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Performance of electrocardiographic criteria for left ventricular hypertrophy as compared with cardiac computed tomography: from the Rule Out Myocardial Infarction Using Computer Assisted Tomography trial

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Abstract

Objective—Cardiac computed tomography (CT) is a state-of-the-art technology that provides an accurate noninvasive method to quantify left ventricular mass for analysis of left ventricular hypertrophy (LVH). We aimed to examine seven ECG-based LVH criteria against two CT indexation criteria for LVH: a CT-specific body surface area cutoff and the obesity-independent height^{2.7} criteria.

Methods—In 333 patients (mean age 53 ± 12 years, 61% men), 64-slice contrast-enhanced CT was performed and 12-lead surface ECG within 24 h. Left ventricular mass was measured at end-diastole. Using both CT indexation criteria, the cohort was subdivided into patients with LVH and without LVH. The seven ECG criteria for LVH were the Cornell voltage index, Cornell voltage duration product, Cornell/strain index, Sokolow–Lyon index, Romhilt–Estes scores at least 4 and at least 5, and Gubner–Ungerleider.

Results—The ECG parameters had high specificities (85–97%) and variable low sensitivities (4–43%) when compared to either CT criteria of LVH. The three Cornell-based methods performed the best (test-positive likelihood ratio: 4.5–6.7), followed by the Sokolow–Lyon and Romhilt–

Estes scores (test-positive likelihood ratio: 2.3–4.0). With the exception of the Gubner–Ungerleider criterion, the other six ECG criteria were associated with at least one of the CT-based LVH (adjusted odds ratio 2.4–9.5) and had incremental predictive value beyond that of hypertension history.

Conclusion—Using cardiac CT as a gold standard for LVH assessment, ECG criteria for LVH have high specificities with the three Cornell-based criteria providing the best test performance for identifying patients with LVH.

Keywords

computed tomography; electrocardiography; left ventricular hypertrophy; left ventricular mass

Introduction

The presence of left ventricular hypertrophy (LVH) is associated with a marked increase in risk for cardiovascular events [1–4]. Therefore, early identification of patients with LVH is a critical component of clinical risk-reduction strategies. The 12-lead surface ECG is a widely available, inexpensive, and noninvasive method, which is frequently used to assess the presence of LVH. A number of ECG-based methods for LVH assessment are available. The commonly used methods that implement sex-specific cut-points are the Cornell voltage index, Cornell voltage duration product, and Cornell/strain index criteria [5–7]. The Sokolow–Lyon index and Romhilt–Estes scores are also commonly used, but are sex neutral [8,9]. Less frequently utilized ECG criterion, such as Gubner–Ungerleider, has also been described [10]. The assessments produced by these methods have generally been validated by comparison with left ventricular mass (LVM) as measured at the time of autopsy and primarily compared with echocardiography-based measurements of LVM, with variable results [5,11–13]. This variability has been attributed to the effects of body habitus on ECG findings and has resulted in LVH cutoff values based on indexation using both body surface area (BSA) and height^{2.7} criteria [14–16].

With the increase in use of contrast-enhanced cardiac computed tomography (CT) in recent years, information on LVM is readily available for analysis without additional testing. Data are currently lacking on the diagnostic performance of ECG-based assessments of LVH against cardiac CT-based determination of LVH. In the ‘The Rule Out Myocardial Infarction Using Computer Assisted Tomography’ (ROMICAT) trial [17], we have a unique opportunity, wherein a large patient cohort had both ECG and cardiac CT acquired within the same day. This nearly simultaneous acquisition allows for direct comparison of ECG-based measurements of LVH to that by CT.

In this study, we aimed to determine the diagnostic performance of seven ECG-based LVH criteria against cardiac CT as the reference standard with two indexation criteria for LVH: a CT-specific BSA indexation [18] and the height^{2.7} criteria [15,16]. We also sought to determine the association of ECG LVH with that of CT LVH as well as the incremental predictive value of these ECG LVH criteria beyond that of history of hypertension for the detection of LVH by cardiac CT.

