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Improved Electrocardiographic Detection of Echocardiographic Left Ventricular Hypertrophy: Results of a Correlated Data Base Approach

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Objectives. **We used electrocardiographic (ECG) and echocardiographic measurements from 3,351 adults from the Framingham Heart Study to evaluate the performance of 10 ECG criteria in detecting left ventricular hypertrophy before and after adjustment for gender, age and obesity.**

Background. **Significant improvement in the sensitivity and specificity of ECG voltage-based criteria for detection of echocardiographic left ventricular hypertrophy using gender-specific criteria adjusted for age and obesity has been demonstrated.**

Methods. **Gender-specific correlation and regression analyses were used to identify the five most sensitive ECG criteria and to adjust them for age and obesity. Standard and truncated receiver operating characteristic curves were used to compare the selected criteria.**

Results. **Linear regression of left ventricular mass on ECG voltages, body mass index and age yielded considerably stronger relations for women than for men because of the greater correlation between ventricular mass and body mass index in women. Obesity and age adjustment of the five voltage criteria produced considerable improvement in their performance. The voltage sum of the R wave in lead aVL and the S wave in lead V_3, alone and in combination with QRS duration, had a sensitivity at 95% specificity of 32% and 39%, respectively, in men and 46% and 51%, respectively, in women after adjustment. Tables of critical voltages for the adjusted criteria and representative performance values are presented.**

Conclusions. **Incorporation of obesity and age in ECG algorithms consistently improves their performance in the detection of hypertrophy. The development of such criteria will enhance the utility of this inexpensive screening test. Such ECG approaches should be used in clinical trials to assess the efficacy of antihypertensive treatment to effect regression of left ventricular hypertrophy. A search for further improvements in the efficacy of ECG criteria for this purpose is warranted. Independent validation of this approach is needed.**

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In clinical practice, left ventricular hypertrophy is best detected by echocardiography because its sensitivity exceeds that of the electrocardiogram (ECG) at the usual levels of specificity (1,2). However, the greater availability, lower cost and relative simplicity of operation of the ECG continue to support its much wider use as a diagnostic instrument for this purpose. Consequently, it is still recommended and widely used in screening for left ventricular hypertrophy (3), and simple but significant improvements in its performance of this task would be desirable. A number of ECG criteria have been reported that use precordial (4–12) and limb lead (4,7,9,11,13–20) voltages. One of them, the Cornell voltage criterion (the sum of the R wave in lead aVL plus the S wave in lead V_3), was the subject of a previous report (21) showing the improvement in its utility for detecting left ventricular hypertrophy after adjustment for age and obesity.

The purpose of the present investigation was to assess and compare other ECG criteria (Table 1) for their performance in detecting left ventricular hypertrophy, using data gathered in a population-based cohort study. The results identify a subset of these criteria with superior performance, both before and after adjustment for obesity and age, on the basis of a large correlated ECG–echocardiographic data base.

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Methods

Subjects. The Framingham Heart Study comprises two populations: an original group of 5,209 men and women from Framingham, Massachusetts, recruited and first medically examined in 1948, and their offspring (and spouses of offspring), numbering 5,124, first examined in 1971. Written informed consent was obtained from all subjects. All subjects underwent M-mode echocardiographic and electrocardiographic examinations during 1979 to 1983, and these data are the basis of the results reported here. The selection criteria and study design have been described elsewhere (22,23). Echocardiograms and ECGs were available for 1,468 men and 1,883 women after exclusion of subjects with a history of myocardial infarction, bundle branch block or Wolff-Parkinson-White syndrome. Table 1 shows 10 ECG voltage criteria and the earliest citations that describe their use. Echocardiographic methods used in the present study have been described previously (24).

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Table 1. Electrocardiographic Criteria for Detection of Left Ventricular Hypertrophy

	Source	
ECG Criteria*	Ref. No.	Publication Year
1 (RaVL)	4	1949
2 (RI + SIII)	15	1943
3 (RI − RIII + SIII − SI)	13	1914
4 (RaVL + SV_3)	18	1985
5 [(RaVL + SV_3) × QRS duration]	29	1992
6 [S(V_1, V_2)]†	9	1969
7 [total 12-lead QRS voltage]	31	1989
8 [R(V_5, V_6)]	4	1949
9 [S(V_1, V_2) + R(V_5, V_6)]	9	1969
10 [SV_1 + R(V_5, V_6)]	4	1949

*The delimiting or critical values of the criteria proposed in the listed citations are not included here because there is generally a range of such values, depending on the particular study. †The notation (V_1, V_2) means that the larger voltage of the two leads, V_1 and V_2, is chosen. All voltages for S waves are taken as the absolute (positive) value. ECG = electrocardiographic; Ref = reference.

