Relationship between Electrocardiographic Voltage and Geometric Patterns of Left Ventricular Hypertrophy in Patients with Essential Hypertension

Shin Tomita, Hitoshi Ueno, Masanobu Takata, Kotaro Yasumoto, Fumihiro Tomoda, and Hiroshi Inoue

To assess whether we could predict left ventricular (LV) geometric patterns on echocardiography from voltages in standard electrocardiograms (ECG) in patients with essential hypertension, standard 12-lead ECG and echocardiograms were recorded in 106 consecutive, untreated patients (50±11 yr old) with essential hypertension. Subjects were assigned to the following four groups based on relative wall thickness (RWT) and LV mass index (LVMI) as determined by echocardiography: a normal geometry group (n = 44), a concentric remodeling group (increased RWT and normal LVMI, n = 10), an eccentric hypertrophy group (increased LVMI and normal RWT, n = 23), and a concentric hypertrophy group (increased RWT and LVMI, n = 29). The following ECG variables were determined: Sokolow-Lyon voltage (SV, + RV5: SL), Cornell voltage (RaVL - 5V3 : CN), sum of 12-lead QRS voltage (12-lead sum), and RV6 / RV5 ratio (RV6 / V5). LVMI correlated with SL, CN, and 12-lead sum, but not with RV6 / V5 in the study group as a whole. The concentric hypertrophy group showed increased voltages for all ECG variables except RV6 / V5. The concentric remodeling group showed increased voltages for SL and 12-lead sum, but a decreased RV6 / V5 ratio. In contrast, the eccentric hypertrophy group had increased voltage only for the 12-lead sum. The combination of SL, RV6 / V5, and CN showed modest sensitivity and specificity in the diagnosis of concentric remodeling, concentric hypertrophy, and normal geometry, but not in the diagnosis of eccentric hypertrophy. Conventional ECG criteria can predict LVMI, but not LV geometry in the patients with essential hypertension. The combination of SL, CN, and RV6 / V5 is useful in differentiating the four LV geometric patterns seen in essential hypertension. (Hypertens Res 1998; 21: 259-266)

Key Words: left ventricular hypertrophy, essential hypertension, left ventricular geometric pattern, electrocardiography

Left ventricular hypertrophy (LVH) is associated with a poor prognosis in patients with hypertension (1). An increased left ventricular (LV) mass is a major risk factor and a powerful independent predictor of cardiovascular events (2). In the Framingham Study, LVH as determined by electrocardiography (ECG) was associated with a 3- to 15-fold increase in the incidence of cardiovascular events, with the risk ratios being highest for cardiac failure and stroke (3).

Evaluation of LV mass is therefore important in patients with hypertension. ECG is a simple method used to diagnose LVH and to stage the severity of hypertensive heart disease (4). Echocardiography has been used to determine the LV mass for over 25 yr (5). Although sophisticated new techniques, including ECG-gated magnetic resonance imaging (6), computed tomography (7), and threedimensional echocardiography (8), provide more accurate measurements of LV mass and LV volume, these methods are more expensive and are not as widely available as conventional ECG.

Ganau et al. (9) have reported that cardiovascular mortality and morbidity differ significantly among patients with different LV geometric patterns as determined by echocardiography. Although the relationship between ECG findings and LV mass has been extensively investigated, data on the association between geometric patterns of hypertensive LVH and ECG changes are limited. We therefore investigated the relationship between LV geometry and ECG voltage changes in untreated patients with essential hypertension.

