Performance of Classic Electrocardiographic Criteria for Left Ventricular Hypertrophy in an African Population

Christian Jaggy, François Perret, Pascal Bovet, Guy van Melle, Nic Zerkiebel, George Madeleine, Lukas Kappenberger, Fred Paccaud

Abstract—ECG criteria for left ventricular hypertrophy (LVH) have been almost exclusively elaborated and calibrated in white populations. Because several interethnic differences in ECG characteristics have been found, the applicability of these criteria to African individuals remains to be demonstrated. We therefore investigated the performance of classic ECG criteria for LVH detection in an African population. Digitized 12-lead ECG tracings were obtained from 334 African individuals randomly selected from the general population of the Republic of Seychelles (Indian Ocean). Left ventricular mass was calculated with M-mode echocardiography and indexed to body height. LVH was defined by taking the 95th percentile of body height–indexed LVM values in a reference subgroup. In the entire study sample, 16 men and 15 women (prevalence 9.3%) were finally declared to have LVH, of whom 9 were of the reference subgroup. Sensitivity, specificity, accuracy, and positive and negative predictive values for LVH were calculated for 9 classic ECG criteria, and receiver operating characteristic curves were computed. We also generated a new composite time-voltage criterion with stepwise multiple linear regression: weighted time-voltage criterion $= (0.2366R_{aVL} + 0.0551R_{V5} + 0.0785S_{V3} + 0.2993T_{V1}) \times QRS$ duration. The Sokolow-Lyon criterion reached the highest sensitivity (61%) and the $R_{aVL}$ voltage criterion reached the highest specificity (97%) when evaluated at their traditional partition value. However, at a fixed specificity of 95%, the sensitivity of these 10 criteria ranged from 16% to 32%. Best accuracy was obtained with the $R_{aVL}$ voltage criterion and the new composite time-voltage criterion (89% for both). Positive and negative predictive values varied considerably depending on the concomitant presence of 3 clinical risk factors for LVH (hypertension, age $\geq 50$ years, overweight). Median positive and negative predictive values of the 10 ECG criteria were 15% and 95%, respectively, for subjects with none or 1 of these risk factors compared with 63% and 76% for subjects with all of them. In conclusion, the performance of classic ECG criteria for LVH detection was largely disparate and appeared to be lower in this population of East African origin than in white subjects. A newly generated composite time-voltage criterion might provide improved performance. The predictive value of ECG criteria for LVH was considerably enhanced with the integration of information on concomitant clinical risk factors for LVH. (Hypertension. 2000;36:54-61.)

Key Words: left ventricle $\bullet$ hypertrophy $\bullet$ ethnic groups $\bullet$ electrocardiography $\bullet$ echocardiography

Left ventricular hypertrophy (LVH) is associated with a substantially increased risk of cardiac morbidity and mortality,$^{1-4}$ so its detection is of major importance, especially for individuals with hypertension or other cardiovascular risk factors. Although echocardiography has become the gold standard for LVH detection in clinical practice, ECG remains widely used due to its simplicity and accessibility. Caution should nevertheless be taken when using ECG criteria for LVH detection because they exhibit only limited accuracy (generally due to poor sensitivity).$^{5-8}$ Furthermore, their unrestricted applicability to nonwhite individuals remains to be demonstrated; historically, these criteria have been almost exclusively elaborated on and calibrated in white (or mixed) populations, and several interethnic differences in ECG characteristics have been demonstrated, especially in African individuals.$^{9-12}$

In the present study, we examined the performance of 9 classic ECG criteria for LVH prediction in a random sample of the African population of the Seychelles, with the use of echocardiography as the gold standard.

Methods

Study Population

The present study was conducted in the Republic of Seychelles, which consists of 115 islets in the Indian Ocean, located 1800 km east of Kenya. The first inhabitants settled in Seychelles in the 1770s and were of French and African origin (from Madagascar and East Africa); they were later joined by small numbers of Chinese and...
Indian immigrants. The population has grown to 74,331 persons in 1994, and the ethnic distribution of the population is now considered to be predominantly of African descent in 65%, white in 10%, Indian or Chinese in 5%, and evidently mixed in 20%. The Seychelles has experienced rapid socioeconomic development (gross domestic product per capita increased from US $600 to $6000 from 1976 to 1994), followed by fast epidemiological transition with increasing rates of cardiovascular diseases. A joint program by the local Ministry of Health and the University of Lausanne (Switzerland) was initiated in 1989 in the Seychelles to assess and monitor the cardiovascular situation and to launch a prevention and control program.

