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# Electrocardiographic Detection of Left Ventricular Hypertrophy Using Echocardiographic Determination of Left Ventricular Mass as the Reference Standard

## Comparison of Standard Criteria, Computer Diagnosis and Physician Interpretation

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**Electrocardiographic findings of left ventricular hypertrophy were compared with echocardiographic left ventricular mass in 148 patients to assess performance of standard electrocardiographic criteria, the IBM Bonner program and physician interpretation. On echocardiography, 43% of the patients had left ventricular hypertrophy (left ventricular mass > 215 g). Sokolow-Lyon voltage (S in $V_1$ + R in $V_5$ or $V_6$) and Romhilt-Estes point score correlated modestly with left ventricular mass (r = 0.40, p < 0.001 and r = 0.55, p < 0.001, respectively). Sensitivity of Sokolow-Lyon voltage greater than 3.5 mV for left ventricular hypertrophy was only 22%, but specificity was 93%. Point score for probable left ventricular hypertrophy (≥ 4 points) had 48% sensitivity and 85% specificity, whereas definite hypertrophy (≥ 5 points) had 34% sensitivity and 98% specificity. Computer analysis resulted in 45% sensitivity and 83% specificity. Overall diagnostic accuracy of the IBM Bonner program (67%) was better than that of Sokolow-Lyon voltage (62%), but worse than the Romhilt-Estes point score (69% for ≥ 4 points or 70% for ≥ 5 points). Three cardiologists interpreted electrocardiograms independently and in a blinded fashion. Physician sensitivity was 56%, specificity 92% and accuracy 76%. Correlation with left ventricular hypertrophy was good (r = 0.70, p < 0.001).**

**It is concluded that: 1) computer diagnosis of left ventricular hypertrophy by the IBM Bonner program is no more accurate than diagnosis by Sokolow-Lyon or Romhilt-Estes criteria, and 2) physician recognition of left ventricular hypertrophy is more accurate. This suggests that additional information about left ventricular hypertrophy is present in the electrocardiogram that is not detectable by standard criteria or the IBM computer program.**

Chronic pressure or volume overload of the systemic circulation leads to left ventricular hypertrophy The degree of adaptive hypertrophy has been found to parallel the severity of overload (1,2) and detection of extreme hypertrophy has been a powerful predictor of a poor prognosis (1,3) Thus, estimation of left ventricular mass is an important variable in evaluating the functional state of the heart

A variety of electrocardiographic criteria have been proposed for the recognition of left ventricular hypertrophy, but the limitations of these methods have been well documented (4–7) Complex electrocardiographic systems, such as multiple dipole electrocardiography, have improved the ability to estimate left ventricular mass and suggest that computer analysis may improve electrocardiographic diagnosis of left ventricular hypertrophy (8)

Computer programs for electrocardiographic interpretation are categorized into two types those that utilize a decision tree in which various criteria are either present or absent (called "first generation" programs by Pipberger et al [9]) and those that rely on multivariate statistical anlaysis of numerous electrocardiographic measurements ("second generation" programs) Second generation programs, developed most extensively by Pipberger et al (8–12), have

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been shown to improve the prediction of a limited number of diagnostic probabilities, especially when correct prior clinical probabilities of various diagnoses are also used (9) However, second generation programs have had limited acceptance, in large part because of their limited range of diagnostic possibilities and because of the absence of information in the computer report concerning the measurements that led to a given diagnosis (13) Therefore, most programs in clinical use are of the first generation type

Unfortunately, the accuracy of these programs remains uncertain Although numerous studies have compared computer electrocardiographic detection of left ventricular hypertrophy with cardiologists' diagnoses (14–18), only limited information is available comparing computer performances with independent, nonelectrocardiographic standards (8–12, 19–20) Only one study (20) of this type has evaluated a widely used, commercially available computer system Although this study relied on nonelectrocardiographic evidence to establish the diagnosis of left ventricular hypertrophy, measurements of left ventricular mass were not employed Therefore, the present study was undertaken to compare the performance of standard electrocardiographic criteria with that of a widely used computerized program, the IBM Bonner 2 V2MO, and with physician interpretations for diagnosis of left ventricular hypertrophy using echocardiographic determination of left ventricular mass as the reference standard

## Methods

**Subjects.** The study group consisted of 148 consecutive patients with computerized electrocardiograms and technically excellent echocardiograms obtained within a mean of 4 days of each other (range 0 to 26) with no intervening change in cardiac status Subjects with electrocardiograms obtained during paced rhythm were excluded