**Methods**

Hypertensive subjects were consecutively enrolled from patients presenting at the outpatient clinic of Toyama Medical and Pharmaceutical University Hospital between May 1994 and September 1996. All patients underwent routine laboratory studies, including measurements of serum levels of electro-
lytes and creatinine, blood urea nitrogen, fasting blood glucose level, liver function tests, and urinalysis. Chest roentgenography and ECG were also performed. The diagnosis of essential hypertension was based on the results of laboratory tests and the guidelines of the World Health Organization (10). Blood pressure was measured with a standard cuff and a sphygmanomanometer after patients rested for 5 to 10 min in the sitting position. Patients were enrolled in the study if their systolic blood pressure (SBP) was >160 mmHg, their diastolic blood pressure (DBP) was >95 mmHg, or both on three separate occasions. Patients with intraventricular conduction abnormalities on ECG and peripheral edema were excluded. Subjects were also excluded if echocardiograms were inadequate for analysis. After giving informed consent, 106 patients with essential hypertension (51 men and 55 women; mean age, 50 ± 11 yr; range, 23 to 76 yr) were enrolled in the study. Mean body weight, height, and body mass index (BMI) were 62.8 ± 10.6 kg, 159.2 ± 8.9 cm, and 24.7 ± 3.2 kg/m², respectively. No patient had any evidence of, or a history of, acute or chronic cardiac, pulmonary, hepatic, or renal diseases. The serum creatinine level was below 1.2 mg/dl, and the results of urinalysis were normal in all patients.

**Study Protocol**

Before studies were performed, patients were instructed to eat a normal diet (NaCl 8 to 10 g daily) for 2 wk, avoiding a very high or a low intake of sodium. Patients were asked to refrain from caffeine, alcohol, and smoking for 12 h before the examination and to eat a light breakfast about 3 h before the examination. Conventional transthoracic echocardiography was performed after patients had rested for 10 min in the supine position, followed by recording of a standard 12-lead ECG. After 30 min of rest, blood samples were obtained from an antecubital vein for measurement of plasma renin activity and plasma aldosterone concentration (PAC). PRA and PAC were measured by radioimmunoassays (11, 12).

**Echocardiography**

Two-dimensionally guided M-mode echocardiography was performed with a Toshiba SSH-HA phased array ultrasonic sector scanner and a Toshiba FR-08A recorder. All patients were studied in the supine position or in the left lateral position, with the transducer placed in the third to fifth intercostal space at the left sternal border. The tracings used to determine LV dimensions were recorded at or just below the tip of the mitral leaflets. The echocardiograms were read blindly and randomly by two independent observers. The LV mass (LVM) was calculated according to the formula of Devereux and Reichek (13):

\[
LVM(g) = 1.04[(LVDd + PWd + IVSd)^3 - LVDd^3] - 13.6,
\]

where LVDd is the LV internal dimension in diastole, PWd is the LV posterior wall thickness in diastole, and IVSd is the interventricular septal thickness in diastole. The LVM index (LVMI) was determined by dividing the LVM by the patient's body surface area. The relative wall thickness (RWT) was calculated according to the following formula (9):

\[
RWT = \frac{(IVSd + PWd)}{LVDd}.
\]

The upper limit of normal for LVMI was 111 g/m² for men and 106 g/m² for women as previously reported by our laboratory (14). We used an RWT of 0.44 as the cut-off value for normal in both men and women. The subjects were divided into four groups based on the LV geometric pattern according to the classification system of Ganau et al. (9): a normal geometry group with normal LVMI and normal RWT, a concentric remodeling group with normal LVMI and increased RWT, an eccentric hypertrophy group with increased LVMI but normal RWT, and a concentric hypertrophy group with increased LVMI and increased RWT. The LV volume in diastole (LVEDV) was calculated according to the following formula (15):

\[
LVEDV = \left[\frac{7}{(2.4 + LVDd)}\right] \times LVDd^3.
\]

**ECG**

Standard 12-lead ECGs were recorded at a paper speed of 25 mm/s and a sensitivity of 1 mV/cm according to the recommendations of the American Heart Association (16). All ECGs were recorded by the same examiner, who was unaware of the echocardiographic data. ECG variables were averaged over five consecutive heart cycles. The voltage is expressed in millimeters in all figures except for Fig. 4 (see Results).

R-wave and S-wave voltages were determined in all 12 leads. The following widely used ECG voltage criteria for detection of LVH were employed in the present study: the Sokolow-Lyon voltage (sum of amplitude of S-wave in V1 and that of R-wave in V5) (17), the Cornell voltage (sum of amplitude of R-wave in aVL and that of S-wave in V3) (18), the Siegel and Roberts voltage (sum of QRS amplitude of 12-leads: 12-lead sum) (19), and the R-wave ratio of V6 to V5 (RV6/V5) (20).