**Study Design**

A cardiovascular health survey was conducted in the Seychelles in 1994. The study protocol was approved by the review committee of the Ministry of Health. Methods and basic findings have been previously published. An age- and gender-stratified random sample of 1280 subjects was drawn from the residents of the Seychelles aged 25 to 64 years, with data from a census in 1987. Fifty-four subjects of 1280 subjects was drawn from the residents of the Seychelles aged 25 to 64 years, with data from a census in 1987. Fifty-four subjects were dead or abroad at the time of the survey and were subsequently excluded. Of the remaining 1226 eligible participants, 1067 attended the survey (504 men and 563 women), with a resultant participation rate of 87%. A randomly selected subgroup of 572 individuals underwent M-mode echocardiography. These individuals were selected by matching each participant’s rank of arrival at the study center with a list of 7 numbers (between 1 and 14) that were randomly generated each day. The group consisted of 378 African persons, as defined from phenotypic appearance assessed by a single independent examiner. Forty-four of these individuals (12%) were subsequently excluded from the analysis due to poor-quality ECG tracings (n=3) or left ventricular M-mode echographic tracings (n=14), the presence of bundle-branch block (BBB, n=10), QRS duration of >130 ms (without specific criteria for BBB), or ECG signs of old myocardial infarction (n=17). Thus, the present report is based on a sample of 334 individuals (158 men and 176 women).

**Basic Measurements**

Blood pressure, weight, body height, body surface area (BSA), and body mass index were assessed according to common standards. Subjects with systolic blood pressure of ≥160 mm Hg, diastolic blood pressure of ≥95 mm Hg, or both were considered to be hypertensive. Overweight was defined as a body mass index of ≥27.8 kg/m² in men and ≥27.3 kg/m² in women. Although body mass index is a specific measure for neither fat content nor fat distribution, these cutoff values have been strongly associated with morbidity and mortality rates in several populations.

**ECG Measurement**

A 12-lead resting ECG was recorded for each participant with a Food and Drug Administration–approved device with frequency response characteristics that meet the recommendations of the American Heart Association (Schiller AT-6C system; Schiller Ltd.). The device is equipped with ECG analysis software that automatically measures amplitudes (to the nearest 5 μV) and the duration of ECG waves (P, Q, R, S, R’, QRS, T, U) in each of the 12 leads. Standard intervals (RR, PQ, QT) are also automatically computed. All tracings and measurements were exported and stored on a computer with the use of dedicated software (Sema Version 4.0; Schiller Ltd). For the present analysis, 9 ECG criteria for LVH were chosen by the authors in consideration of both their general acceptance and recognized performance. The criteria are listed in Table 1 and consist of 6 “pure voltage” criteria (ie, based only on wave amplitude measurements), including the Sokolow-Lyon, Cornell, Gubner-Ungerleider, R-Voltage, Lewis, Cornell product, mV×ms, Sokolow-Lyon voltage×QRS duration, Cornell product, mV×ms, Gubner-Ungerleider product, mV×ms, Cornell voltage×QRS duration, and Gubner-Ungerleider voltage×QRS duration. For each of these criteria, 5 different cutoff (or partition) values (PVs) for LVH were investigated: the PV traditionally used in clinical practice (traditional PV (TPV)) and the cutoff values that return a specificity of 95% (Sp95 PV), 90% (Sp90 PV), 85% (Sp85 PV), and 80% (Sp80 PV) in our sample.

**Echocardiography Measurement**

The 334 selected individuals underwent a complete echocardiographic investigation performed by 1 trained cardiologist (F. Perret) with a high-minded CPM 800C echographic system (Horton) equipped with a mechanical 3.25-MHz annular phased-array probe. Three successive 2-dimensionally guided M-mode tracings (5 in the case of atrial fibrillation) were recorded according to the recommendations of the American Society of Echocardiography. The averaged measurements of end-diastolic septal thickness, posterior wall thickness, and internal diameter were used to calculate left ventricular mass (LVM) according to Devereux’s anatomically validated formula:

\[
LVM = 0.8 \times 1.04 \times \left( \frac{LVID + VST + PWT}{3} \right)^3 - 0.6
\]

