Electrocardiographic Diagnosis of Left Ventricular Hypertrophy by the Time-Voltage Integral of the QRS Complex

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Objectives. This study was conducted to test the hypothesis that the time-voltage integral of the QRS complex can improve the electrocardiographic (ECG) identification of left ventricular hypertrophy.

Background. Standard ECG criteria have exhibited poor sensitivity for left ventricular hypertrophy at acceptable levels of specificity. However, left ventricular mass may be more closely related to the time-voltage integral of the summed left ventricular dipole than to QRS duration or voltages used in standard ECG criteria.

Methods. Standard 12-lead ECGs, orthogonal lead signal-averaged ECGs and echocardiograms were obtained in 62 male control subjects without left ventricular hypertrophy and 51 men with left ventricular hypertrophy defined by echocardiographic criteria (indexed left ventricular mass > 125 g/m²). Voltage of the QRS complex was integrated over the total QRS duration in leads X, Y and Z to calculate the time-voltage integral of each orthogonal lead, of the maximal spatial vector complex and of the X, Y and Z to calculate the time-voltage integral of each orthogonal lead, of the maximal spatial vector complex and of the horizontal, frontal and sagittal plane vector complexes.

Results. At matched specificity of 99%, the 73% (37 of 51) sensitivity of the time-voltage integral of the vector QRS complex in the horizontal plane was significantly greater than the 16% sensitivity of the Sokolow-Lyon voltage (each p < 0.001). Sensitivity of Sokolow-Lyon voltage (each p < 0.001). Sensitivity of the horizontal plane time-voltage integral was also greater than the 10% to 51% sensitivity of the time-voltage integral calculated in the individual X, Y or Z leads (p < 0.01 to < 0.001), the 18% and 35% sensitivity of the time-voltage integrals of the frontal and sagittal plane vectors (p < 0.001) and the 49% sensitivity of the time-voltage integral of the maximal spatial vector complex calculated from all three orthogonal leads (p < 0.001). Comparison of receiver operating characteristic curves confirmed that the superior performance of the horizontal plane time-voltage integral relative to standard and other signal-averaged criteria was independent of partition value selection.

Conclusions. These findings suggest that use of the time-voltage integral of the QRS complex, a method that can be readily implemented on commercially available computerized ECG systems, can improve the accuracy of ECG methods for the identification of left ventricular hypertrophy.

(J Am Coll Cardiol 1994;23:133-40)
evaluate the accuracy of the time-voltage integral of the QRS complex for the identification of left ventricular hypertrophy and to determine the optimal frequency bandwidth for this analysis.

Methods

Study patients. Signal-averaged and standard 12-lead ECGs were prospectively acquired in 144 patients who underwent echocardiography at The New York Hospital-Cornell Medical Center as part of several ongoing, longitudinal studies. Group 1 consisted of 62 normotensive or mildly hypertensive men (mean age 49 ± 12 [SD] years) with normal left ventricular mass indexed to body surface area.

Groups 2 and 3 were drawn from 82 men with regurgitant valvular heart disease. Group 2 consisted of 31 patients (mean age 56 ± 14 years) without left ventricular hypertrophy, and Group 3 consisted of 51 patients (mean age 52 ± 15 years) with hypertrophy. Because of the low proportion of women in the original cohort patients with normal blood pressure or mild hypertension, the high prevalence of left ventricular hypertrophy in patients with left bundle branch block (30,31) and the absence of any patients with left bundle branch block in Group 1, we excluded women and patients with complete left bundle branch block from the present study. The study was performed in accordance with protocols approved by the Committee on Human Rights in Research of Cornell University Medical College.

Electrocardiography. Standard 12-lead ECGs were recorded at 25 mm/s and 1-mV/cm standardization with equipment whose frequency response characteristics met recommendations of the American Heart Association (32). All ECGs were digitized at 250 Hz, and all measurements were performed by computer with verification by a single investigator who had no knowledge of left ventricular mass. The QRS duration was measured to the nearest ms. and QRS amplitudes were measured to the nearest µV.