**Statistical Analysis**

The results are presented as means ± SD. Intergroup differences were analyzed by one-way analysis of variance followed by Bonferroni's test. The correlation between LVMI and ECG voltage criteria was analyzed by linear regression analysis. Differences in sex distribution were analyzed by chi-square test. P values <0.05 were considered to indicate statistical significance.

**Results**

**Baseline Characteristics**

Of the 106 patients, 44 (42%) belonged to the normal geometry group, 23 (9%) to the concentric remodeling group, 25 (22%) to the eccentric hypertrophy group, and 29 (27%) to the concentric hypertrophy group. There were no significant differences in age, sex, duration of hypertension, BMI, SBP, DBP, PRA, or PAC among the groups. Echocardiographic indices differed significantly among
Table 1. Patient Characteristics in the Four Study Groups

<table>
<thead>
<tr>
<th></th>
<th>Normal geometry</th>
<th>Concentric remodeling</th>
<th>Eccentric hypertrophy</th>
<th>Concentric hypertrophy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number (%)</td>
<td>44 (42%)</td>
<td>10 (9%)</td>
<td>23 (22%)</td>
<td>29 (27%)</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>49 ± 10</td>
<td>51 ± 8</td>
<td>53 ± 14</td>
<td>54 ± 10</td>
</tr>
<tr>
<td>Sex (Male/Female)</td>
<td>21/23</td>
<td>6/4</td>
<td>10/13</td>
<td>14/15</td>
</tr>
<tr>
<td>Duration of HT (yr)</td>
<td>5 ± 4</td>
<td>7 ± 6</td>
<td>6 ± 5</td>
<td>9 ± 10</td>
</tr>
<tr>
<td>SBP (mmHg)</td>
<td>157 ± 12</td>
<td>161 ± 10</td>
<td>163 ± 15</td>
<td>167 ± 22</td>
</tr>
<tr>
<td>DBP (mmHg)</td>
<td>100 ± 78</td>
<td>102 ± 5</td>
<td>99 ± 9</td>
<td>102 ± 13</td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>70 ± 12</td>
<td>75 ± 12</td>
<td>71 ± 8</td>
<td>66 ± 10</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>24.1 ± 2.7</td>
<td>25.0 ± 1.9</td>
<td>25.4 ± 3.7</td>
<td>25.1 ± 3.6</td>
</tr>
<tr>
<td>IVSd (mm)</td>
<td>8.7 ± 1.2</td>
<td>10.6 ± 0.7*</td>
<td>9.9 ± 0.7*</td>
<td>12.0 ± 1.3*,†,‡‡</td>
</tr>
<tr>
<td>PWd (mm)</td>
<td>8.6 ± 1.1</td>
<td>10.2 ± 0.6*</td>
<td>9.7 ± 0.8*</td>
<td>11.5 ± 1.2*,†,‡‡</td>
</tr>
<tr>
<td>LVDd (mm)</td>
<td>47.1 ± 3.9</td>
<td>42.8 ± 1.9*</td>
<td>51.4 ± 4.2*,†,‡‡</td>
<td>46.8 ± 3.0*,‡‡</td>
</tr>
<tr>
<td>RWT</td>
<td>0.37 ± 0.04</td>
<td>0.49 ± 0.03*</td>
<td>0.39 ± 0.03††</td>
<td>0.51 ± 0.05*,†,‡‡</td>
</tr>
<tr>
<td>LVMI (g/m²)</td>
<td>85 ± 15</td>
<td>96 ± 9</td>
<td>126 ± 15*,†,‡‡</td>
<td>140 ± 24*,†,‡‡</td>
</tr>
<tr>
<td>PRA (ng/ml/h)</td>
<td>1.3 ± 1.6</td>
<td>1.3 ± 1.2</td>
<td>0.7 ± 0.7</td>
<td>1.9 ± 2.7</td>
</tr>
<tr>
<td>PAC (ng/ml)</td>
<td>9.4 ± 7.5</td>
<td>9.6 ± 5.8</td>
<td>8.7 ± 5.5</td>
<td>9.5 ± 8.4</td>
</tr>
</tbody>
</table>