where LVID is left ventricular internal diameter, VST is ventricular septal thickness, and PWT is posterior wall thickness. As recently recommended, LVM values were indexed to body height rather than to BSA. This choice was further supported by the lack of residual correlation we found between body height–indexed LVM and body height itself (men \(r = -0.08, P = 0.34\); women \(r = -0.01, P = 0.87\)), whereas BSA-indexed LVM remained correlated to BSA in women (men \(r = -0.10, P = 0.2\); women \(r = 0.20, P = 0.01\)). Inter-session reproducibility of LVM measurements was tested in 10 randomly selected individuals, who were reexamined in a blinded fashion 2 to 6 weeks after the first session. The correlation coefficient between the 2 sets of values attained a value of 0.95, and the mean absolute difference between paired measurements was 10.6 ± 8.6 g (ie, 8.0% of the initial mean value).

**TABLE 1. Definition and Partition Values for Investigated ECG Criteria for LVH Detection**

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Definition</th>
<th>TPV</th>
<th>Sp95 PV</th>
<th>Sp90 PV</th>
<th>Sp85 PV</th>
<th>Sp80 PV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sokolow-Lyon voltage, mV</td>
<td>(S_1^3 + R_9^3, \text{ for men and women})</td>
<td>3.50</td>
<td>5.07</td>
<td>4.48</td>
<td>4.21</td>
<td>3.92</td>
</tr>
<tr>
<td>Cornell voltage, mV</td>
<td>(R_{49}^3 + S_2^3, (+0.8 \text{ mV for women}))</td>
<td>2.80</td>
<td>3.16</td>
<td>2.79</td>
<td>2.52</td>
<td>2.39</td>
</tr>
<tr>
<td>Gubner-Ungerleider voltage, mV</td>
<td>(R_1^3 + S_4)</td>
<td>2.50</td>
<td>2.48</td>
<td>2.01</td>
<td>1.81</td>
<td>1.67</td>
</tr>
<tr>
<td>RaVL voltage, mV</td>
<td>(R_{ax})</td>
<td>1.30</td>
<td>1.15</td>
<td>0.96</td>
<td>0.87</td>
<td>0.79</td>
</tr>
<tr>
<td>Lewis voltage, mV</td>
<td>((R_1^3 + S_3) - (R_9^3 + S))</td>
<td>1.70</td>
<td>2.14</td>
<td>1.86</td>
<td>1.63</td>
<td>1.45</td>
</tr>
<tr>
<td>12-Lead QRS sum, mV</td>
<td>(\text{QRS} + \text{QRS} + \text{QRS} + \text{QRS} + \text{QRS} + \text{QRS})</td>
<td>50.0</td>
<td>45.0</td>
<td>40.0</td>
<td>35.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Sokolow-Lyon product, mV×ms</td>
<td>Sokolow-Lyon voltage×QRS duration</td>
<td>371.0</td>
<td>354.0</td>
<td>347.0</td>
<td>339.0</td>
<td>306.0</td>
</tr>
<tr>
<td>Cornell product, mV×ms</td>
<td>Cornell voltage×QRS duration</td>
<td>286.0</td>
<td>278.0</td>
<td>270.0</td>
<td>262.0</td>
<td>234.0</td>
</tr>
<tr>
<td>Gubner-Ungerleider product, mV×ms</td>
<td>Gubner-Ungerleider voltage×QRS duration</td>
<td>207.0</td>
<td>239.0</td>
<td>202.0</td>
<td>180.0</td>
<td>163.0</td>
</tr>
<tr>
<td>WTV criterion, mV×ms</td>
<td>See text</td>
<td>58.0†</td>
<td>58.0</td>
<td>53.6</td>
<td>46.9</td>
<td>44.0</td>
</tr>
</tbody>
</table>

*Partition values taken from Okin et al.\(^7\)†Sp95 PV taken as TPV.
LVH Definition
As in previous population studies,28,35,41,42 the cutoff points were determined through selection of the 95th percentile of body height-indexed LVM values in a reference subgroup composed of participants with normal blood pressure (<140/90 mm Hg), no history of hypertension, no medication for hypertension, and no significant left-sided valvular disease (65 men and 99 women). Accordingly, LVH was defined as an indexed LVM of 122 g/m or more in men and 106 g/m or more in women, thereby identifying 9 individuals of the reference subgroup as having LVH. In the entire study sample, 16 men and 15 women (prevalence 9.3%) were finally declared to have LVH on the basis of echocardiographic results.

