogonal variables. The sample of 139 subjects was divided into a training set (92) for estimating parameters in the density function and a test set (47) for an independent evaluation of consistency of the resulting likelihood ratio.

**Results**

Correlation coefficients and standard errors of estimate for LVM are given in table 2. Using the Sokolow-Lyon criterion for LVH, the correlation with LVM is 0.61, while the orthogonal-lead criteria resulted in an improved correlation of 0.78. Best results are achieved with the 126-lead MDECG with a correlation of 0.89. The standard errors of estimate follow a similar pattern.

The scattergrams for LVM and each of the three ECG correlates are given in figures 1–3, with the respective regression lines (heavy solid) drawn through the data points. The inner bands around each of the

\(*\)The spatial magnitude of point \(J\), \(J_{xyz} = \sqrt{J_x^2 + J_y^2 + J_z^2}\), where \(J\) is the end of QRS.
regression lines denote the range delimited by one standard error of estimate, while the outer bands are the 95% fiducial limits that must be used when an ECG measurement is used to compute an estimate of LVM. For example, a value of 2000 for DA would allow an estimate of LVM of 218 g, but the 95% confidence interval for this estimate would be from 100–335 g.

Using the likelihood ratio for classification into normal and above-normal LVM categories, sensitivity and specificity levels were consistent from the training set to the test set. Therefore, the data sets were combined to give the sensitivity, specificity and performance index levels in Table 3 for each lead system. These results show that general agreement between estimated and predicted LVM is approximately three out of four for the 12-lead criterion, increases by 5% with the three-lead measurements and is highest at 86% with DA of the MDECG.

**Discussion**

The results in Table 2 show that additional ECG information is available with which to estimate LVM as the model for the heart and its surrounding volume conductor becomes increasingly complex and presumably more realistic. The standard error of estimated LVM for the MDECG is almost half that of the standard-lead criterion. However, the practicality of estimating LVM using the regression equation is limited clinically. For the best estimate, the MDECG

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**Table 2. Correlation Coefficients and Standard Errors of the Estimate for Left Ventricular Mass**

<table>
<thead>
<tr>
<th>Lead system</th>
<th>Measurements</th>
<th>Standard error of estimate</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard 12-lead ECG</td>
<td>( SV_1 + RV_{5,6} ) or ( V_6 )</td>
<td>103 g</td>
<td>0.61</td>
</tr>
<tr>
<td>Orthogonal three-lead ECG</td>
<td>Max QR, R, duration, Jxyz</td>
<td>82 g</td>
<td>0.78</td>
</tr>
<tr>
<td>Multiple-dipole 126-lead ECG</td>
<td>Left ventricular + interventricular septum dipole activity</td>
<td>60 g</td>
<td>0.89</td>
</tr>
</tbody>
</table>

**Figure 1. Scattergram of left ventricular mass (LVM) and measurements from the conventional 12-lead ECG (Sokolow-Lyon criterion).** The heavy solid line represents the linear regression of LVM on \( SV_1 + RV_{5,6} \). The light solid lines indicate the range given by 1 standard error of estimate and the dashed lines, the range for 2 standard errors for prediction (95% range). LVM = left ventricular muscle weight.

**Figure 2. Scattergram of left ventricular muscle weight (LVMW) and three combined ECG measurements from the orthogonal ECG.** The regression line and ranges are given as in figure 1.
should be used. Using 254 g as the upper limit for normal LVM and the 95% range for estimated values using the regression equation, only a DA value below 1000 nanoamperemeter-seconds allows a confident assumption of normal LVM and, conversely, only DA values exceeding 4200 would allow confident statements that LVM is abnormally high. Of the 139 subjects in this study, 117 (84%) had DA values between 1000–4200. For these the 95% confidence range of estimated LVM would include the cutoff value of 254 g. Therefore, even with more comprehensive models distinction between normal and abnormal LVM could not be made in five out of six cases using ECG measurements.

With statistical tools such as the likelihood ratio, which is more powerful for decision-making problems, the usefulness of ECG measurements is enhanced. Table 3 shows that a minimum of three out of four people would be correctly classified on the average using the Sokolow-Lyon criterion and the results can be improved to 86% with the MDECG. For all ECG systems the performance index is a balance between relatively low sensitivity and high specificity for determining abnormal LVM.

**Acknowledgment**

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