HT, hypertension; SBP, systolic blood pressure; DBP, diastolic blood pressure; HR, heart rate; BMI, body mass index; IVSd, interventricular septal thickness in diastole; PWd, left ventricular posterior wall thickness in diastole; LVDd, left ventricular dimension in diastole; RWT, relative wall thickness; LVMI, left ventricular mass index; PRA, plasma renin activity; PAC, plasma aldosterone concentration. Values are expressed as means ± SD. *p<0.01 vs. normal geometry; †p<0.05, ‡p<0.01 vs. concentric remodeling; ††p<0.05, ‡‡p<0.01 vs. eccentric hypertrophy.

Fig. 1. Correlations between the electrocardiographic voltages and left ventricular mass index (LVMI). Sokolow-Lyon voltage (panel a, r = 0.34, p < 0.01), Cornell voltage (panel b, r = 0.36, p < 0.01), and 12-lead sum (panel c, r = 0.27, p < 0.01) correlated positively with LVMI. In contrast, RV6/V5 did not correlate with LVMI (panel d, r = −0.18).

Association between Echocardiographic Variables and ECG Voltage

In the study group as a whole, IVSd and PWd positively correlated with R-wave voltage in leads I, aV1, V4, V5, and V6, and with Sokolow-Lyon voltage. Cornell voltage, and 12-lead sum. IVSd negatively inversely correlated with R-wave voltage in leads III, aVf, and RV6/V5, but PWd did not
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Table 2. Correlation Coefficients of the Relation between Echocardiographic Variables and Electrocardiographic Variables in the Study Group as a Whole

<table>
<thead>
<tr>
<th></th>
<th>IVSd</th>
<th>PWd</th>
<th>LVDD</th>
<th>LVEDV</th>
<th>LVMRI</th>
<th>RWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI</td>
<td>0.45*</td>
<td>0.39*</td>
<td>0.23*</td>
<td>0.24*</td>
<td>0.44*</td>
<td>0.30*</td>
</tr>
<tr>
<td>RII</td>
<td>-0.08</td>
<td>-0.05</td>
<td>0.05</td>
<td>0.04</td>
<td>-0.05</td>
<td>-0.08</td>
</tr>
<tr>
<td>RIII</td>
<td>-0.21*</td>
<td>-0.13</td>
<td>-0.06</td>
<td>-0.07</td>
<td>-0.21*</td>
<td>-0.13</td>
</tr>
<tr>
<td>RaVL1</td>
<td>0.01</td>
<td>0.06</td>
<td>-0.03</td>
<td>-0.03</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>RaVL2</td>
<td>0.47*</td>
<td>0.04*</td>
<td>0.20*</td>
<td>0.21*</td>
<td>0.45*</td>
<td>0.33*</td>
</tr>
<tr>
<td>RaVL4</td>
<td>-0.21*</td>
<td>-0.14</td>
<td>-0.09</td>
<td>-0.10</td>
<td>-0.21*</td>
<td>-0.12</td>
</tr>
<tr>
<td>RV1</td>
<td>0.01</td>
<td>0.04</td>
<td>0.14</td>
<td>0.13</td>
<td>0.10</td>
<td>-0.05</td>
</tr>
<tr>
<td>RV2</td>
<td>0.12</td>
<td>0.12</td>
<td>0.18</td>
<td>0.18</td>
<td>0.19</td>
<td>0.04</td>
</tr>
<tr>
<td>RV3</td>
<td>0.16</td>
<td>0.12</td>
<td>0.23*</td>
<td>0.23*</td>
<td>0.24*</td>
<td>0.04</td>
</tr>
<tr>
<td>RV4</td>
<td>0.25*</td>
<td>0.25*</td>
<td>0.18</td>
<td>0.19</td>
<td>0.25*</td>
<td>0.17</td>
</tr>
<tr>
<td>RV5</td>
<td>0.32*</td>
<td>0.35*</td>
<td>0.10</td>
<td>0.10</td>
<td>0.27*</td>
<td>0.28*</td>
</tr>
<tr>
<td>RV6</td>
<td>0.25*</td>
<td>0.28*</td>
<td>0.06</td>
<td>0.06</td>
<td>0.22*</td>
<td>0.23*</td>
</tr>
<tr>
<td>RaVL1+SV3</td>
<td>0.43*</td>
<td>0.40*</td>
<td>0.11</td>
<td>0.13</td>
<td>0.36*</td>
<td>0.36*</td>
</tr>
<tr>
<td>SV1+RV5</td>
<td>0.35*</td>
<td>0.39*</td>
<td>0.13</td>
<td>0.13</td>
<td>0.34*</td>
<td>0.30*</td>
</tr>
<tr>
<td>12-lead sum</td>
<td>0.45*</td>
<td>0.46*</td>
<td>0.16</td>
<td>0.16</td>
<td>0.41*</td>
<td>0.38*</td>
</tr>
<tr>
<td>RV6/V5</td>
<td>-0.19*</td>
<td>-0.18</td>
<td>-0.13</td>
<td>-0.13</td>
<td>-0.18</td>
<td>-0.13</td>
</tr>
</tbody>
</table>