Methods

Study population

The ROMICAT trial was a prospective, observational cohort study of consecutive adult patients at low-to-intermediate likelihood of acute coronary syndrome who presented to the emergency department (ED) of a tertiary hospital with acute chest pain whose initial ECGs

and biomarkers were inconclusive and were awaiting hospital admission. Enrollment was cumulative for 18 months and ended in May 2007. The details of the study design and results have been previously reported [17]. Briefly, all eligible patients who consented had normal or inconclusive ECGs prior to having the ECG-gated, contrast-enhanced, 64-slice CT performed. Patients received standard of care for evaluation of acute coronary syndrome during index hospitalization and the results of the cardiac CT remained blinded to both caregivers and patients. Of note, patients must be in sinus rhythm and not have new diagnostic ECG changes such as ST-segment elevation or depression at least 1 mm, or T-wave inversion more than 4 mm in two or more anatomical contiguous leads. Our institutional review board approved the study protocol and all patients provided written informed consent.

In this substudy, we included patients who had both ECG and CT scans performed within 24 h. For patients with multiple ECGs, we used the ECG with closest temporal proximity to that of the CT scan. We excluded four patients whose ECGs were either atrial-paced or ventricular-paced, as well as 14 patients with left or right bundle branch block. We excluded 16 patients in whom we were unable to measure LVM at end-diastole on the multiphase reconstruction dataset due to poor quality (two), no multiphase available (six), or partially cutoff left ventricle (eight). One additional patient was excluded due to missing height, which is needed for the calculation of both CT LVH indexation using BSA and height^{2.7} criteria. A total of 333 patients in whom LVM could be measured on the multiphase reformatted dataset and in whom the ECG was available for review were included in our final analysis.

ECG measurements

Twelve-lead ECGs were recorded at 25 mm/s and 1 mV/cm standardization. ECG intervals were measured quantitatively by a single reader. These assessments were performed using an electronic caliper (Cardio Calipers; Iconico Inc., New York, New York, USA). Qualitative assessments of ECG readings were performed by consensus from two independent cardiologists with disagreement resolved by adjudication from a third cardiologist. All ECG readers were blinded to the CT imaging results. Table 1 outlines the seven ECG-based LVH algorithms that we used in our analyses and consists of the three sex-specific Cornell criteria (Cornell voltage index, Cornell voltage duration product, and Cornell/strain index) as well as the Sokolow–Lyon index, Gubner–Ungerleider criterion, Romhilt–Estes score of at least 5 (definite LVH), and Romhilt–Estes score of at least 4 (probable LVH) criteria.

Computed tomography data acquisition and measurement

A standard 64-slice coronary CT angiography protocol (Sensation 64; Siemens Medical Solutions, Forchheim, Germany) was used with acquisition at end inspiration and a test bolus protocol. The administration of sublingual nitroglycerin (0.6 mg) and intravenous β -blocker (metoprolol 5–20 mg) was done for those with the baseline heart rate more than 60 beats per minute and no other contraindications. CT images were acquired in spiral mode, gantry rotation time of 330 ms, 64×0.6 mm slice collimation, tube voltage of 120 kV, maximum effective tube current of 850 mA, and ECG-correlated tube current modulation used in 152 patients (46%). Transaxial images were reconstructed for 10 phases, each at 10% of the RR-interval, for the multiphase reformatted data-set with 1.5 mm slice thickness and 1.5 mm increments for the LVM analyses.

Two experienced readers, blinded to the ECG results, performed the quantitative CT measurements of LVM offline using a dedicated cardiac workstation (Vitrea software; Vital Images, Minnetonka, Minnesota, USA). LVM was derived by semi-automated delineation

with manual correction of the endocardial and epicardial borders at end-diastole, with exclusion of the papillary muscles. The cohort was also subdivided into two mutually exclusive groups: patient with LVH and those without LVH (Fig. 1). We used two separate criteria to determine the presence of LVH and performed analyses for each method separately. Using the recently described CT criterion indexed to BSA, LVH_{BSA} was defined as LVM/BSA_{CT} more than 89 g/m² for women and more than 103 g/m² for men [18]. Using the height^{2.7} criterion, where LVM was indexed to height^{2.7}, $LVH_{height^{2.7}}$ was defined as $LVM/height^{2.7}$ at least 47 g/m^{2.7} for women and at least 50 g/m^{2.7} for men [15,16].