Briefly, M-mode echocardiograms were acquired in the parasternal window with the subject in the left lateral decubitus position. In >90% of studies, the M-mode echocardiogram was obtained by two-dimensionally guided imaging. The parasternal long-axis view was used to obtain M-mode recordings of the left ventricle. Measurements of end-diastolic septal and posterior wall thickness and internal diameter were obtained in accordance with the Penn (25) convention. Left ventricular mass (LVM) was calculated using the modified cubed formula:

$$LVM = 1.04[(LVID + VST + PWT)^3 - (LVID)^3] - 13.6,$$

where LVID = left ventricular diameter; VST = ventricular septal thickness; and PWT = posterior wall thickness. *Echocardiographic left ventricular hypertrophy* was defined as a height-indexed left ventricular mass that was ≥2 SD above the mean values derived from 864 apparently healthy Framingham Heart Study subjects: 143 g/m in men and 102 g/m in women (24).

Analytic methods. *Regression and correlation analysis.* Linear regressions relating left ventricular mass to ECG voltage, body mass index (a measure of obesity) and age were performed for all 10 ECG criteria investigated. Pearson correlation coefficients were obtained for the regression relating left ventricular mass to ECG voltage alone as well as to all three variables. The five best criteria were considered for additional analyses.

The adjustment of ECG voltage criteria was accomplished by fitting a multiple linear regression of height-indexed left ventricular mass (echocardiographically estimated left ventricular mass (LVM) [g] divided by height [m]) to voltage, age and body mass index (weight [kg] divided by the square of height [m]). The age and body mass index (BMI) terms were then incorporated into a formula for adjusted voltage. When the regression formula is written as

$$LVM/Height = A + B \times Volts + C \times Age + D \times BMI,$$

an equivalent formula is

$$LVM/Height = A + B \times [Volts + (C/B) \times Age + (D/B) \times BMI],$$

where A, B, C and D are parameters estimated for each ECG criterion. The term in brackets is the voltage adjusted for age and body mass index. A critical value of this adjusted voltage can be chosen to correspond to a desired percentile value in the cohort. Those subjects whose adjusted voltage exceeds this value are assigned, by this algorithm, to the left ventricular hypertrophy category.

This approach was found to be slightly superior to one based on logistic regression of left ventricular hypertrophy status on ECG criteria, body mass index and age. The linear regression approach also facilitates ECG estimation of echocardiographic left ventricular mass as a continuous measure.

Also explored was the effect of the addition of repolarization features (amplitudes of the T wave in leads V_1, V_5 and aVL) to the regression model. We found significance for the T wave voltage in lead V_5 for men and marginal significance for women, but in neither case did this information improve the fit of the regression models; hence, repolarization information was not incorporated in the final regression models.

Statistical comparisons. Pairwise sensitivity comparisons of voltage criteria for a selected specificity were made using the McNemar (26) chi-square test. Overall comparisons of the performance of the criteria were made using receiver operating characteristic curves. Because the critical voltage value for any given criterion varies from its lowest to highest possible value, the algorithm based on this voltage criterion will assign fewer and fewer subjects to the hypertrophy group, and the corresponding sensitivity of the procedure will decrease while its specificity increases. When the sensitivity is plotted on the vertical axis and its false positive rate, which equals (1 − specificity), is plotted on the horizontal axis, the result is the receiver operating characteristic curve (27). The area beneath this curve represents the overall performance of the voltage criterion; the greater the area, the greater the overall accuracy of the criterion in correctly identifying subjects with and those without hypertrophy. This area provides the basis for comparison of the overall performance of any two criteria across all specificity and sensitivity levels. The areas and their estimated standard deviations were evaluated by means of a Fortran program written for this task (G. Campbell, personal communication, September 1994).