Abbreviations for echocardiographic variables are as in Table 1. *p<0.05, *p<0.01.

Consequently, LVMRI positively correlated with R-wave voltage in leads I, aVL, V3, V4, V5, and V6 as well as with Sokolow-Lyon voltage, Cornell voltage, and 12-lead sum (Table 2). LVMI negatively correlated with R-wave voltage in leads III and aVF, but not with RV6/V5 (Table 2, Fig. 1).

**Geometric Patterns and ECG Characteristics**

Electrocardiographic voltages of selected leads in the four study groups are summarized in Fig. 2. Apparent ST-T changes were observed only in five patents.

In Fig. 3, four ECG voltage criteria (Sokolow-Lyon voltage, Cornell voltage, 12-lead sum, and RV6/V5) are compared among the four groups with different geometry. Sokolow-Lyon voltage was higher in the concentric remodeling and concentric hypertrophy groups than in the normal group. Cornell voltage was significantly higher in the concentric hypertrophy group than in the normal group and the eccentric hypertrophy group. The voltage of the 12-lead sum was significantly higher in the three groups with abnormal geometry than in the normal group. However, RV6/V5 showed a different trend and was smaller in the concentric remodeling group than in the normal geometry and concentric hypertrophy groups.

When the Sokolow-Lyon voltage (SV1 + RV5 ≥ 3.5 mV) was considered a positive result, a sensitivity of 68%, a specificity of 66%, and an accuracy of 67% were found (Table 3). The sensitivity was lower for the Cornell voltage (men, >2.8 mV; women, >2.2 mV) (21), 12-lead sum (>17.5 mV) (22), and RV6/V5 ratio (>0.7) (23) than for the Sokolow-Lyon voltage.

Figure 4 shows a simplified flow chart showing how to differentiate individual geometry on the basis of three voltage criteria, i.e., Sokolow-Lyon voltage, Cornell voltage, and RV6/V5 ratio. Moderate sensitivity and specificity were obtained in the concentric remodeling group on the basis of a high Sokolow-Lyon voltage and low RV6/V5 ratio and in the normal geometry group on the basis of a low Sokolow-Lyon voltage. However, it was difficult to identify patients belonging to the eccentric hypertrophy group because the ECG characteristics were similar to those in the normal geometry group. In the detection of patients in the eccentric hypertrophy group, the specificity was moderate but the sensitivity was not so high when a high Sokolow-Lyon voltage and a low Cornell voltage were used.
Table 3. Sensitivity and Specificity of Conventional Voltage Criteria for the Detection of Abnormal Geometry

<table>
<thead>
<tr>
<th>Voltage criterion</th>
<th>Cut-off value</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sokolow-Lyon (SV₁ + RV₅)</td>
<td>≥3.5 (mV)</td>
<td>68</td>
<td>66</td>
<td>67</td>
</tr>
<tr>
<td>Cornell (RaVL + SV₃)</td>
<td>men &gt;2.8 (mV)</td>
<td>37</td>
<td>91</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>women &gt;2.2 (mV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12-lead sum</td>
<td>&gt;17.5 (mV)</td>
<td>47</td>
<td>80</td>
<td>58</td>
</tr>
<tr>
<td>RV₆/V₅ ratio</td>
<td>&gt;0.7</td>
<td>59</td>
<td>30</td>
<td>58</td>
</tr>
</tbody>
</table>