Statistical analysis

Demographics, risk factors, medication history, and presenting vital signs were obtained during ED triage or at the time of the CT scan. Hypertension was defined as systolic blood pressure of at least 140 mmHg or diastolic blood pressure of at least 90 mmHg or current antihypertensive treatment. Descriptive statistics were expressed as mean $\pm$ SD for continuous variables and as frequency and percentages for nominal variables. The differences in means between groups were determined using Student's *t*-tests. In determining the diagnostic test characteristics of the seven ECG parameters of LVH against the CT reference standard for LVH, we calculated the sensitivity, specificity, accuracy, and test-positive, and test-negative likelihood ratios (LR+ and LR-). Comparisons between sensitivities of two tests and specificities of two tests were performed using McNemar's test. We used logistic regression to determine the association of the ECG LVH measures with CT-based LVH. Multivariable logistic regression models were adjusted for age and sex for all the ECG parameters, except for the Cornell criteria, which were adjusted for age only, as they inherently are stratified by sex. Hosmer and Lemeshow's goodness-of-fit test was tested for all the models and demonstrated good model fit. To evaluate the incremental predictive value of the ECG measurements for the detection of CT LVH beyond the risk factor of hypertension, we used logistic regression and compared the *C* statistic of nested models using the likelihood ratio test. Baseline model included hypertension only and subsequent models included the addition of the individual ECG criterion of LVH. The interobserver reproducibility for the ECG quantitative measures and LVM was determined for 20 randomly selected studies and assessed using intraclass correlation coefficient (ICC). The interobserver ICC ranged from 0.92 to 0.997 for all ECG quantitative measures. The interobserver ICC for LVM measurement by CT was 0.98. A two-tailed *P* value of less than 0.05 was considered to indicate statistical significance. All analyses were performed using SAS (Version 9.2; SAS Institute Inc., Cary, North Carolina, USA) and SPSS (Version 16.0; SPSS Inc., Chicago, Illinois, USA).

Results

Baseline characteristics in the Rule Out Myocardial Infarction Using Computer Assisted Tomography cohort

Table 2 depicts the baseline demographics of the 333 patients included in our analysis. The patients were predominantly nonblack (91%), 63% men, with a mean age of 53 years (range 21–86 years), average BMI of 29 kg/m², and normal estimated glomerular filtration rate (84.6 ml/min per 1.73 m²). The risk factor of hypertension was present in 40.2% of patients, with all but two patients being on antihypertensive medications (39.6%). During initial triage, the mean systolic blood pressure was 138 mmHg and the mean diastolic blood pressure was 80 mmHg.

ECG and computed tomography assessment of left ventricular hypertrophy and comparison of left ventricular mass and index

In this study cohort, the average LVM by CT was 148.4 ± 40.7 g. When indexed by BSA and height^{2.7}, LVM/BSA was 74.3 ± 16.7 g/m² and LVM/height^{2.7} was 35.2 ± 8.9 g/m^{2.7}. Using LVH_{BSA} criterion, 23 (6.9%) of patients had LVH, whereas using LVH_{Height}^{2.7} criterion, 24 (7.2%) had LVH.

Of the ECG criteria for LVH, 15 patients (5%) met criteria for ECG LVH with the Cornell voltage index criterion, 31 patients (9%) by the Cornell voltage duration product, 27 patients (8%) by the Cornell/strain index, 40 patients (12%) by Sokolow–Lyon index, 17 patients (5%) by Gubner–Ungerleider, and 13 patients (4%) had a Romhilt–Estes score at least 5 with 53 patients (16%) by the Romhilt–Estes score at least 4.

Table 3 depicts the differences in CT-based LVM, LVM indexed by BSA, and LVM indexed to height^{2.7} in patients with or without ECG LVH using the seven ECG parameters. For six of the ECG parameters, LVM was greater by 22.1–29.6 g in patients meeting the ECG LVH criteria (all $P \leq 0.04$), with the exception of Gubner–Ungerleider ($\Delta 3.1$ g, $P = 0.76$). When LVM is indexed to BSA, LVM/BSA was greater in patients by 11.0–16.9 g/m² for five of the ECG parameters (all $P < 0.05$), trended to be greater by 14.9 g/m² in those meeting the Cornell voltage index criterion ($P = 0.06$) and had no difference between patients with presence or absence of the Gubner–Ungerleider criterion ($\Delta 1.5$ g/m², $P = 0.71$). For the LVM indexation by height^{2.7}, LVM/height^{2.7} was greater in patients meeting the Cornell voltage index, Cornell voltage duration product, Sokolow–Lyon index, and Romhilt–Estes score at least 4 criteria ($\Delta 4.6$ – 8.1 g/m^{2.7}, all $P \leq 0.04$), but not significantly different between patients with or without LVH by the Gubner–Ungerleider or Romhilt–Estes score at least 5 criteria (all $P > 0.16$). Although the ECG criterion that exhibits the greatest difference in LVM or LVM index is variable, irrespective of whether LVM or the LVM indexation used, there was consistently no significant difference seen in LVM or either LVM index with the Gubner–Ungerleider criterion (all $P > 0.41$).