Several widely used ECG criteria for the detection of left ventricular hypertrophy were examined. These included QRS duration, the amplitude of the R wave in lead aVL, Gubner-Ungerleider voltage (sum of the amplitude of R wave in lead I and the amplitude of the S wave in lead III) (15), Sokolow-Lyon voltage (sum of the amplitude of the S wave in lead V_{1} and the R wave in lead V_{R} or V_{6}) (14), Cornell voltage (sum of the amplitude of the R wave in lead aVL and the amplitude of the S wave in lead V_{3}) (7,29), the sum of QRS voltage in all 12 leads (33) and the Romhilt-Estes point score (34), a complex ECG criterion for hypertension based on a weighted score that incorporates QRS duration, QRS voltages, repolarization changes and P wave abnormalities. On the basis of the observation that the product of QRS duration and voltage as an approximation of the time-voltage area under the QRS complex may be a useful marker for left ventricular hypertrophy (29), a voltage-duration product was calculated for Cornell voltage, Sokolow-Lyon voltage and the 12-lead sum of QRS voltage.

Signal-averaged electrocardiography. After careful skin preparation with the patient lying quietly in the supine position, three orthogonal X, Y and Z leads were acquired (Predictor Signal Averaging ECG, Corazonix Corporation) using an operator-selected template at a sampling frequency of 2,000 Hz. Signal-averaging was terminated when the residual RMS noise in the ST segment was ≤1 µV and in the majority of cases when the residual noise reached 0.3 µV. The mean residual RMS noise was 0.31 ± 0.05 µV (range 0.30 to 0.66) and was 0.3 µV in 92% (133 of 144) of patients.

Digital filtering was performed on averaged orthogonal lead complexes with a standard frequency (0 to 100 Hz) low pass filter. Vector magnitudes were calculated for each filtered orthogonal lead as (X^{2} + Y^{2} + Z^{2})^{1/2}. Additional vector magnitudes were calculated for the horizontal plane (X^{2} + Z^{2})^{1/2}, the frontal plane (X^{2} + Y^{2})^{1/2} and the sagittal plane (Y^{2} + Z^{2})^{1/2}. Vector QRS complex onset and offset were determined by a computer algorithm that determined the first and last points at which voltage exceeded the mean of the baseline noise level plus three times the standard deviation to the nearest 0.5 ms. Time-voltage integrals of each vector QRS magnitude were measured over the duration of the QRS complex to the nearest 0.01 µV-s. In addition, the peak amplitude of the maximal spatial vector was measured to the nearest µV to replicate previous vector studies (19–21).

To test whether alternate frequency content of the vector QRS might more accurately identify patients with left ventricular hypertrophy, additional maximal spatial vector magnitudes were calculated by reprocessing the unfiltered averaged orthogonal lead complexes with 40 to 250, 80 to 250 and 150 to 250-Hz bandpass spectral filters, which were selected from previous reports as potentially useful bandwiths for evaluating the high frequency content of QRS voltage (28,35,36). Time-voltage integrals of each high frequency vector magnitude were also measured to the nearest 0.01 µV-s.

Echocardiography. All subjects underwent standard M-mode and two-dimensional echocardiography performed by a highly skilled research technician using a commercially available echocardiograph equipped with 2.5- and 3.5-MHz imaging transducers. Left ventricular dimensions were obtained from two-dimensionally guided M-mode tracings according to the recommendations of the American Society of Echocardiography (37). Measurements were performed on multiple cardiac cycles by use of a digitizing tablet and were averaged. If M-mode tracings were technically inadequate, left ventricular wall thicknesses and internal dimensions were measured from the two-dimensional study by the method recommended by the American Society of Echocardiography (38). Left ventricular mass was calculated according to an anatomically validated formula (39), and left ventricular hypertrophy was considered present in this group of men if the left ventricular mass indexed to body surface area was >125 g/m², a partition value chosen on the
Table 1. Patient Characteristics