*Cardiac diagnoses were established* by review of complete inpatient and outpatient charts for each patient, subjects with inadequate records were excluded All pertinent cardiac diagnoses were recorded along with noncardiac conditions that might induce secondary changes in cardiac anatomy Multiple cardiac diagnoses were possible for each patient

*The study group included* 62 patients with hypertension, 44 patients with atherosclerotic cardiovascular disease, 38 patients with valvular heart disease, 13 patients with mitral valve prolapse, 13 patients with pericardial disease, 12 patients with diabetes mellitus, 11 patients with cardiomyopathy, 11 patients with bacterial endocarditis, 12 patients with miscellaneous conditions and 15 patients with no cardiac disease A total of 17 patients had clinically documented myocardial infarction and 15 had ventricular conduction defects The median age was 50 years (range 16 to 84), 52 7% of the patients were women and 61 5% were Caucasian

**Electrocardiographic data.** Electrocardiograms were recorded using a Marquette (Marquette Electronic, Inc ) analog transmitting cart at 25 mm/s and 1 mV/cm standardization and fed by direct telephone circuits to computer with the IBM Bonner 2 V2MO electrocardiogram analysis program

*Electrocardiographic evidence of left ventricular hypertrophy was analyzed in three ways* First, the electrocardiograms were interpreted by the computer program and classified (see Appendix) into those showing no left ventricular hypertrophy, possible left ventricular hypertrophy and definite left ventricular hypertrophy Second, the coded 12 lead electrocardiogram was examined for the two most widely used standard criteria for left ventricular hypertrophy, Sokolow and Lyon's precordial voltage criteria (S in $V_1$ + R in $V_5$ or $V_6 > 3\ 5$ mV) (4) and Romhilt-Estes point score (5,6)

Finally, the coded electrocardiograms were read independently in a blinded fashion and with no clinical information by three investigators (R B D , P K , D H M ), who were required to make a diagnostic judgment as to whether the tracings exhibited no left ventricular hypertrophy or possible, probable or definite left ventricular hypertrophy Each of these categories was assigned an ordinal value with respect to degree of left ventricular hypertrophy none = 0 points, possible = 1 point, probable = 2 points and definite = 3 points When assessing the sensitivities and specificities of the physician's readings, all categories of left ventricular hypertrophy were considered to be positive In addition to the individual readings, a group score of the three cardiologists was derived using the arithmetic mean of the scores assigned by individual readers to determine whether interobserver variability affected interpretation (21) Clinician performance was assessed to determine whether additional electrocardiographic information about left ventricular hypertrophy was detectable by experienced observers beyond that incorporated in existing classification schemes

**Echocardiographic data.** M-mode echocardiograms were recorded using standard techniques with 2 25 mHz transducers interfaced to either a Smith-Kline Ekoline echograph with a Honeywell 1856A recorder or a Picker Echo-View system 80c echograph Strip chart recordings were made at 50 mm/s paper speed Echocardiograms were coded and read in a blinded fashion without knowledge of other findings Simultaneous visualization of interventricular septal thickness (IVS), left ventricular internal dimension (LVID) and posterior wall thickness (PWT) was sought, at or just below the tips of the mitral valve leaflets End-diastolic measurements were made by the Penn convention (22) *Left ventricular mass was calculated from these measurements by the following formula* (22)

Left ventricular mass =

$$1\ 04\ ([LVID + PWT + IVS]^3 - [LVID]^3) - 13\ 6\ g$$

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In keeping with our previous studies (7,22–24), left ventricular mass greater than 215 g was considered to represent left ventricular hypertrophy.

**Statistical methods.** Biostatistical analysis was conducted at the Rockefeller University Computer Center using an IBM 390 computer and the BMD 35 Programming System. The strength of associations was evaluated by least squares linear regression and its test of significance. Differences among groups were assessed by analysis of variance. *Statistical definitions were as follows:*

$$\text{Sensitivity (\%)} = 100 \times \frac{\text{Patients with disease with positive test}}{\text{All patients with disease tested}}$$

$$\text{Specificity (\%)} = 100 \times \frac{\text{Patients without disease with negative test}}{\text{All patients without disease tested}}$$

Correct diagnosis (%)

$$= 100 \times \frac{+ \text{ Patients without disease with negative test}}{\text{All subjects tested}}$$

Positive predictive accuracy (%)

$$= 100 \times \frac{\text{Patients with disease with positive test}}{\text{All subjects with a positive test}}$$

Negative predictive accuracy (%)

$$= 100 \times \frac{\text{Patients without disease with negative test}}{\text{All subjects with a negative test}}$$

$$\text{Prevalence} = \frac{\text{All subjects with disease tested}}{\text{All subjects tested}}$$

Analyses were performed utilizing echocardiographic measurements of left ventricular mass as the nonelectrocardiographic reference standard. In addition, to simulate the methods of previous studies (16), computer diagnoses of left ventricular hypertrophy were compared with diagnoses based on a Romhilt-Estes point score of 4 points or more.