Diagnostic test performance of ECG as compared to computed tomography for left ventricular hypertrophy

Table 4 summarizes the diagnostic test characteristics of the seven ECG LVH criteria as compared to the CT definitions of LVH by BSA and height^{2.7}. Overall, there were high specificities (ranging from 85 to 97%), whereas the sensitivities were less impressive and varied considerably among the ECG criteria (ranging from 4 to 43%).

Regardless of CT indexation criteria, the ECG criterion with the best overall magnitude of test-positive likelihood ratio was the three Cornell-based criteria (LR+ of 4.5–6.7), with similar magnitudes for the Sokolow–Lyon index and either Romhilt–Estes scores (LR+ of 2.3–4.0). As expected, due to the low sensitivity of these ECG parameters, the test-negative likelihood ratio ranged from 0.6 to 1.0. Notably, the Gubner–Ungerleider criterion performed poorly and had a LR+ of 0.8 and LR– of 1.0 for both CT indexation criteria for LVH.

Using either CT indexation method, when we compared the two best performing ECG criteria of the Cornell voltage index vs. the Cornell/strain index, there was slightly improved specificity (LVH_{BSA}: 97 vs. 94%, $P = 0.005$; LVH_{height}^{2.7}: 96 vs. 94%, $P = 0.005$) at the expense of lower sensitivity (LVH_{BSA}: 22 vs. 39%, $P = 0.046$; LVH_{height}^{2.7}: 17 vs. 33%, $P = 0.046$). As expected, the sensitivity was higher for the Romhilt–Estes score at least 4 when compared to Romhilt–Estes score at least 5 (LVH_{BSA}: 43 vs. 13%, $P = 0.008$; LVH_{height}^{2.7}: 33 vs. 8%, $P = 0.01$), whereas the Romhilt–Estes score at least 5 had better specificity than

Romhilt–Estes score at least 4 (LVH_{BSA}: 97 vs. 86%, $P < 0.0001$; LVH_{height^{2.7}}: 96 vs. 85%, $P < 0.0001$).

Association and predictive value of ECG as compared to computed tomography for left ventricular hypertrophy

Table 5 shows the unadjusted and adjusted analyses for the association of the ECG measures of LVH with CT-based LVH. Patients with the presence of LVH by the ECG criterion of Cornell voltage index, Cornell voltage duration product, or Cornell/strain index had the greatest magnitude of effect with a 5–10-fold increased odds of having LVH by either CT indexation criteria [LVH_{BSA}: odds ratio (OR) 8.3–10.4, $P \leq 0.0004$; LVH_{height^{2.7}}: OR 5.4–7.6, $P \leq 0.007$]. For both these sex-specific criteria, the effect size persisted even after age adjustment (LVH_{BSA}: adjusted OR 7.7–9.5, $P \leq 0.0006$; LVH_{height^{2.7}}: adjusted OR 5.2–6.8, $P \leq 0.01$). The risks of patients with the presence of Sokolow–Lyon or either Romhilt–Estes at least 5 or at least 4 scores were similar, with a 4–5-fold increase in risk of having LVH by CT indexation of BSA when unadjusted (OR 4.5–4.8, all $P \leq 0.03$) and when adjusted for age and sex (OR 4.3–5.4, all $P \leq 0.02$). Interestingly, when using the CT indexation criteria of height^{2.7}, the presence of Romhilt–Estes at least 4 score carried a near three-fold risk for CT LVH for both unadjusted (OR 2.9, $P = 0.02$) and adjusted (OR 2.8, $P = 0.03$) models, whereas the Sokolow–Lyon and Romhilt–Estes at least 5 scores were not significantly associated with LVH_{height^{2.7}} (all $P \geq 0.10$). Regardless of the CT indexation criteria used, the presence of LVH by the Gubner–Ungerleider criterion was not associated with CT-based LVH (all $P > 0.83$).