The difference between two such areas, when divided by its estimated standard deviation, which includes a correlation term when the curves are derived from the same subjects, has a probability distribution closely approximated by the unit normal (*z* score) (28). A significance test of the difference in areas between two receiver operating characteristic curves derived from different ECG voltage criteria measured in the same subjects is based on this approach. In addition, two criteria were compared on the basis of truncated receiver operating characteristic curve areas, defined by restricting

Table 2. Regression Analysis of Left Ventricular Mass on Electrocardiographic Voltage, Body Mass Index and Age: Contributions to Model R

ECG Criterion	Men (n = 1,468) Voltage	Men (n = 1,468) Voltage, BMI, Age	Women (n = 1,883) Voltage	Women (n = 1,883) Voltage, BMI, Age
1 (RaVL)	0.290	0.432	0.400	0.587
2 (RI + SIII)	0.262	0.434	0.375	0.589
3 (RI − RIII + SIII − SI)	0.272	0.441	0.325	0.584
4 (RaVL + SV_3)	0.367	0.520	0.397	0.618
5 [(RaVL + SV_3) × QRS duration]	0.405	0.544	0.430	0.631
6 [$S(V_1, V_2)$]	0.123	0.465	0.001	0.596
7 [total 12-lead QRS voltage]	0.181	0.484	0.222	0.609
8 [$R(V_5, V_6)$]	0.056	0.441	0.095	0.588
9 [$S(V_1, V_2) + R(V_5, V_6)$]	0.115	0.478	0.068	0.601
10 [$SV_1 + R(V_5, V_6)$]	0.069	0.448	0.050	0.588

BMI = body mass index; ECG = electrocardiographic.

values of specificity to ≥85%. This significance test has the same form as that for comparing areas beneath two entire receiver operating characteristic curves.

Tabulated values of specificities for selected sensitivities and sensitivities for selected specificities were derived using the definition of left ventricular hypertrophy stated earlier. In additional analyses, levels of severity of left ventricular hypertrophy are expressed as 2, 3 and 4 SD above the mean value.

Results

Regression analysis. Left ventricular mass was positively correlated with body mass index, age and each of the 10 ECG voltages initially chosen for this investigation. Table 2 shows the values of the correlations for the regression relating ventricular mass to ECG voltage alone and to all three predictors. A regression of height-indexed left ventricular mass on these variables produces larger correlations, at least 30% greater than those in Table 2 because body height is a factor common to body mass index as well as to the dependent variable. Table 2 shows that of the 10 voltage criteria, the largest relative contributions of ECG voltage to the total correlation were made by criteria 1 to 5. Criteria 4 and 5 are most highly correlated with left ventricular mass; in contrast, criteria 6 to 10 had very much smaller correlations. Consequently, the remainder of our investigation focused on the first five criteria. An interesting byproduct of this analysis was the finding that for both genders, body mass index was negatively

Table 3. Electrocardiographic Voltage Criteria Evaluated for Framingham Men: Sensitivity and Specificity

	Criterion 1 (RaVL)	Criterion 2 (RI + SIII)	Criterion 3 (RI − RIII + SIII − SI)	Criterion 4 (RaVL + SV_3)	Criterion 5 [(RaVL + SV_3) × QRS duration]
	Specificity Required to Achieve Corresponding Sensitivity				
Sensitivity					
30%	0.892	0.890	0.887	0.914	0.911
50%	0.752	0.735	0.745	0.791	0.816
	Sensitivity Required to Achieve Corresponding Specificity				
Specificity					
85%	0.371	0.353	0.353	0.422	0.422
95%	0.168	0.164	0.172	0.194	0.224
	Voltage Criteria Adjusted for Age and Body Mass Index				
	Specificity Required to Achieve Corresponding Sensitivity				
Sensitivity					
30%	0.931	0.938	0.937	0.958	0.964
50%	0.854	0.863	0.864	0.898	0.888
	Sensitivity Required to Achieve Corresponding Specificity				
Specificity					
85%	0.517	0.526	0.526	0.560	0.565
95%	0.250	0.272	0.272	0.323	0.388

Table 4. Electrocardiographic Voltage Criteria Evaluated for Framingham Women: Sensitivity and Specificity

	Criterion 1 (RaVL)	Criterion 2 (RI + SIII)	Criterion 3 (RI − RIII + SIII − SI)	Criterion 4 (RaVL + SV_3)	Criterion 5 [(RaVL + SV_3) × QRS duration]
	Specificity Required to Achieve Corresponding Sensitivity				
Sensitivity					
30%	0.926	0.926	0.925	0.909	0.926
50%	0.826	0.836	0.841	0.807	0.829
	Sensitivity Required to Achieve Corresponding Specificity				
Specificity					
85%	0.471	0.477	0.477	0.428	0.445
95%	0.224	0.236	0.244	0.218	0.221
Voltage Criteria Adjusted for Age and Body Mass Index					
	Specificity Required to Achieve Corresponding Sensitivity				
Sensitivity					
30%	0.979	0.975	0.977	0.978	0.977
50%	0.938	0.936	0.934	0.934	0.954
	Sensitivity Required to Achieve Corresponding Specificity				
Specificity					
85%	0.675	0.687	0.681	0.718	0.715
95%	0.431	0.457	0.454	0.463	0.509

correlated with precordial lead ECG voltages; in contrast, body mass index was positively correlated with limb lead voltages.