<table>
<thead>
<tr>
<th>Group</th>
<th>p Value</th>
<th>p Value vs. Group 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>40 ± 12</td>
<td>0.66</td>
</tr>
<tr>
<td>Body surface area (m²)</td>
<td>2.00 ± 0.20</td>
<td>0.23</td>
</tr>
<tr>
<td>Left ventricular mass (g)</td>
<td>166 ± 39</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Left ventricular mass index (g/m²)</td>
<td>83 ± 17</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Fractional shortening (%)</td>
<td>35 ± 5</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Group 1 = normotensive or mildly hypertensive men; Group 2 = men with regurgitant valve disease without left ventricular hypertrophy; Group 3 = men with regurgitant valve disease with left ventricular hypertrophy.

Results

Study patients. Characteristics of the patient groups are presented in Table 1. Among patients without left ventricular hypertrophy, Group 1 and Group 2 patients were similar with regard to mean age, body surface area and fractional shortening. However, the Group 2 patients with regurgitant valvular heart disease had higher left ventricular mass and higher left ventricular mass indexed to body surface area than did Group 1 patients. Patients with left ventricular hypertrophy (Group 3) were similar to Group 1 and Group 2 patients with respect to age and body surface area but had a slightly lower mean fractional shortening than did Group 2 patients. By group definition, Group 3 patients had higher indexed and unindexed left ventricular mass than did either Group 1 or Group 2 patients.

Test sensitivity for left ventricular hypertrophy. Relative performance of ECG and vectorcardiographic criteria using the standard frequency filter (0 to 100 Hz) for the identification of left ventricular hypertrophy is examined in Table 2 and Figures 1 to 4. Using a partition with a specificity of 99% by percentile estimation in Group 1 patients, the time-voltage integral of the horizontal plane vector QRS had the highest sensitivity for the identification of left ventricular hypertrophy (73% [37 of 51]). At a matched specificity of 99%, simple QRS voltage and duration criteria had a significantly lower sensitivity for left ventricular hypertrophy, ranging from 65% for the R wave in lead aVL to 37% for Sokolow-Lyon voltage (each p < 0.001). Comparison of receiver operating characteristic curves further demonstrated that improved performance of the horizontal plane
Table 2. Test Sensitivity and Specificity for the Identification of Left Ventricular Hypertrophy Using Partitions With Matched Specificity of 99% in Group 1 Patients