Table 6 depicts the incremental predictive value of the individual ECG criterion of LVH beyond that of the risk factor of hypertension. The predictive value for detecting LVH_{BSA} with hypertension alone significantly improved when any of the ECG criteria was added (C statistic improved from 0.63 to 0.68–0.75, all $P < 0.05$) with the exception for the Gubner–Ungerleider criterion ($P = 0.75$). The greatest incremental value was seen with the addition of the Romhilt–Estes at least 4 score (C statistic improved to 0.75, $P = 0.001$), followed by the Cornell/strain index (C statistic improved to 0.73, $P < 0.0001$). In addition, the predictive value for detecting LVH_{height^{2.7}} with hypertension (C statistic 0.76) was most improved with the addition of the Cornell/strain index (C statistic improved to 0.81, $P = 0.002$). For detection of CT-based LVH with either indexation methods, there was no incremental value when adding the Gubner–Ungerleider criterion to hypertension. Furthermore, for the detection of LVH_{height^{2.7}}, the ECG criteria of Sokolow–Lyon index and Romhilt–Estes at least 5 score provided no significant incremental predictive value beyond that of hypertension (both $P > 0.13$).

Discussion

In our study consisting of a large number of 333 patients, we examined seven ECG-based LVH criteria against two CT indexation criteria for LVH: a recently described CT-specific BSA cutoff [18] and the obesity-independent height^{2.7} criteria [15,16]. Of the seven ECG criteria, we found that the three sex-specific Cornell-based criteria had consistently the overall best diagnostic performance for detecting CT-based LVH, followed by the Sokolow–Lyon index and either Romhilt–Estes scores of at least 5 or at least 4, which had comparable performance. In addition, there was incremental predictive value beyond the risk factor of hypertension for six ECG criteria for the detection of CT LVH_{BSA}, but only four ECG criteria (Cornell/strain index, Cornell voltage duration product, Cornell voltage index, and Romhilt–Estes score of at least 4) for the detection of CT LVH_{height^{2.7}}. The less known ECG parameter of Gubner–Ungerleider criterion performed poorly and constantly showed no association with CT-based LVH or incremental predictive value for the detection of LVH beyond that of hypertension.

Cardiac CT is a state-of-the-art technology that provides an accurate noninvasive method to quantify cardiac chamber size, allowing for reliable LVM calculation [19]. The advantage of our methodology is the near-simultaneous measurement of ECG and CT to determine LVH, as both tests were performed within 24 h of one another. Overall, the ECG parameters in our study had high specificities (85–97%) and variable low sensitivities (4–43%) when compared to either CT criteria of LVH. Our values are comparable to those reported in the literature based on autopsy and echocardiography studies, in which the ECG assessments of LVH using the various algorithms are highly specific, yet the sensitivity was suboptimal not exceeding 45% [5,12,20–25]. Similar to an extensive autopsy series in which the sensitivity of the Cornell voltage duration product was higher than the Cornell voltage index measurement alone [6], we found significant differences in results with higher sensitivities of 33–39% for the Cornell voltage duration product vs. 17–22% for the Cornell voltage index, depending on the CT indexation of LVH used. Our comparable results in sensitivities and specificities as compared with autopsy and other imaging modalities further provide support for LVM and LVH assessment with cardiac CT.

The test-positive and test-negative likelihood ratios of these ECG criteria for detecting CT-based LVH are a direct reflection of the high specificities and low sensitivities of these ECG criteria. Whereas there was slight attenuation in the diagnostic test characteristics of the ECG LVH parameters when comparing to the CT indexation criteria of height^{2.7} over BSA, the pattern of the ECG test performance was consistent. With the exception of the Gubner–Ungerleider criterion, six out of the seven ECG LVH criteria had favorable test characteristic likelihood ratio profiles. The presence of any of the sex-specific Cornell-based criteria had the greatest magnitude in test-positive likelihood ratios (LR+ ranged from 4.5 to 6.7) for CT-based LVH, followed by the Sokolow–Lyon index and Romhilt–Estes scores of at least 5 or at least 4 for CT-based LVH which had similar ranges for test-positive likelihood ratios (LR+ ranged from 2.3 to 4.0). Not surprisingly, due to the low sensitivity, the test-negative likelihood ratios of the ECG criteria did not vary greatly and ranged from 0.6 to 1.0. Interestingly, the Gubner–Ungerleider system consistently failed to show a statistically significant association with CT-based LVH and even had an inverse likelihood ratio test profile.