Elaboration of a New ECG Criterion
We used our set of ECG tracings to elaborate a new ECG time-voltage criterion for LVH that would presumably better predict LVH in this sample. Thirty-six basic time-voltage products (R, S, or T voltage in any of the 12 standard leads multiplied by the QRS duration) were first tested for the strength of their univariate correlation with indexed LVM, and only the 16 products (The Cornfield rule requires us to limit the number of independent variables introduced in a multiple regression model to 1/20 of the sample size [here 16 variables], yielding the highest correlation coefficients were introduced in a backward stepwise multiple linear regression analysis with indexed LVM.28) The final model included 4 parameters that had an independent association with indexed LVM at P<0.01. The new criterion was subsequently designed with the regression coefficients of the final model as follows:

\[
\text{WTV criterion} = (0.2366R_{aVL} + 0.0551R_{v5} + 0.0785S_{v3} + 0.2993T_{v1}) \times \text{QRS duration}
\]

The median value for this new criterion was 32.7 mV×ms in our sample (range 1.3 to 81.6 mV×ms). The value that yielded 95% specificity for LVH detection was 58 mV×ms, and this value was chosen as the cutoff for the weighted time-voltage (WTV) criterion.

Data Analysis and Statistical Methods
Statistical analyses were performed with the Intercooled Stata for Windows version 5.0 software package (Stata Corporation). Differences were assessed with the 2-tailed Student’s t test for continuous variables and the 2-tailed Fisher’s exact test for proportions. A P value of ≤0.05 was chosen to indicate statistical significance. Using echocardiographic measurements as reference standard, we calculated sensitivity, specificity, PVs for a given specificity, accuracy (the proportion of correct results whether positive or negative), positive predictive value (PPV), and negative predictive value (NPV) for each tested criterion. Finally, we examined receiver operating characteristic (ROC) curves,24 which show in a graph format sensitivity versus 1−specificity as the cutoff is varied, and we calculated the area under the curve (AUC) (a model with no predictive power would result in a 45° line and have area 0.5; a perfect model has area 1). These curves were obtained with univariate logistic regression models that included LVH or normal indexed LVM as outcomes and each ECG criterion as an independent variable.

Results
Subjects and Prevalence of LVH
The main characteristics of the subjects are presented in Table 2. Compared with women, men had significantly higher body height, BSA, systolic blood pressure, diastolic blood pressure, LVM, and indexed LVM but significantly lower body mass index and heart rate. The prevalence of LVH determined by echocardiography was 9.3% in the entire study sample and was similar among men and women (10.1% versus 8.5%, NS, ratio 1.2). However, LVH prevalence rates were significantly higher in hypertensives (15.1% versus 6.6% in normotensives, P=0.02, ratio 2.3), in subjects aged ≥50 (14.3% versus 7.0% in those aged <50, P=0.04, ratio 2.0), and in overweight individuals (16.2% versus 6.1% in those with normal weight, P=0.01, ratio 2.7). Hypertension, age ≥50 years, and overweight are referred to as “risk factors for LVH.”

PVs of the ECG Criteria to Predict LVH at Given Specificity
Table 1 shows the different PVs for test positivity that returned a specificity of 95% (Sp95 PV), 90% (Sp90 PV), 85% (Sp85 PV), and 80% (Sp80 PV). The table also shows TPV. In our sample, the TPV was smaller than the Sp80 PV for the Sokolow-Lyon voltage, the Sokolow-Lyon product, and the 12-lead QRS sum criterion. The TPV of the Lewis voltage and the Cornell product criterion lay between the Sp85 and Sp90 PV, and for the remaining criteria, the TPV was higher than the Sp90 PV.

ECG Identification of LVH
Table 3 displays in detail the performance of each tested ECG criterion for LVH. The different indexes include sensitivity, specificity, and accuracy at TPVs7-45; sensitivity at several fixed levels of specificity (95%, 90%, 85%, and 80%); correlation coefficient with indexed LVM; and area under the ROC curve. At TPV, the sensitivity of the 10 tested criteria ranged from 10% to 61%, their specificity ranged from 68% to 97%, and their accuracy ranged from 67% to 89%. The highest sensitivity was reached with the Sokolow-Lyon voltage criterion, the highest specificity was reached with the R_{aVL} voltage criterion, and the best accuracy was reached with both the R_{aVL} voltage criterion and the WTV criterion. At a fixed specificity of 95%, sensitivity ranged from 16% to 32%, with the WTV criterion reaching the highest value and the R_{aVL} voltage criterion reaching the lowest value. As expected,
higher levels of sensitivity were observed at lower levels of specificity: up to 45% at 90% specificity (WTV criterion) and 68% at 80% specificity (Gubner-Ungerleider product criterion). Correlation coefficients with indexed LVM ranged between 0.28 (Cornell voltage criterion) and 0.67 (WTV criterion).