Performance comparisons. Tables 3 and 4 show specificity values at 30% and 50% sensitivity and sensitivity values at 85% and 95% specificity for men and women, respectively, for the five criteria. A pronounced improvement is evident in the performance of each criterion after adjustment for age and obesity. Both before and after adjustment, the best performers among men were criteria 5 (the Cornell voltage criterion multiplied by the QRS duration) and 4 (the Cornell criterion).

Table 5. Electrocardiographic Voltage Criteria Evaluated for Framingham Men: Sensitivity, Specificity and Critical Voltage

	Criterion 1 (RaVL)	Criterion 2 (RI + SIII)	Criterion 3 (RI − RIII + SIII − SI)	Criterion 4 (RaVL + SV_3)	Criterion 5 [(RaVL + SV_3) × QRS duration]
	Critical Voltage Required to Achieve Corresponding Sensitivity				
Sensitivity					
30%	0.890	1.75	1.53	2.31	2,297.1
50%	0.690	1.31	1.15	1.96	1,976.2
	Critical Voltage Required to Achieve Corresponding Specificity				
Specificity					
85%	0.810	1.60	1.41	2.11	2,091.0
95%	1.090	2.15	1.89	2.53	2,529.6
Voltage Criteria Adjusted for Age and Body Mass Index					
	Critical Voltage Required to Achieve Corresponding Sensitivity				
Sensitivity					
30%	1.373	2.391	1.655	2.481	2,736.0
50%	1.224	2.102	1.478	2.250	2,444.4
	Critical Voltage Required to Achieve Corresponding Specificity				
Specificity					
85%	1.220	2.058	1.445	2.150	2,339.9
95%	1.436	2.430	1.699	2.430	2,623.0

Criterion 5 in mV-ms; all other criteria are in mV.

Table 6. Electrocardiographic Voltage Criteria Evaluated for Framingham Women: Sensitivity, Specificity and Critical Voltage

	Criterion 1 (RaVL)	Criterion 2 (RI + SIII)	Criterion 3 (RI − RIII + SIII − SI)	Criterion 4 (RaVL + SV_3)	Criterion 5 [(RaVL + SV_3) × QRS duration]
	Critical Voltage Required to Achieve Corresponding Sensitivity				
Sensitivity					
30%	0.800	1.59	1.42	1.85	1,727.2
50%	0.590	1.21	1.09	1.58	1,453.4
	Critical Voltage Required to Achieve Corresponding Specificity				
Specificity					
85%	0.620	1.26	1.12	1.66	1,519.8
95%	0.890	1.74	1.55	2.03	1,847.3
	Voltage Criteria Adjusted for Age and Body Mass Index				
	Critical Voltage Required to Achieve Corresponding Sensitivity				
Sensitivity					
30%	1.056	2.272	2.378	2.020	1,745.4
50%	0.933	2.009	2.083	1.781	1,572.0
	Critical Voltage Required to Achieve Corresponding Specificity				
Specificity					
85%	0.795	1.720	1.801	1.532	1,325.5
95%	0.962	2.071	2.148	1.830	1,558.7

Criterion 5 units in mV-ms; all other criteria are in mV.

In women, criteria 2 and 3 were nearly equal in sensitivity at the given levels of specificity and slightly outperformed criteria 4 and 5 before adjustment. In both of these pairs one criterion is a refinement of the other, so their similar performances are predictable. Their sensitivities remained comparable after adjustment, but the Cornell criteria pair, 4 and 5, were seen to be superior.

Critical voltage and voltage–duration product values required to produce sensitivity levels of 30% and 50% and specificity levels of 85% and 95% are displayed in Tables 5 and 6. The sensitivity values were derived from the 232 men (16%) and 348 women (18%) who fulfilled echocardiographic criteria for left ventricular hypertrophy and the rankings of the values of each ECG criterion within each gender-specific group. Similarly, the specificity values were determined from the ranking of voltages in the 1,236 men (84%) and 1,535 women (82%) without left ventricular hypertrophy. The formulas used for calculating the adjustments are presented in Table 7. It is the estimated regression coefficients for age (a) and body mass index (b) that uniquely characterize each criterion. The constants C and D were chosen to produce voltage values of the same order of magnitude as those of the original criteria. They does not affect the performance of the criteria because it is only the rank order of the voltages that determine their sensitivities and specificities.