## Results

**Correlation of electrocardiographic criteria with left ventricular mass.** Modest correlations were observed between left ventricular mass and Sokolow-Lyon (4) precordial voltage (correlation coefficient [r] = 0.40, probability [p] < 0.001) or Romhilt-Estes (5) point score (r = 0.55, p < 0.001). A similar correlation occurred between left ventricular mass and the point score system of the IBM Bonner 2 V2M0 program (r = 0.45, p < 0.001), while the average of physician scores for left ventricular hypertrophy achieved a closer correlation with left ventricular mass (r = 0.70, p < 0.001). The difference between the correlations of left ventricular mass with the physician score and the IBM score was significant (p < 0.05). The coefficient of determination ($r^2$) for physician readings (0.49) was substantially higher than for computer readings (0.20), Romhilt-Estes point score (0.30) or Sokolow-Lyon precordial voltage (0.16).

**Diagnostic accuracy of electrocardiographic criteria for left ventricular hypertrophy.** The accuracy of classification of patients as either manifesting or not manifesting left ventricular hypertrophy in the electrocardiogram was assessed for standard criteria, the computer diagnosis and physician interpretation (Table 1). Sokolow-Lyon voltage criteria correctly identified only 14 of the 64 patients with left ventricular hypertrophy on echocardiogram (22% sensitivity) but correctly identified 78 of 84 patients without left ventricular hypertrophy (93% specificity). The positive predictive accuracy of this method was 70% while negative predictive accuracy was 61%.

*The Romhilt-Estes point score*, using left ventricular hypertrophy of 4 points or more, correctly identified 31 of the 64 patients with left ventricular hypertrophy (48% sensitivity) and 71 of the 84 patients without left ventricular hypertrophy (85% specificity). The predictive accuracy of a positive test was 71% and that of a negative test was 68%. Using the more stringent criterion (left ventricular hypertrophy ≥ 5 points), the point score system correctly identified only 22 of 64 patients with left ventricular hypertrophy (34% sensitivity) but correctly identified 82 of 84 patients without it (98% specificity). The positive predictive accuracy was 91% while the negative predictive accuracy was 66%.

*The computer using the IBM Bonner 2 V2MO system* correctly identified 29 of 64 patients with hypertrophy of the left ventricle (45% sensitivity) and only 70 of 84 patients without left ventricular hypertrophy (83% specificity). This resulted in a positive predictive accuracy of 67% and a negative predictive accuracy of 67%. When the Romhilt-Estes point score was used as the reference standard rather than echocardiographic left ventricular mass, the sensitivity of the IBM computer was 55% with a specificity of 81%.

**Performance of physicians in detecting left ventricular hypertrophy.** Physician interpretation of electrocardiograms showed improved results compared with either standard criteria or computer readings. The three physicians identified between 40 and 49 of the 64 patients with left ventricular hypertrophy correctly, yielding a range of sensitivities from 63 to 77%, while they correctly identified from 67 to 77 of the 84 patients without left ventricular hypertrophy correctly (specificities 80 to 92%). The range of positive predictive accuracy was from 70 to 84% while the range of negative predictive accuracy was from 73 to 82%.