Fig. 3. Differences in electrocardiographic voltages among the four groups. Sokolow-Lyon voltage (panel a) was significantly higher in the concentric remodeling group (R) and concentric hypertrophy group (C) than in the normal geometry group (N). Cornell voltage (panel b) was significantly higher in the C group than in the N group and eccentric hypertrophy group (E). Voltage of the 12-lead sum (panel c) was higher in the R, E, and C groups than in the N group. However, RV₆/V₅ (panel d) was significantly lower in the R group than in the N and C groups. Values are means±SD. *p<0.05, **p<0.01 vs. N; *p<0.05 vs. R, p<0.05 vs. E.

Fig. 4. Flow chart identifying the four geometric patterns. Sensitivity, specificity, and accuracy are summarized.
Discussion

Major Findings of the Present Study

The major findings of the present study were as follows. First, in the study group as a whole, LVM correlated positively with Sokolow-Lyon voltage, Cornell voltage, and 12-lead sum, but not with RV$_6$/V$_5$. Second, an abnormal geometry pattern of the LV had a characteristic voltage pattern as compared with a normal geometry pattern. The concentric hypertrophy group had increased Sokolow-Lyon voltage, Cornell voltage, and 12-lead sum. The eccentric hypertrophy group only showed increased voltage for the 12-lead sum criterion. In contrast, the concentric remodeling group had increased Sokolow-Lyon voltage and 12-lead sum, but a decreased RV$_6$/V$_5$ ratio. To our knowledge, this is the first report describing ECG characteristics of the four LV geometric patterns in patients with essential hypertension.

Factors Affecting ECG Voltage

ECG voltage can be affected by several factors. A change in the number (24) or size of cardiac fibers (25) in the hypertrophied ventricle is an important factor. An increase in ECG voltage is also related to the ventricular surface area, the intracavitary blood volume, and the distance from the ventricular surface to the chest wall (26-28). For instance, precordial R-wave amplitudes increase after left mastectomy (27). ECG voltage has been found to be significantly correlated with LVM as estimated by angiography (29, 30) and echocardiography (31, 32). Although previous studies have suggested that ECG voltage is only weakly correlated with LVM as determined by echocardiography (33, 34), the present study showed that LVM was also associated with the Sokolow-Lyon voltage, the Cornell voltage, and the 12-lead sum, confirming that LVM is an important determinant of ECG voltage. R-wave voltage is also influenced by LVEDV, that is, intracavitary blood volume (29, 30).

Feldman et al. (35) found that the R-wave amplitude increased as the LV lateral wall moved closer to the V$_5$ and V$_6$ electrodes and concluded that the proximity of the LV to the anterior chest wall is a major determinant of the R-wave amplitude in these precordial leads. However, our results did not clarify whether the ECG voltage was directly affected by the intracavitary blood volume itself or was influenced by the distance between the LV and the chest wall.

ECG Characteristics and LV Geometry

Sokolow-Lyon voltage (17), Cornell voltage (18), and 12-lead sum (19) are widely used criteria for LVH. The accuracy of Sokolow-Lyon voltage, Cornell voltage, and RV$_6$/V$_5$ ratio in the present study was similar to that in previous reports (23, 36). The sensitivity and specificity of the 12-lead sum in the present study were similar to those in previous reports (21, 22).

An RV$_6$/V$_5$ >1.0 was used as a diagnostic marker of LVH and was found to be correlated with LVMI as determined by echocardiography in patients with heart disease (20). However, Reichek and Devereux (36) concluded that the RV$_6$/V$_5$ ratio is not useful for evaluating LVH. When the cut-off value was set at >1.0 for RV$_6$/V$_5$, the sensitivity was quite low (2%) with a high specificity (98%) in the present study. However, RV$_6$/V$_5$ >0.70 was used as the cut-off value and yielded a sensitivity of 59%. This cut-off value was reported to yield the highest diagnostic accuracy for diagnosis of LVH in systemic hypertension (23).