The areas beneath the receiver operating characteristic curves for the adjusted ECG criteria and their standard errors appear in Table 8. They provide, as stated earlier, a global measure of the ability of an ECG criterion to detect left ventricular hypertrophy. The curves for criteria 4 and 5 for

Table 7. Voltage Adjustment Formulas*

Voltage Criterion	Men a	Men b	Men C	Men D	Women a	Women b	Women C	Women D
1	0.0212	0.2166	4.5	3	0.0435	0.1926	4.4	5
2	0.0373	0.3855	8.4	3	0.0738	0.3333	7.7	4
3	0.0332	0.3386	7.0	4	0.1032	0.4554	10.5	5
4	0.0174	0.1914	4.0	2	0.0387	0.2122	4.9	3
5	1.8289	19.0417	360.0	2	3.2963	18.1142	420.0	3

*Adjusted voltage (VADJ) is derived from the original voltage criterion (VCRIT) by the following formula, using the appropriate constants from Table 7:

VADJ = [VCRIT (mV) + a × Age (years) + b × Body mass index (kg/m2) − C]/D.

For criterion 5, VADJ and VCRIT are in mV-ms.

Table 8. Areas and Standard Errors for Receiver Operating Characteristic Curves for Electrocardiographic Criteria Adjusted for Age and Body Mass Index

ECG Criterion	Men		Women	
	Area	SE	Area	SE
1 (RaVL)	0.75586	0.01778	0.86036	0.01062
2 (RI + SIII)	0.75752	0.01733	0.86054	0.01066
3 (RI − RIII + SIII − SI)	0.76058	0.01768	0.85967	0.01070
4 (RaVL + SV_3)	0.80655	0.01501	0.87082	0.01018
5 [(RaVL + SV_3) × QRS duration]	0.81658	0.01458	0.87323	0.01011

ECG = electrocardiographic.

both genders had the largest areas, a result implicit in the regression R values of Table 2. The sensitivities of all five criteria at 95% specificity are displayed at three levels of severity of left ventricular hypertrophy in Table 9. The levels shown are defined as left ventricular mass exceeding 2, 3 and 4 SD above the gender-specific mean values. Values for the first category are taken from Tables 3 and 4. Beyond the 3-SD level, criteria 4 and 5 remained generally superior to the others. Receiver operating characteristic curves for these two criteria are depicted in Figures 1 and 2. For men and women, they show the degree of overall improvement in performance that result from the adjustments for age and obesity. Pairwise tests of significance of the differences in the areas beneath the two full curves and beneath the curves truncated at a false positive rate of 15% (minimal specificity of 85%) produced a p value of 0.016 for men for the full curves; the differences for the truncated curve for men and for both full and truncated curves for women were not significant ($p > 0.05$).

Results of significance tests of pairwise comparisons between these two criteria at increasing levels of hypertrophy are shown in Table 10. Criterion 5 was the most sensitive indicator at all three levels of hypertrophy and significantly so, except at the highest level in men.

Table 9. Sensitivity of Adjusted Electrocardiographic Criteria as a Function of Level of Height-Indexed Left Ventricular Mass/Height at 95% Specificity by Gender*

ECG Criterion	Men: LV Mass/Height >			Women: LV Mass/Height >		
	$\mu + 2\sigma$	$\mu + 3\sigma$	$\mu + 4\sigma$	$\mu + 2\sigma$	$\mu + 3\sigma$	$\mu + 4\sigma$
1	25.0	32.3	40.5	43.1	57.3	71.4
2	27.2	36.6	45.2	45.7	59.6	72.5
3	27.2	35.5	40.5	45.4	60.2	72.5
4	32.3	41.9	57.1	46.3	62.0	71.4
5	38.8	53.8	59.5	50.9	65.5	75.8

*Column headings denote levels of height-indexed left ventricular (LV) mass expressed as the gender-specific mean value plus two, three or four gender-specific standard deviations. ECG = electrocardiographic.