Table 4 displays the PPVs obtained for each investigated ECG criterion across categories of concomitant risk factors for LVH. Considerable variation in PPV (0% to 100%) was observed depending on the selected ECG criterion and on the group considered. Despite the relatively high specificity of these criteria, PPV was low (ranging from 16% to 40%) when computed in the entire study sample and even lower (ranging from 5% to 31%) in the subgroup with none or only 1 of the aforementioned clinical risk factors. Conversely, PPV was higher (ranging from 40% to 100%) in the subgroup of individuals presenting with all 3 clinical risk factors for LVH. In all of the considered subgroups, the WTV criterion reached the highest PPV among the set of ECG criteria.

A similar analysis was performed for NPVs and is displayed in Table 5. NPV ranged from 91% to 94% when it was computed for the entire study sample, from 94% to 97% in the subgroup with none or only 1 risk factor, and from 69% to 82% in the subgroup with all 3 risk factors.

The Figure displays the ROC curves obtained for all tested LVH criteria as well as the actual location of the corresponding TPV and the AUC. Sokolow-Lyon voltage, Sokolow-Lyon product, and the 12-lead QRS sum criteria showed poor performance in the entire range of the ROC curve and obtained an AUC of 0.70, whereas most other criteria yielded an AUC of close to 0.80. The steepest initial increase of sensitivity was observed for the WTV criterion so that it

### Table 3. Performance of ECG Criteria for LVH

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Sensitivity at TPV</th>
<th>Specificity at TPV</th>
<th>Accuracy at TPV</th>
<th>Sensitivity at Indicated Specificity 95%</th>
<th>Sensitivity at Indicated Specificity 90%</th>
<th>Sensitivity at Indicated Specificity 85%</th>
<th>Sensitivity at Indicated Specificity 80%</th>
<th>Correlation Coefficient</th>
<th>AUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sokolow-Lyon voltage, mV</td>
<td>61</td>
<td>68</td>
<td>67</td>
<td>16</td>
<td>23</td>
<td>23</td>
<td>32</td>
<td>0.41</td>
<td>0.63</td>
</tr>
<tr>
<td>Cornell voltage, mV</td>
<td>23</td>
<td>90</td>
<td>84</td>
<td>19</td>
<td>23</td>
<td>42</td>
<td>48</td>
<td>0.28</td>
<td>0.70</td>
</tr>
<tr>
<td>Gubner-Ungerleider voltage, mV</td>
<td>19</td>
<td>95</td>
<td>88</td>
<td>19</td>
<td>35</td>
<td>48</td>
<td>58</td>
<td>0.42</td>
<td>0.79</td>
</tr>
<tr>
<td>RaVL voltage, mV</td>
<td>10</td>
<td>97</td>
<td>89</td>
<td>16</td>
<td>35</td>
<td>42</td>
<td>58</td>
<td>0.41</td>
<td>0.79</td>
</tr>
<tr>
<td>Lewis voltage, mV</td>
<td>39</td>
<td>87</td>
<td>83</td>
<td>23</td>
<td>32</td>
<td>45</td>
<td>58</td>
<td>0.39</td>
<td>0.79</td>
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<tr>
<td>12-Lead QRS sum, mV</td>
<td>42</td>
<td>78</td>
<td>74</td>
<td>19</td>
<td>32</td>
<td>39</td>
<td>42</td>
<td>0.45</td>
<td>0.65</td>
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<tr>
<td>Sokolow-Lyon product, mV×ms</td>
<td>58</td>
<td>73</td>
<td>72</td>
<td>19</td>
<td>26</td>
<td>35</td>
<td>45</td>
<td>0.45</td>
<td>0.66</td>
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<tr>
<td>Cornell product, mV×ms</td>
<td>32</td>
<td>89</td>
<td>84</td>
<td>26</td>
<td>32</td>
<td>42</td>
<td>52</td>
<td>0.36</td>
<td>0.75</td>
</tr>
<tr>
<td>Gubner-Ungerleider product, mV×ms</td>
<td>39</td>
<td>91</td>
<td>86</td>
<td>19</td>
<td>42</td>
<td>65</td>
<td>68</td>
<td>0.47</td>
<td>0.81</td>
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<tr>
<td>WTV criterion, mV×ms</td>
<td>32</td>
<td>95</td>
<td>89</td>
<td>32</td>
<td>45</td>
<td>55</td>
<td>61</td>
<td>0.67</td>
<td>0.79</td>
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<tr>
<td>Mean value</td>
<td>35</td>
<td>86</td>
<td>82</td>
<td>21</td>
<td>33</td>
<td>44</td>
<td>52</td>
<td>0.43</td>
<td>0.74</td>
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<tr>
<td>Median value</td>
<td>35</td>
<td>90</td>
<td>84</td>
<td>19</td>
<td>32</td>
<td>42</td>
<td>55</td>
<td>0.42</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Correlation coefficient with indexed LVM.