An average of the three physicians' scores of at least 1

**Table 1.** Performance of Electrocardiographic Criteria to Detect Left Ventricular Hypertrophy

| ECG Method | Sensitivity (%) | Specificity (%) | Accuracy (%) | + Predictive Accuracy (%) | − Predictive Accuracy (%) |
|---|---|---|---|---|---|
| Sokolow-Lyon | 22 | 93 | 62 | 70 | 61 |
| R-E score ≥ 4 points | 48 | 85 | 69 | 71 | 68 |
| R-E score ≥ 5 points | 34 | 98 | 70 | 91 | 66 |
| Bonner 2 V2MO computer program | 45 | 83 | 67 | 67 | 67 |
| Physician 1 | 66 | 91 | 80 | 84 | 78 |
| Physician 2 | 63 | 80 | 72 | 70 | 74 |
| Physician 3 | 77 | 82 | 80 | 77 | 82 |
| Mean physician score ≥ 1 point | 56 | 92 | 76 | 84 | 73 |

ECG = electrocardiographic, R-E = Romhilt-Estes, + = positive, − = negative

point correctly identified 36 of 64 patients with left ventricular hypertrophy (56% sensitivity) and correctly identified 77 of 84 patients without left ventricular hypertrophy (92% specificity) This resulted in a predictive accuracy of a positive test of 84% and a predictive accuracy of a negative test of 73%

Analysis of the relation between electrocardiographic interpretations and left ventricular mass (Table 2) revealed that the physician interpretations achieved the best separation between left ventricular mass measurements in groups considered to have either possible, or probable or no left ventricular hypertrophy

## Discussion

In recent years, computerized interpretation of electrocardiograms has evolved from an investigational oddity into a widely used technique with substantial clinical and commercial implications (25) Most of the growth in computerized electrocardiographic interpretation reflects widespread application of first generation computer programs that mimic physician decision-making processes Accordingly, it is not surprising that several computer programs have shown excellent sensitivity and specificity when compared with physician interpretations utilizing similar diagnostic criteria (14,16,18) Only rarely, however, have widely-used first-generation programs been evaluated by comparison with nonelectrocardiographic data bases (20)

**Detection of left ventricular hypertrophy by electrocardiogram, computer and clinicians.** The present study has evaluated critically the performance of a widely-used first-generation computer program, the IBM Bonner 2 V2MO, as well as electrocardiographic detection of left ventricular hypertrophy by standard criteria and experienced cardiologists, in comparison with echocardiographic measurements of left ventricular mass Two important conclusions emerge from our data First, the diagnostic performance of this widely-used computer program, while poor, is approximately equal to that obtained with conventional criteria Interestingly, when the Romhilt-Estes point score is used as the standard, the computer performance was less than one might expect, considering that the computer substantially incorporates the point score in its program, and was also poorer than that reported by Bailey et al (16)

*The second conclusion that emerges from our data is more positive* Three experienced cardiologists' blinded readings of the presence or absence of left ventricular hypertrophy correlated more closely with echocardiographic

**Table 2.** Relation of Echocardiographic Left Ventricular Mass to Electrocardiographic Findings

| | No ECG-LVH | | | Possible ECG-LVH | | | Probable Definite ECG-LVH | |
|---|---|---|---|---|---|---|---|---|
| ECG Method | n | LV Mass (g) | | n | LV Mass (g) | | n | LV Mass (g) |
| Computer | 105 | 205 ± 102 | ← p = NS → | 22 | 251 ± 133 | → p < 0.01 → | 21 | 373 ± 144 |
| R-E score | 104 | 200 ± 101 | ← p = NS → | 20 | 243 ± 110 | → p < 0.001 → | 24 | 385 ± 134 |
| Physician 1 | 98 | 181 ± 85 | ← p < 0.001 → | 23 | 289 ± 103 | → p < 0.005 → | 27 | 390 ± 127 |
| Physician 2 | 91 | 185 ± 86 | ← p < 0.001 → | 37 | 270 ± 116 | → p < 0.001 → | 20 | 402 ± 142 |
| Physician 3 | 84 | 172 ± 75 | ← p < 0.001 → | 36 | 265 ± 111 | → p < 0.001 → | 28 | 392 ± 122 |
| Mean physician score | 105 | 188 ± 89 | ← p < 0.001 → | 23 | 301 ± 102 | → p < 0.003 → | 20 | 415 ± 131 |
| Echocardiogram | 84 | 149 ± 44 | ← | | p < 0.0001 | → | 64 | 351 ± 107 |

ECG = electrocardiographic, LV = left ventricular, LVH = left ventricular hypertrophy, n = number of patients, NS = not significant, R-E = Romhilt-Estes

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left ventricular mass and yielded more accurate diagnostic conclusions than either standard electrocardiographic criteria or the computer. A similar result was reported by Bourdillon and Kilpatrick (19), who found clinicians' interpretations to be more accurate than those of either the Veterans Administration (8–12) or Mt Sinai program, with respect to independent clinicopathologic data. Pipberger et al (9) also found a slightly poorer classification of electrocardiograms by the Veterans Administration program than by clinicians when equal prior probabilities were used (66 versus 68%), although optimal adjustment of the prior clinical probabilities used in their program increased correct classification to 86%. Clinicians' recognition of myocardial infarction has also been found to compare favorably with a second generation computer program (26). In contrast, when clinicians are constrained to use a specified set of electrocardiographic diagnostic criteria, their performance has been found to be poorer (27), parallel to our findings with respect to Sokolow-Lyon and Romhilt-Estes criteria.