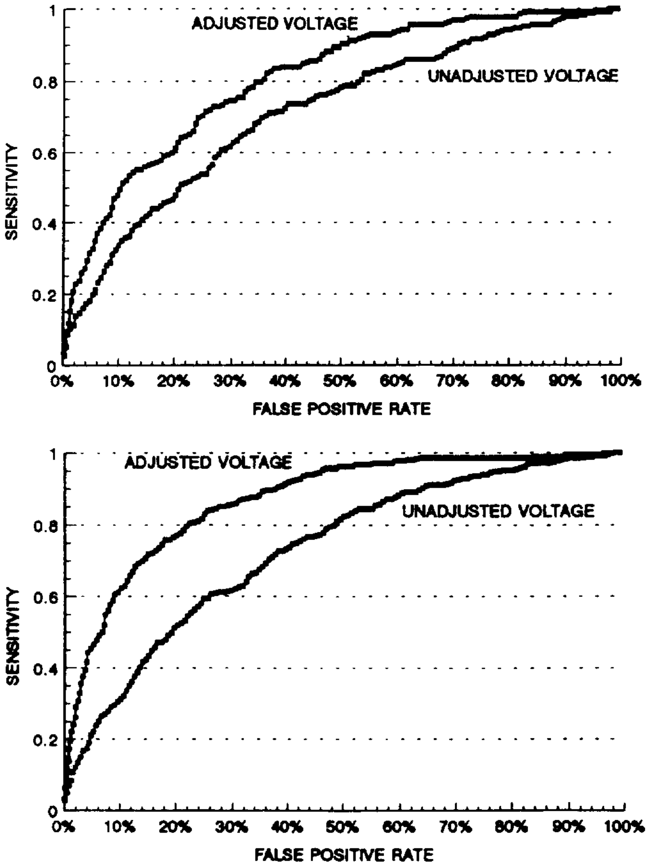

Figure 1. Receiver operating characteristic curves for men (**top**) and women (**bottom**) using electrocardiographic voltage criterion 4.

Discussion

The use of ECG voltage criteria for the diagnosis of left ventricular hypertrophy began 80 years ago (13). Evaluations of the performance of ECG criteria for the diagnosis of left ventricular hypertrophy have largely been carried out on clinical populations using autopsy-derived values of left ventricular mass. Reports of the sensitivity and specificity of various criteria generally ignore the fact that these approaches are quite sensitive to the distribution of left ventricular mass in the population represented by the study sample. Hypertrophy is naturally more prevalent in clinically based samples, so that evaluation of ECG criteria using a population-based cohort of adults affords a more realistic appraisal of their utility in a nonreferral setting. In the present report, using echocardiographically determined left ventricular mass and ECG voltage and duration measurements, we evaluated the performance of 10 ECG criteria before and after adjustment for age and obesity. This adjustment approach appreciably increases sensitivity at any level of specificity, and vice versa, for each of the criteria considered. The greatest portion of this improvement rests on the strong association between body mass index and left ventricular mass.

In the present population, the Cornell voltage criterion 4 (R wave in lead aVL plus S wave in lead V_3) and its derivative,

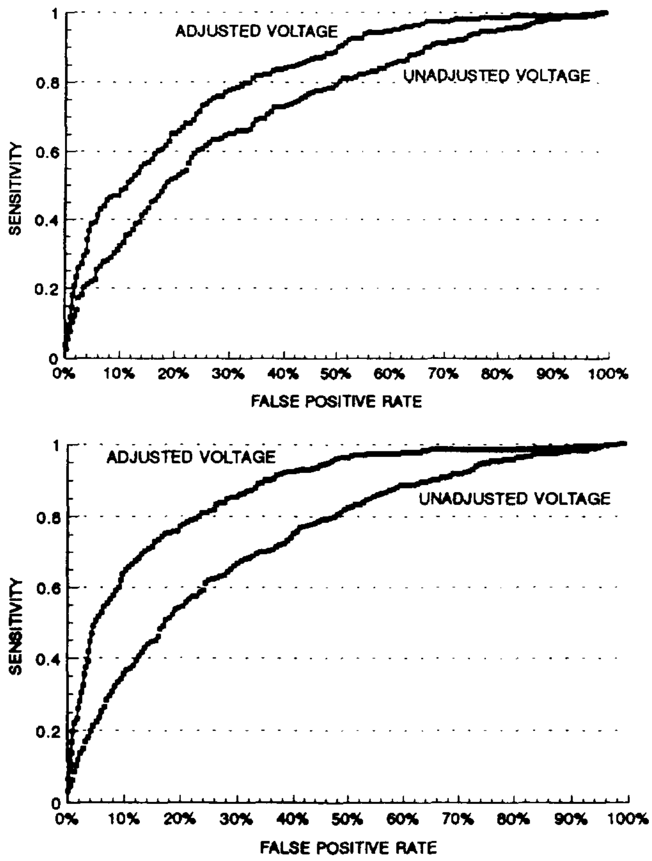

Figure 2. Receiver operating characteristic curves for men (**top**) and women (**bottom**) using electrocardiographic voltage criterion 5.