### Table 4. Positive Predictive Values for ECG Criteria for the Identification of LVH Across Categories of Concomitant Risk Factors

<table>
<thead>
<tr>
<th>Criterion*</th>
<th>All (n=334)</th>
<th>Men (n=158)</th>
<th>Women (n=176)</th>
<th>Hypertension (n=106)</th>
<th>Age≥50 y (n=105)</th>
<th>Overweight (n=105)</th>
<th>0 or 1 (n=245)</th>
<th>2 (n=68)</th>
<th>3 (n=21)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>P</td>
<td>H</td>
<td>P</td>
<td>H</td>
<td>P</td>
<td>H</td>
<td>P</td>
<td>H</td>
<td>P</td>
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<tr>
<td>Sokolow-Lyon voltage, mV</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>21</td>
<td>27</td>
<td>30</td>
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<td>Cornell voltage, mV</td>
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<td>23</td>
<td>32</td>
<td>31</td>
<td>35</td>
<td>5</td>
<td>18</td>
<td>67</td>
</tr>
<tr>
<td>Gubner-Ungerleider voltage, mV</td>
<td>30</td>
<td>27</td>
<td>33</td>
<td>36</td>
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<td>RaVL, mV</td>
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<td>25</td>
<td>25</td>
<td>20</td>
<td>33</td>
<td>33</td>
<td>22</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Lewis voltage, mV</td>
<td>24</td>
<td>23</td>
<td>25</td>
<td>33</td>
<td>28</td>
<td>27</td>
<td>16</td>
<td>20</td>
<td>50</td>
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<tr>
<td>12-Lead QRS sum, mV</td>
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<td>14</td>
<td>22</td>
<td>23</td>
<td>32</td>
<td>25</td>
<td>11</td>
<td>29</td>
<td>40</td>
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<tr>
<td>Sokolow-Lyon product, mV×ms</td>
<td>18</td>
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<td>23</td>
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<td>29</td>
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<td>12</td>
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<tr>
<td>Gubner-Ungerleider product, mV×ms</td>
<td>30</td>
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<td>31</td>
<td>41</td>
<td>29</td>
<td>30</td>
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<td>WTV criterion, mV×ms</td>
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<td>35</td>
<td>18</td>
<td>22</td>
<td>65</td>
</tr>
<tr>
<td>Median value</td>
<td>24</td>
<td>20</td>
<td>25</td>
<td>32</td>
<td>31</td>
<td>33</td>
<td>15</td>
<td>23</td>
<td>63</td>
</tr>
</tbody>
</table>

H indicates number of subjects with LVH in the corresponding category; P, prevalence of LVH in the corresponding category.

*All standard criteria are used at their traditional partition value; the WTV criterion at 58 mV×ms.
obtained the best sensitivity on the entire range of specificity between 100% and 90%.

**Discussion**

Classic ECG criteria for LVH were originally designed to reach a specificity as high as 90% to 95% at their TPV, so sufficiently high PPV would be ensured in population groups with low or moderate LVH prevalence. Based on our data in a nonselected population of African men and women, the Sokolow-Lyon voltage and the 12-lead QRS sum criteria had a very poor specificity at TPV, whereas the Gubner-Ungerleider and RaVL voltage criteria were poorly sensitive (but highly specific) at TPV. Moreover, ROC curve analysis demonstrated that most criteria performing poorly at TPV (mainly the popular Sokolow-Lyon voltage criterion and the 12-lead QRS sum criterion) would not improve significantly through recalibration of their PV (a poor sensitivity was observed on the entire range of intermediate to high specificity values). These findings strongly suggest that most classic ECG criteria taken at TPV have limited value for LVH screening in this population. However, the Gubner-Ungerleider product and the new WTV criterion demonstrated fair performance and may be useful screening tools for LVH in this population. Noticeably, previous studies in white populations resulted in opposite observations. The Sokolow-Lyon voltage and the 12-lead QRS sum criteria clearly had higher sensitivity than the Gubner-Ungerleider voltage criterion at matched specificity.