**Potential for improvement of electrocardiographic criteria.** These data suggest that additional information in the electrocardiogram concerning the presence or absence of left ventricular hypertrophy beyond the findings incorporated in standard electrocardiographic criteria is detectable by skilled clinical electrocardiographers. While none of the three physicians in the present study utilized specifically quantifiable personal criteria, each relied heavily on the presence of repolarization abnormalities as a marker for left ventricular hypertrophy. Despite correct emphasis on the numerous causes of the left ventricular "strain" pattern, recent studies (28,29) confirmed its strong association with left ventricular hypertrophy. Although other factors in the superior performance by physicians, such as recognition of intrinsicoid delay or QRS widening, cannot yet be clearly established, some studies suggest that somewhat different QRS characteristics than those embodied in most widely used electrocardiographic criteria may be most closely related to left ventricular hypertrophy. Thus, several reports (30,31) indicate that the depth of the S wave in standard or orthogonal anterior leads and the height of the R wave in corresponding lateral leads are most closely related to left ventricular mass.

Our finding that clinicians can outperform standard electrocardiographic criteria of left ventricular hypertrophy as well as a widely used computer program, taken together with the recent evidence that carefully selected QRS and repolarization abnormalities are more closely associated with left ventricular hypertrophy, offers hope that diagnostic electrocardiographic criteria can be improved. This effort may be further aided by taking into account other demographic variables that influence electrocardiographic recognition of left ventricular hypertrophy, including age and body habitus (24). Utilization of demographic variables along with electrocardiographic measurements might allow optimization of diagnosis without the need to use corrected prior clinical probabilities.

**Limitations of the study.** Several limitations of the present study require emphasis. First, the superior performance of the clinicians in this study, all of whom are involved in ongoing studies of cardiac hypertrophy, is not necessarily broadly applicable to other clinical electrocardiographers. Second, echocardiographic left ventricular mass, which has been used in this study as the reference standard, is itself an estimate and its use may have weakened observed relation. This effect is unlikely to be a strong one, however, in view of the similarity of findings in previous studies (7,29) when autopsy or echocardiographic left ventricular mass was used as the reference standard. Finally, the present series is small enough that the results might be uncertain. However, the similarity of the relation between left ventricular mass and standard electrocardiographic criteria of left ventricular hypertrophy in this study and in two previous, completely independent groups of patients (7,24) suggests that this is not an important problem.

**Clinical implications.** Evaluation of the performance of the electrocardiogram requires comparison with accurate, independent measurements. Using echocardiographic left ventricular mass as a reference standard, we have shown that computer diagnosis of left ventricular hypertrophy by a widely used first generation program (Bonner 2 V2MO) is no more accurate than with Sokolow-Lyon or Romhilt-Estes criteria. However, recognition of left ventricular hypertrophy by blinded clinician interpretations was more accurate. This suggests that more information about left ventricular hypertrophy is present in the electrocardiogram than is detectable by standard measurement criteria or the Bonner program, and that development of computer electrocardiographic methods that utilize such information will become increasingly important if the role of computer electrocardiographic interpretation is to continue to expand.

## APPENDIX

## Computer Classification of Patients With Electrocardiographic Evidence of Left Ventricular Hypertrophy

Patients with electrocardiographic evidence of left ventricular hypertrophy were classified by the computer into the following six groups:

1) Possible left ventricular hypertrophy
2) Possible left ventricular hypertrophy with strain or digital effect
3) Possible left ventricular hypertrophy but may be normal for age
4) Consider left ventricular hypertrophy if patient not taking digitalis

5) Left ventricular hypertrophy
6) Left ventricular hypertrophy with strain or digitalis effect

We defined groups 1 through 4 as "possible left ventricular hypertrophy" and groups 5 and 6 as "left ventricular hypertrophy " The "no left ventricular hypertrophy" group consisted of patients with no electrocardiographic evidence of left ventricular hypertrophy by the computer reading

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