In the present study, ECG voltage characteristics differed among the subgroups of LV geometry. The 12-lead sum might reflect LVM, wall thickness, or both, and increased in the three groups with abnormal LV geometric patterns. In contrast, Sokolow-Lyon voltage and Cornell voltage reflect the magnitude of the leftward electrical vector, and consequently showed similar results (Figs. 2 and 3). In the eccentric hypertrophy group, LVM and LV dimension were higher than in the normal group, and PRA tended to be lower than in the other groups. These results suggest that blood volume was increased in this group and that interstitial fluid volume was possibly increased, although patients with definite peripheral edema were excluded from the study. This could possibly reduce RV$_5$ and RV$_6$ voltages leading to reduced Sokolow-Lyon and Cornell voltages. The concentric remodeling group showed highest R-wave voltage in V$_2$-6 among the four groups, although this group showed lower values for wall thickness, LVM, and LV dimension than in the concentric hypertrophy group. The highest RV$_5$ voltage seen in this group yielded a lower RV$_6$/V$_5$ ratio than in the other three groups. We have no plausible explanation for the high RV$_5$ voltage and low RV$_6$/V$_5$ ratio in the concentric remodeling group.

Among the four voltage criteria, the Sokolow-Lyon voltage criterion was relatively sensitive in the detection of abnormal LV geometry. An accuracy of 67% is similar to that reported previously (37). The present study supports the use of a combination of various ECG voltage criteria to detect individual LV geometric patterns in patients with hypertension. The combination of a high Sokolow-Lyon voltage with a low RV$_6$/V$_5$ ratio for the concentric remodeling group and a low Sokolow-Lyon voltage for the normal geometry group yielded modest sensitivity and specificity. The combination of a high Sokolow-Lyon voltage with a low Cornell voltage was moderately specific but not highly sensitive for the identification eccentric hypertrophy.

Methodological Considerations

There is a correlation between LVM as determined by echocardiography and that determined at autopsy (38). We therefore echocardiographically determined LVM in the present study. However, LVM as determined by echocardiography does not correlate with LVM as determined by magnetic resonance imaging in hypertensive patients, especially those with severe LVH (39). LVM might be overesti-
mated by echocardiography, although patients with severe hypertrophy were not included in the present study. LVMI >125 g/m² has been accepted as a cut-off value for the diagnosis of LVH (40). In the present study, we employed our own criteria for LVH in Japanese patients (111 g/m² for men and 106 g/m² for women) (14). The sensitivity of the voltage criteria would decrease slightly, if the conventional cut-off value of LVMI >125 g/m² would have been used in the present study.

The study population differed among the four groups in the present study as well as in previous studies by other investigators (14). There were fewer patients in the concentric remodeling group than in the other groups. This uneven distribution of LV geometric patterns may have affected the results of the present study.

Extracardiac factors may influence QRS voltage recorded from the body surface. Such factors include body build, lung effect, tissue edema, and the distance between the heart and chest wall (41). In the present study, patients with apparent peripheral edema were not included, and the distance between the heart and chest wall was not determined.

Repolarization abnormalities including ST depression, T-wave inversion, or both, appear in association with the progression of LVH (41, 42). A combination of repolarization abnormalities, i.e., ST-T changes, with voltage criteria would improve the ability to accurately diagnose LVH. The present study, however, employed diagnostic criteria based on only QRS voltages to maintain a simple study design and because of the small number of patients with apparent ST-T changes. The voltage criteria used in our study were all developed to diagnose LVH in the United States, and were not designed for Japanese people. Although several modifications of voltage criteria have been proposed in Japan, we used conventional voltage criteria for LVH in the present study.

Conclusions

Although this study had several limitations, we showed that ECG voltage characteristics differ according to the geometric pattern of LVH in patients with essential hypertension. A combination of Sokolow-Lyon voltage, Cornell voltage, and RV₆/V₅ in 12-lead ECG was concluded to be useful for identification of four different LV geometric patterns in essential hypertension.

Acknowledgements

The authors are grateful for the expert technical assistance of Ms. Yoshiko Obata.

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