Globally, the 9 considered classic criteria appeared to have lower sensitivity in this African population than in white populations. Sensitivity indeed ranged between 16% and 26% at a fixed specificity of 95% in our study instead of the values of 20% to 50% found in white populations. The sensitivity values in our study certainly have large confidence intervals due to the relatively small study sample size. In this context, the performance of the ECG criteria might be poor just by chance. Nevertheless, because the vast majority of the considered classic criteria showed a lower sensitivity than in previous studies, the small sample size is not likely to account for the whole difference, and other reasons for the low performance must be sought.

Selection bias may account for part of this difference in that most previous studies included dichotomic study populations with normal individuals on the one hand and individuals with clearly documented LVH on the other hand (thereby yielding a bimodal distribution of LVM in the study sample). This design diminishes the probability of misclassification of subjects with or without LVH, thus artificially enhancing both sensitivity and specificity of the tests under evaluation. In the present study, this selection bias could not occur because the subjects were randomly selected from the general population, resulting in a clearly unimodal distribution of indexed LVM.

The performance of a diagnostic test may be underestimated when the reference standard is poorly reliable. This phenomenon is unlikely to have occurred in the present study because LVM measurements were collected with a high-quality echocardiographic system and performed by a cardiologist who was experienced in echocardiography. The high quality of the study data is suggested by the excellent reproducibility of the LVM measurements in the study and the strong correlation observed between indexed LVM and blood pressure values (0.44 with systolic blood pressure in this study compared, for example, with <0.30 in the Framingham Heart Study).

It might be hypothesized that the cutoff values we used for echocardiographic LVH definition in men and women were inadequate and prevented the best expression of ECG criteria. Actually, we thought it would have been erroneous to blindly apply reference values defined in whites living in industrial-
ized countries to African individuals because both genetic or environmental factors (eg, less sedentary lifestyle) could be responsible for dissimilarities. We opted for the simplest and most frequently used method to define the upper normal value for indexed LVM: the 95th percentile value in a reference population without any predisposing factor for LVH. This method implies that 5% of individuals from this reference population will have an abnormally high LVM, a proportion that appears to be reasonable in this context and would, for instance, include individuals with heavy physical training (“athletic heart”) or individuals with LVH not related to hypertension (eg, those with hypertrophic cardiomyopathy) but also some “truly normal” subjects with slightly overestimated measurements (due to the imperfect precision of the method). With this methodology, cutoff values were found to be 143 g/m for men and 102 g/m for women in the Framingham Heart Study, whereas they were slightly lower (122 g/m for men and 106 g/m for women) in our African study population.

Although we used these standard methods, lower or higher cutoff values could have lead to better performance of ECG criteria in this population. To address this issue, we repeated our sensitivity and specificity analyses using a less stringent criterion to define LVH (ie, 117 g/m for men and 97 g/m for women corresponding to the 90th percentile of indexed LVM values in the reference subgroup) and a more restrictive criterion (ie, 132 g/m for men and 111 g/m for women corresponding to the 97th percentile of indexed LVM values in the reference subgroup). With the less stringent criterion, 64 individuals were identified as having LVH, and the mean value of sensitivity and specificity at TPV of the 9 classic ECG criteria under evaluation was 32% and 87%, respectively. With the more restrictive criterion, 18 individuals were identified as having LVH, and the mean value of sensitivity and specificity at TPV of the 9 classic ECG criteria under evaluation was 39% and 84%, respectively. These average values are not significantly different from those that we originally obtained for the same 9 classic ECG criteria (36% for sensitivity and 85% for specificity; P>0.5). The observed low sensitivity of ECG criteria is therefore probably not account for by inadequate cutoff values for echocardiographic LVH.