criterion 5, the product of R wave in lead aVL plus S wave in lead V_3 and the QRS duration, were the most sensitive of those investigated. The Lewis index (R wave in lead I minus R wave in lead III plus S wave in lead III minus S wave in lead I), its close relative, the Gubner-Ungerleider index (R wave in lead I plus S wave in lead III), and the single-lead voltage (R wave in lead aVL) were all moderately less sensitive than the Cornell criteria after adjustment. In addition to exploring the efficacy of including T wave amplitudes in the regression models used to obtain the adjusted versions of the ECG criteria examined

Table 10. Significance Tests of Comparisons of Sensitivities of Cornell-Type Electrocardiographic Criteria at 95% Specificity by Level of Height-Indexed Left Ventricular Mass: Comparisons of Electrocardiographic Criteria 4 and 5*

	LV Mass/Height >		
	$\mu + 2\sigma$	$\mu + 3\sigma$	$\mu + 4\sigma$
Men	0.00006	0.0009	>0.10
Women	0.0003	0.0339	0.0455

*Data presented are p values for statistical tests of significance of indicated comparisons; all suggest that criterion 5 is more sensitive than criterion 4 at 95% specificity. Column headings denote levels of height-indexed left ventricular mass expressed as the gender-specific mean value plus two, three or four gender-specific standard deviations.

here, we also tried augmenting the adjusted criteria with observed T wave abnormalities. This approach also failed to improve performance.

Two other recently reported studies (11,29) evaluated the performance of criterion 4 in clinical series. The first study reported 42% sensitivity among 135 subjects with left ventricular mass measured at autopsy and 96% specificity in a group of 92 healthy subjects with echocardiographically derived values of ventricular mass. The second study compared several criteria, including 4 and 5, in a series of subjects, 220 with autopsy-established left ventricular masses, including 95 with hypertrophy and 125 without hypertrophy. Criterion 4 detected hypertrophy in 36% and 5 in 51% of the 95 hypertrophic subjects, and both were 95% specific in the 125 nonhypertrophic subjects. Both studies used body surface area-indexed values of left ventricular mass. Comparisons with results of the present study are problematic because the degree of hypertrophy among Framingham Heart Study subjects is probably less than that of subjects in clinically based investigations and because of the different methods of indexing left ventricular mass values derived from autopsy and echocardiography.

In a previous report (21), the age and obesity adjustment approach was introduced as an improvement of the original Cornell criterion on the basis of data from the same Framingham Heart Study subjects, with the methodologic precaution of randomly classifying the sample subjects into calibration and test groups; the results obtained in this manner differed only very slightly from those obtained by deriving the regression variables from, and applying them to, the entire study sample. For this reason, this precaution was omitted in the present study.

Study limitations. The present investigation is based on M-mode echocardiographic estimation of left ventricular mass. The geometric assumptions of the modified cubed formula are violated in cases in which left ventricular geometry is distorted. This distortion occurs most commonly in subjects with a myocardial infarction. Because myocardial infarction was a criterion for exclusion from analysis, the limitations of M-mode echocardiography in this study sample are minor.

Conclusions. Recent guidelines maintain that the ECG is a diagnostic test that should be obtained routinely for the evaluation of the hypertensive patient (3,30). Improvements in the performance of ECG criteria for left ventricular hypertrophy should enhance its utility for the detection of target organ damage. Such approaches would have applicability in population screening and in evaluating response to treatment in hypertension intervention trials when the limitations of cost do not permit assessment by echocardiography. Independent validation of the approach used in the present investigation is needed.

References

1. Devereux RB, Casale PN, Wallerson DC, et al. Cost effectiveness of echocardiography and electrocardiography in patients with systemic hypertension. Hypertension 1987;9 Suppl II:II-69-76.
2. Levy D, Labib SB, Anderson KM, Christiansen JC, Kannel WB, Castelli WB. Determinants of sensitivity and specificity of electrocardiographic criteria for left ventricular hypertrophy. Circulation 1990;81:815-20.