<table>
<thead>
<tr>
<th>Criteria Partition</th>
<th>Sensitivity (%) (Group 3; n = 51)</th>
<th>Specificity (%) (Group 2; n = 31)</th>
<th>p vs. 99% Specificity in Group 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>R wave in lead aVL</td>
<td>1.650 µV</td>
<td>6*</td>
<td>94</td>
</tr>
<tr>
<td>Gubner-Ungerleider voltage</td>
<td>3.373 µV</td>
<td>6*</td>
<td>96</td>
</tr>
<tr>
<td>Cornell voltage</td>
<td>3.334 µV</td>
<td>22*</td>
<td>87</td>
</tr>
<tr>
<td>12-lead sum</td>
<td>21.737 µV</td>
<td>33*</td>
<td>90</td>
</tr>
<tr>
<td>Sokolow-Lyon voltage</td>
<td>3.591 µV</td>
<td>37*</td>
<td>90</td>
</tr>
<tr>
<td>QRS duration</td>
<td>116 ms</td>
<td>16*</td>
<td>81</td>
</tr>
<tr>
<td>Romhilt-Estes point score</td>
<td>6 points</td>
<td>10*</td>
<td>97</td>
</tr>
<tr>
<td>Cornell product</td>
<td>386.744 µV-s</td>
<td>18*</td>
<td>87</td>
</tr>
<tr>
<td>12-lead product</td>
<td>2,521,492 µV-s</td>
<td>27*</td>
<td>94</td>
</tr>
<tr>
<td>Sokolow-Lyon product</td>
<td>404.664 µV-s</td>
<td>45*</td>
<td>90</td>
</tr>
<tr>
<td>Maximal spatial vector amplitude</td>
<td>3.696 µV</td>
<td>35*</td>
<td>81</td>
</tr>
<tr>
<td>Lead X integral</td>
<td>65.62 µV-s</td>
<td>51†</td>
<td>87</td>
</tr>
<tr>
<td>Lead Y integral</td>
<td>99.25 µV-s</td>
<td>10*</td>
<td>100</td>
</tr>
<tr>
<td>Lead Z integral</td>
<td>95.93 µV-s</td>
<td>43*</td>
<td>77</td>
</tr>
<tr>
<td>Horizontal plane vector integral</td>
<td>99.19 µV-s</td>
<td>73</td>
<td>84</td>
</tr>
<tr>
<td>Frontal plane vector integral</td>
<td>114.18 µV-s</td>
<td>18*</td>
<td>94</td>
</tr>
<tr>
<td>Sagittal plane vector integral</td>
<td>125.62 µV-s</td>
<td>35*</td>
<td>81</td>
</tr>
<tr>
<td>Maximal spatial vector integral</td>
<td>136.88 µV-s</td>
<td>49*</td>
<td>84</td>
</tr>
</tbody>
</table>

*p < 0.001, †p < 0.01 versus horizontal plane vector integral.

The performance of additional time-voltage areas is also

integral relative to simple ECG criteria was independent of
partition value selection (Fig. 1).

Test performance of standard ECG criteria was not
improved by the use of more complex ECG criteria; at
matched specificity of 99%, the Romhilt-Estes point score
identified left ventricular hypertrophy with a sensitivity of
only 10% (p < 0.001), and the sensitivity of the QRS
time-duration products ranged from only 18% for the
Cornell product to 45% for the Sokolow-Lyon product
(Table 2). In addition, the 73% sensitivity of the horizontal
plane integral was significantly higher than the 35% sensitivity
of the maximal amplitude of the three-dimensional vector
magnitude (the maximal spatial vector amplitude, p <
0.001). Comparison of receiver operating characteristic
curves confirmed the superior performance of the horizontal
plane integral relative to ECG criteria and the maximal
spatial vector amplitude (Fig. 2). Comparison of receiver
operating characteristic curve areas demonstrated a signifi-
cant improvement in overall performance for the Cornell
product (area 0.95 ± 0.04 vs. 0.82 ± 0.04, p < 0.05), the
Sokolow-Lyon product (area 0.93 ± 0.02 vs. 0.88 ± 0.03,
p < 0.01) and the 12-lead product (0.90 ± 0.03 vs. 0.86 ±
0.04, p < 0.05) compared with their respective simple
voltage criteria.

The performance of additional time-voltage areas is also

Figure 1. Receiver operating characteristic curves demonstrating
the superior overall performance of the horizontal plane vector
integral compared with simple QRS voltage and duration criteria.
*p < 0.001 versus the horizontal plane vector integral.

Figure 2. Receiver operating characteristic curves demonstrating
the superior overall performance of the horizontal plane vector
integral compared with complex electrocardiographic criteria and
the maximal spatial vector amplitude. *p < 0.05, **p < 0.01, ***p <
0.001 versus the horizontal plane vector integral.
examined in Table 2 and Figures 3 and 4. At a matched specificity of 99%, the sensitivity of the time-voltage integral of the area under the QRS complex in the individual orthogonal leads ranged from only 10% in lead Y to 51% in lead X (p < 0.01 to p < 0.001 vs. horizontal plane integral). As a consequence of the poor performance of the lead Y voltage integral, calculation of the time-voltage area of the QRS complex in the frontal or sagittal plane resulted in significantly lower sensitivities than that found for the horizontal plane integral. Similarly, incorporation of all three orthogonal leads into a maximal spatial vector QRS complex did not improve sensitivity of the time-voltage integral for left ventricular hypertrophy (49%, p < 0.001 vs. the horizontal plane integral). Comparison of receiver operating characteristic curves further confirmed the superior performance of the horizontal plane vector integral relative to the other time-voltage integrals for the identification of left ventricular hypertrophy (Fig. 3 and 4).