Similar to other imaging modalities, including echocardiography [26–29] and cardiac magnetic resonance imaging [30], we found significant association for six out of the seven ECG LVH criteria for the detection of CT-based LVH, with the Gubner–Ungerleider criterion being the one without association. Moreover, in our cohort wherein 40% of patients had a history of hypertension, there was incremental predictive value for the detection of LVH on CT with the addition of the individual ECG criterion beyond that of the risk factor of hypertension. Regardless of the CT indexation methods, the Gubner–Ungerleiden criterion did not provide incremental value beyond the history of hypertension. Although the ECG criteria of Sokolow–Lyon index and Romhilt–Estes at least 5 score provided no significant incremental predictive value beyond history of hypertension when using the indexation of height^{2.7}, both these criteria were incrementally predictive when using the CT-specific BSA cutoff values. One potential explanation for the discrepancy is that despite using the obesity-independent cutoff values described for height^{2.7}, these cutoff values were originally validated for echocardiography studies [15,16] and not specifically for CT. Thus, there may be a need for a separate obesity-independent CT-specific height^{2.7} cutoff value for defining LVH.

The presence of Cornell/strain index criterion places patients at an almost two-fold risk for cardiovascular events even after adjustment for risk factors and has been used to determine interim development of LVH in high-risk patients on antihypertensive therapy [7,31]. Those meeting the Cornell voltage duration product criteria for LVH had further progression and

development of LVH [32] and higher cardiovascular mortality and future cardiac events [33]. In addition, for patients meeting the Cornell voltage index, Cornell voltage duration product, or Sokolow–Lyon criteria, there is a higher increase in risk of ischemic stroke [33,34]. In patients treated for hypertension, those with a lower Cornell voltage duration product and Sokolow–Lyon voltage have a lower likelihood of cardiovascular morbidity and mortality, independent of blood pressure-lowering and treatment modality [35]. Thus, our findings that six out of the seven ECG criteria demonstrated excellent test profiles for the detection of CT-based LVH and should be used to guide clinicians to treat patients meeting these ECG criteria more aggressively with antihypertensive medications. Conversely, clinicians may choose to avoid the Gubner–Ungerleider method, given its suboptimal test profile and lack of association with CT-based LVH.

Study limitations

Several limitations are noteworthy in our study. This is a substudy of the ROMICAT trial, which consists of ED chest pain patients with low-to-intermediate risk for acute coronary syndrome and predominantly nonblack race. Thus, the generalizability of our results may be limited to this patient population. Although the percentage of patients with CT-based LVH was small (7%) in our cohort wherein 40% of patients had a history of hypertension, this disparity is likely due to the high percentage of patients (39%) who were on an antihypertensive medical regimen at the time of study enrollment, which may retard the progression of myocardial hypertrophy. However, test characteristics such as sensitivity, specificity, and the likelihood ratios should not be affected by the prevalence of disease. The radiation exposure inherent in the acquisition of CT images should preclude cardiac CT from being performed solely for the evaluation of LVM. We were able to perform our analysis, as our CT acquisitions were performed primarily for coronary artery analysis with retrospective gating, providing us with data to evaluate at end-diastole. The use of dose-saving algorithms, such as ECG tube modulation and use of lower tube current and voltage, could still allow assessment of the LVM measurements at end-diastole.

In conclusion, with the exception of the Gubner–Ungerleider criterion, these ECG criteria have favorable test profiles due to their high specificity and test-positive likelihood ratios when compared to the reference standard of cardiac CT, were associated with CT-based LVH, and had incremental predictive value for detecting CT-based LVH beyond that of history of hypertension. Of these ECG criteria, the three Cornell-based criteria provided the best test performance for identifying patients with LVH.