3. Joint National Committee. Fifth report on detection, evaluation, and treatment of high blood pressure. Arch Intern Med 1993;153:154–83.
4. Sokolow M, Lyon TP. The ventricular complex in left ventricular hypertrophy as obtained by unipolar precordial and limb leads. Am Heart J 1949;32:1517.
5. McPhie J. Left ventricular hypertrophy: electrocardiographic diagnosis. Aust Ann Med 1958;7:317–27.
6. Rosenfeld I, Goodrich C, Kassenbauem G, Winston AL, Reader G. The electrocardiographic diagnosis of left ventricular hypertrophy. Am Heart J 1964;68:173–82.
7. Mazzoleni A, Wolff R, Wolff L, Reiner L. Correlations between component cardiac weights and electrocardiographic patterns in 185 cases. Circulation 1964;30:808–29.
8. Rodstein M, Gubner RS. Specificity and sensitivity of QRS voltage criteria of left ventricular hypertrophy. Am J Cardiol 1964:13:619–23.
9. Romhilt DW, Bove KE, Norris RJ, et al. A critical appraisal of the electrocardiographic criteria for the diagnosis of left ventricular hypertrophy. Circulation 1969;40:185–95.
10. Murphy ML, Thenabadu PL, Blue LR, et al. Descriptive characteristics of the electrocardiogram from autopsied men free of cardiopulmonary disease—a basis for evaluating criteria for ventricular hypertrophy. Am J Cardiol 1983;52:1275–80.
11. Casale PN, Devereux RB, Alonso DR, Campo E, Kligfield P. Improved sex-specific criteria of left ventricular hypertrophy for clinical and computer interpretation of electrocardiograms: validation with autopsy findings. Circulation 1987;75:565–72.
12. Koito H, Spodick DH. Electrocardiographic RV_6:RV_5 voltage ratio for diagnosis of left ventricular hypertrophy. Am J Cardiol 1989;63:252–4.
13. Lewis T. Observations upon ventricular hypertrophy with especial reference to preponderance of one or other chamber. Heart 1914;5:367–403.
14. Herrmann GR, Wilson FN. Ventricular hypertrophy. Heart 1922;9:91–147.
15. Gubner R, Ungerleider HE. Electrocardiographic diagnosis of left ventricular hypertrophy. Arch Intern Med 1943;72:196–209.
16. Schack JA, Rosenman RH, Katz LN. The aV limb leads in the diagnosis of ventricular strain. Am Heart J 1950;40:696–705.
17. Goldberger E. Unipolar Lead Electrocardiography. Philadelphia: Lea & Febiger, 1953.
18. Casale PN, Devereux RB, Kligfield P, et al. Electrocardiographic detection of left ventricular hypertrophy: development and prospective validation of improved criteria. J Am Coll Cardiol 1985;6:572–89.
19. Nath A, Alpert MA, Terry BE, Kelly DL. Sensitivity and specificity of electrocardiographic criteria for left and right ventricular hypertrophy in morbid obesity. Am J Cardiol 1988;62:126–30.
20. Koito H, Spodick DH. Accuracy of the RV_6:RV_5 voltage ratio for increased left ventricular mass. Am J Cardiol 1988;62:985–7.
21. Norman JE, Levy D, Campbell G, Bailey JJ. Improved detection of echocardiographic left ventricular hypertrophy using a new electrocardiographic algorithm. J Am Coll Cardiol 1993;21:1680–6.
22. Dawber TR, Meadors GF, Moore FE. Epidemiological approaches to heart disease: The Framingham Study. Am J Public Health 1951;41:279–86.
23. Kannel WB, Feinleib M, McNamara PM, Garrison RJ, Castelli WP. An investigation of coronary heart disease in families. Am J Epidemiol 1979; 110:281–90.
24. Levy D, Savage DD, Garrison RJ, Anderson KM, Kannel WB, Castelli WP. Echocardiographic criteria for left ventricular hypertrophy: the Framingham Heart Study. Am J Cardiol 1987;59:956–60.
25. Devereux RB, Reichek N. Echocardiographic determination of left ventricular mass in man. Anatomic validiation of the method. Circulation 1977;55: 613–8.
26. McNemar Q. Note on the sampling error of the difference between correlated proportions or percentages. Psychometrika 1947;12:153–7.
27. Metz CE. Basic principles of ROC analysis. Semin Nucl Med 1978;8:283.
28. Hanley JA, McNeil BJ. A method of comparing the areas under receiver operating characteristic curves derived from the same cases. Radiology 1983;148:839–43.
29. Molloy TJ, Okin PM, Devereux RB, Kligfield P. Electrocardiographic detection of left ventricular hypertrophy by the simple QRS voltage–duration product. J Am Coll Cardiol 1992;20:1180–6.
30. WHO/ISH committee. 1993 guidelines for the management of mild hypertension: memoranda from a WHO/ISH meeting. Hypertens Res 1993;16:149–61.
31. Dollar AL, Roberts WC. Usefulness of total 12-lead QRS voltage compared with other criteria for determining left ventricular hypertrophy in hypertrophic cardiomyopathy: analysis of 57 patients studied at necropsy. Am J Med 1989;87:377–81.