Table 3. Sensitivity of Left Ventricular Hypertrophy According to the Severity of Hypertrophy Using Partitions With 99% Specificity in Group I

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Sensitivity (%) of Left Ventricular Mass Index &gt; 164.6 g/m²</th>
<th>Sensitivity (%) of Left Ventricular Mass Index &gt; 164.6 g/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria</td>
<td>n = 26</td>
<td>p Value</td>
</tr>
<tr>
<td>R wave in lead aVL</td>
<td>4*</td>
<td>0.61</td>
</tr>
<tr>
<td>Gubner-Ungerleider voltage</td>
<td>4*</td>
<td>0.61</td>
</tr>
<tr>
<td>Cornell voltage</td>
<td>15*</td>
<td>0.32</td>
</tr>
<tr>
<td>12-lead sum</td>
<td>15*</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Sokolow-Lyon voltage</td>
<td>19*</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>QRS duration</td>
<td>15*</td>
<td>1.00</td>
</tr>
<tr>
<td>Rouchik-Estes point score</td>
<td>8*</td>
<td>0.67</td>
</tr>
<tr>
<td>Cornell product</td>
<td>8*</td>
<td>0.08</td>
</tr>
<tr>
<td>12-lead product</td>
<td>12*</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Sokolow-Lyon product</td>
<td>31*</td>
<td>0.05</td>
</tr>
<tr>
<td>Maximal spatial vector amplitude</td>
<td>23*</td>
<td>0.08</td>
</tr>
<tr>
<td>Lead X integral</td>
<td>42*</td>
<td>0.27</td>
</tr>
<tr>
<td>Lead Y integral</td>
<td>12*</td>
<td>1.00</td>
</tr>
<tr>
<td>Lead Z integral</td>
<td>27*</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Horizontal plane vector integral</td>
<td>50*</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Frontal plane vector integral</td>
<td>12*</td>
<td>0.29</td>
</tr>
<tr>
<td>Sagittal plane vector integral</td>
<td>31*</td>
<td>0.57</td>
</tr>
<tr>
<td>Maximal spatial vector integral</td>
<td>35*</td>
<td>0.05</td>
</tr>
</tbody>
</table>

*p < 0.001, *p < 0.01, *p < 0.05, *p = 0.29 versus horizontal plane vector integral. Partitions as in Table 2.

Figure 3. Receiver operating characteristic curves demonstrating the superior overall performance of the horizontal plane vector integral compared with the time-voltage integral of the individual orthogonal vector leads. *p < 0.05, **p < 0.01, ***p < 0.001 versus the horizontal plane vector integral.

Figure 4. Receiver operating characteristic curves demonstrating the superior overall performance of the horizontal plane vector integral compared with the time-voltage integral of the QRS complex in the frontal plane, sagittal plane and maximal spatial vector (XYZ integral) calculated from all three orthogonal leads. *p < 0.05. **p < 0.01 versus the horizontal plane vector integral.