The best explanation for the lower performance found in African individuals might be that some race-specific ECG features interfere with components of LVH criteria independent of actual LVM. Lee et al investigated the performance of 5 ECG criteria for LVH by comparing 122 African Americans with 148 whites who had a similar LVM index and LVH prevalence. The sensitivity of the ECG criteria was poor for both subgroups, but the specificity was significantly lower for the African Americans. In a similar study with 170 African American and 664 whites, Crow et al found that the correlation coefficients of 8 ECG criteria and LVM index was significantly lower for the African American individuals. In several investigations, African subjects were shown to have larger ECG amplitudes than whites, possibly as a result of higher skin conductivity. For example, Rautaharju et al
found significantly larger amplitudes in the leads $R_{V5}$, $R_{V2}$, and $S_{V1}$, as well as combined criteria (e.g., Sokolow-Lyon and Cornell voltage), when comparing African Americans with whites. In the same study, the African individuals also showed a more pronounced left-axis deviation, which is generally reflected in larger $R_{V1}$, $R$, and $S_{III}$ amplitudes. Axis deviation may also modify the performance of frontal-plane ECG criteria like the $R_{V1}$, Lewis, and Gubner-Ungerleider criteria. These findings are consistent with results in the present study. However, generalization of findings in African Americans to the present study participants should be made carefully because the former originate from West Africa and the latter originate from East Africa, and there may be large ethnic differences.

According to Bayes’ theorem, the predictive value of any diagnostic test that generates positive or negative results depends on the prevalence of the condition investigated in the tested population. In the present study, LVH prediction was strongly improved by combining ECG analysis with some elementary clinical information. For instance, the 10 criteria gathered a median PPV as low as 24% in the entire study group (thus, as much as a 76% chance for a predicted case to be a false-positive) but as high as 63% when considered for individuals >50 years old who have hypertension and are overweight (thus, only a 37% chance for a predicted case to be a false-positive). Furthermore, with all except 2 criteria (the Gubner-Ungerleider product and WTV criterion), individuals with all 3 risk factors but a negative ECG criterion were still more likely to have LVH than individuals with none or only 1 of these risk factors but a positive ECG criterion. These observations do therefore stress the need to interpret ECG criteria for LVH in view of the pretest clinical probability for this disorder.

We took advantage of the large number of data to attempt to generate a new, efficient ECG criterion (WTV criterion) in this population. This criterion uses time-voltage data (i.e., the product of voltage amplitudes and QRS duration); this procedure has repeatedly been shown to improve performance compared with criteria based on voltage amplitude alone.6,7 Our criterion finally included the 4 products that showed the strongest multivariate relationship with LVH: $R_{V3}$, $R_{V5}$, $S_{V3}$, and $T_{V3}$. Interestingly, each of these 4 waves has been separately included in previously defined criteria,28,51 but they were never combined within the same criterion or weighted according to their relationship with LVH.

In the present analysis, the WTV criterion gathered the best values of sensitivity and accuracy for the detection of LVH, the highest correlation coefficient with indexed LVM, and the sharpest increase in sensitivity at the origin of the ROC curve (which represents the portion of interest in clinical use). However, the high scores obtained with this criterion must be interpreted with caution due to methodological limitation. The new criterion should have been developed on a training set (e.g., a random half of our study sample) and then evaluated on a separate test set (e.g., the other half of our study sample). This procedure could not be applied here due to the relatively small study sample size. Therefore, the high performance of this new criterion should be validated in a new group of African individuals before it can be used in clinical practice.

In that case, the relatively complex computation of this criterion should not limit its use, because most new ECG instruments include interpretation software.

In conclusion, in the study population of East African origin, 9 widely used ECG criteria for LVH were found to have largely dissimilar sensitivity and specificity values, with most of them revealing poor sensitivity at their TPV. In particular, the sensitivity of these ECG criteria was lower in this African population than in white populations. A new criterion derived from this sample yielded encouraging results in this population and deserves further validation. Finally, the performance of ECG criteria to predict LVH was largely enhanced through integration of information on concomitant clinical risk factors for LVH.

Acknowledgments

We thank Michel Abel (Ministry of Health, Seychelles) for his technical assistance in the study; Sonotron Ltd (Switzerland); all the participants of the survey for their kind cooperation; and the government of the Seychelles for its support of cardiovascular research. Dr Perret received financial support from the Fondation Vaudoise de Cardiologie (Switzerland) and a grant from the Fondation Emma Muschamp (Lausanne, Switzerland). Dr Bovet received a grant from the Swiss National Foundation for Science (3235-038792/93).

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