Test sensitivity in relation to severity of left ventricular hypertrophy. Relation of the sensitivity of ECG and vectorcardiographic criteria to the severity of left ventricular hypertrophy is examined in Table 3. The sensitivity of both ECG and vectorcardiographic criteria was higher among patients with more severe left ventricular hypertrophy when patients with hypertrophy were classified according to whether indexed left ventricular mass was higher or lower than the median value (164.6 g/m²). Among the patients with less severe left ventricular hypertrophy, the 58% sensitivity (15 of 26) of the horizontal plane integral remained significantly greater than the 4% to 35% sensitivity of all other criteria except the 42% sensitivity of the time-voltage integral in lead X (p = 0.29). Similarly, among patients with more severe hypertrophy, the 88% sensitivity (22 of 25) of the horizontal plane integral was significantly higher than the 8% to 60% sensitivity of the other ECG and vectorcardiographic criteria.

Test specificity for left ventricular hypertrophy. Relative test specificity of ECG and vectorcardiographic criteria for
left ventricular hypertrophy is examined in Table 2. As expected, partitions with a specificity of 99% by percentile estimation in Group 1 patients tended to perform with slightly lower specificities (range 77% to 100%) in the patients with regurgitant valvular heart disease and left ventricular mass that tended to be in the upper part of the normal range. The 84% (26 of 31) specificity of the horizontal plane integral in Group 2 patients was significantly less than the 99% specificity in Group 1 (p < 0.05), but did not differ significantly from the specificity of any of the other ECG or vectorcardiographic criteria in this group (p = 0.07 to 1.00).

**Vectorcardiographic test performance in relation to frequency content.** The relation of test performance of the time-voltage area to frequency content of the QRS complex was examined in the maximal spatial vectors. Higher band-pass filtering of the maximal spatial vector magnitude significantly reduced test performance relative to standard frequency (0 to 100 Hz) low pass filtering: the 10% (5 of 51) sensitivity of the 40- to 250-Hz filtered vector, the 16% (8 of 51) sensitivity of the 100- to 250-Hz filtered vector and the 8% (4 of 51) sensitivity of the 150- to 250-Hz filtered vector were all significantly lower than the 49% (25 of 51) sensitivity of the 0- to 100-Hz standard frequency maximal spatial vector magnitude integral (all p < 0.001).

**Discussion**

**Improved ECG sensitivity for left ventricular hypertrophy.** Although the standard 12-lead ECG remains the most commonly utilized initial diagnostic test in the screening process for left ventricular hypertrophy, the relatively poor sensitivity of both simple and complex ECG criteria for hypertrophy has limited the clinical utility and cost-effectiveness of the ECG (5). The present study demonstrates that measurement of the time-voltage area under the QRS complex, by integrating voltage over the total duration of the QRS complex, can appreciably improve the accuracy of ECG methods for the identification of patients with left ventricular hypertrophy. These findings further suggest that improved accuracy of this approach can be found in the 0- to 100-Hz frequency range of the standard ECG and may be localized to the horizontal plane.

**Relation of QRS voltage and duration to left ventricular hypertrophy.** Increased QRS voltage, attributed to increased size of the electrical activation boundary according to solid angle theory (45), is a highly specific but poorly sensitive finding in left ventricular hypertrophy (6-10). The QRS duration has also been found to correlate with left ventricular mass (8,16-24,29,46,47). Although the mechanism for QRS prolongation in left ventricular hypertrophy has not been determined, it may be related to the longer time required to activate myocardium that is increasingly distant from specialized conduction tissue (17,47), decreased conduction velocity in hypertrophied myocardium (48) or changes in activation sequence and the relative conductivity of fibrotic intracellular and extracellular spaces (16,49,50).

However, QRS duration alone has also proved to be poorly sensitive for left ventricular hypertrophy at clinically relevant levels of specificity (29).

Several observations suggest that ECG criteria incorporating both QRS duration and QRS voltages should improve identification of left ventricular hypertrophy. The Romhilt-Estes point score (12), multivariate score of Rautaharju (13) and the more recently derived Cornell multivariate regression score (6,7) have all shown improved correlation with left ventricular mass compared with purely voltage-based criteria. However, the sensitivity for left ventricular hypertrophy has remained relatively poor with these criteria (6-13). A recent study (29) from our laboratory demonstrated that several voltage-duration products as approximations of the time-voltage area of the QRS complex can improve the ECG identification of left ventricular hypertrophy.

**Time-voltage area of the QRS complex and left ventricular hypertrophy.** Observations that the time-voltage integral of the orthogonal lead vectorcardiographic QRS complex and the summed time-strength left ventricular dipole derived from the 126-lead multiple dipole ECG can improve the ECG correlation with left ventricular mass (16-24) suggest that an ECG representation of the time-voltage integral of ventricular activation should more accurately reflect the presence of left ventricular hypertrophy than do standard QRS voltage and duration criteria. The present study further extends these findings, demonstrating that the time-voltage integral of the horizontal plane vector QRS has optimal accuracy for the detection of left ventricular hypertrophy among the variables tested. These observations suggest that increases in left ventricular mass may be paralleled by subtle increases in both QRS voltage and duration that together produce a proportionally greater increase in the area under the QRS complex than in either QRS voltage or duration alone. Thus, the time-voltage integral of the QRS complex may more accurately reflect the presence and severity of hypertrophy than do ECG scores that incorporate both QRS duration and voltage only as weighted linear sums: the time-voltage integral also performs better than simple voltage-duration products that only approximate the area under the QRS complex (29).

The present study confirms previous findings (27) suggesting that most of the diagnostic power of the time-voltage integral of the QRS complex for the detection of left ventricular hypertrophy in humans can be found in the standard 0- to 100-Hz frequency bandwidth. In contrast, higher performance of the time-voltage integral of the vector QRS complex after high pass filtering at 44 Hz (28) was found in a small group of rabbits. These differences in optimal bandwidths between species may reflect the substantial differences in heart size and weight and significantly higher heart rates found in rabbits.

**Limitations and implications.** The present study confirms previous findings that sensitivity of ECG criteria for the detection of left ventricular hypertrophy varies with the severity of hypertrophy (6,10) and further demonstrates that
test specificity is also dependent on the level of left ventricular mass among patients without left ventricular hypertrophy. The significantly lower specificity of the horizontal plane integral and many of the other ECG and vectorcardiographic criteria among Group 2 as compared with Group 1 patients most likely reflects the significantly higher indexed and unindexed left ventricular mass found in the Group 2 patients with valvular heart disease. Thus, the new time-voltage integral criteria are more likely to be falsely positive among patients with values of indexed left ventricular mass near the top of an arbitrary “normal” range and to be only rarely falsely negative among patients with the greatest degrees of left ventricular hypertrophy.

These findings suggest that application of a time-voltage integral method to the area under the QRS complex should improve the diagnostic accuracy of the ECG for the detection of left ventricular hypertrophy. Current computerized ECG equipment can perform similar analyses on the standard 12 leads, and new methodology may allow synthesis of the horizontal plane vector from 12-lead data, facilitating both further testing and eventual clinical utility of this method. The improved overall performance of the voltage-duration products as simple approximations of the time-voltage area of the QRS complex supports the use of this less sophisticated approach in the absence of computerized ECG equipment capable of measuring the area under the QRS complex in a more precise manner.

Further validation of this approach to the analysis of the ECG is required in larger and clinically more heterogeneous groups of patients that include an adequate number of women. The small number of women in the normotensive or mildly hypertensive control group did not allow establishment of a separate normal range of test values in women: the lower QRS voltages and shorter QRS duration in women as compared with men (6,7,51,52) suggest that gender-specific groups of patients that include an adequate number of women with左 ventricular mass are more precisely found in the Group 2 patients with valvular heart disease. Thus, the new time-voltage integral criteria are more likely to be falsely positive among patients with values of indexed left ventricular mass near the top of an arbitrary “normal” range and to be only rarely falsely negative among patients with the greatest degrees of left ventricular hypertrophy.

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