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Abbreviations

BSA	body surface area
CAD	coronary artery disease
CT	computed tomography
ED	emergency department

eGFR	estimated glomerular filtration rate
ICC	intraclass correlation coefficient
LVH	left ventricular hypertrophy
LVM	left ventricular mass

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Fig. 1. Cardiac computed tomography images in a patient without computed tomography-based left ventricular hypertrophy in the short-axis (a) and four-chamber views (b) and meeting none of the seven ECG criteria for left ventricular hypertrophy. Short-axis (c) and four-chamber views (d) from a patient with computed tomography-based left ventricular hypertrophy (LVH) by both indexation method and meeting the six of the seven ECG criteria for LVH except for Gubner–Ungerleider criterion.

Table 1

Definitions for ECG measures of left ventricular hypertrophy

ECG criteria name	Definition of ECG criteria
Cornell voltage index	Sum of R in aVL and S in V ₃ > 28 mm (men) or 20 mm (women)
Cornell voltage duration product	[Sum of R + S + (8 mm for women)] × QRS duration >2440 ms × mm
Cornell/strain (C/S) index	Sum of R in aVL + S in V ₃ >24 mm (men) or 20 mm (women); ST changes typical of strain pattern
Sokolow–Lyon index	R wave height >26 mm Sum of S in V ₁ and R in V ₅ divided by R in V ₆ ≥ 35 mm aVL ≥ 11 mm
Gubner–Ungerleider	R in lead I + S in lead III >25 mm
Romhilt–Estes score of ≥4 (probable LVH)	Sum of the following: 3 points for P terminal force in V ₁ >1 mm in depth with a duration of ≥40 ms 1 point if the interval between the QRS and peak of R wave in V ₅ or V ₆ is ≥50 ms 1 point if QRS duration ≥90 ms 3 points if any one of the following: R or S in limb leads is ≥20 mm; S in V ₁ or V ₂ ≥30 mm; R in V ₅ or V ₆ ≥30 mm 3 points if exhibits ST changes typical of LVH while not taking digitalis or 1 point if taking digitalis 2 points for left axis deviation of > −30°
Romhilt–Estes score of ≥5 (definite LVH)	

LVH, left ventricular hypertrophy.

Table 2

Demographics of the study group

Demographics	(n = 333)
Age (years)	52.9 ± 11.7
Men	209 (62.8%)
Race, black	30 (9.0%)
BSA (m ²)	1.99 ± 0.26
BMI (kg/m ²)	29.0 ± 5.86
Risk factors	
Hypertension	134 (40.2%)
Diabetes mellitus	34 (10.2%)
Hyperlipidemia	136 (40.8%)
History of CAD	37 (11.1%)
Smoking	177 (53.2%)
Medications	
Hypertensive medication	132 (39.6%)
β-Blockers	82 (24.6%)
ACE-I	53 (15.9%)
Nitrates	18 (5.4%)
Presenting characteristics	
SBP (mmHg)	138.2 ± 22.7
DBP (mmHg)	80.0 ± 13.5
HR of ECG (beats/min)	69.5 ± 14.2
HR during CT scan (beats/min)	65.1 ± 11.7
eGFR, ml/min/1.73 m ²	84.6 ± 17.6

ACE-I, angiotensin-converting enzyme inhibitor; BSA, body surface area; CAD, coronary artery disease; CT, computed tomography; eGFR, estimated glomerular filtration rate; HR, heart rate; LV, left ventricular.

Table 3

Comparison of computed tomography-measured left ventricular mass and left ventricular mass index in patients with and without ECG criteria for left ventricular hypertrophy

ECG LVH criteria	LVM	P	LVM/BSA	P	LVM/height ^{2,7}	P
Cornell voltage index						
Present	169.5 ± 52.8	0.04	88.5 ± 28.4	0.06	42.8 ± 13.5	0.04
Absent	147.4 ± 39.8		73.6 ± 16.5		34.8 ± 8.6	
Cornell voltage duration product						
Present	168.0 ± 53.0	0.03	85.0 ± 26.1	0.02	41.2 ± 12.6	0.007
Absent	146.4 ± 38.7		73.2 ± 15.1		34.5 ± 8.3	
Cornell/strain index						
Present	175.6 ± 52.9	0.008	89.8 ± 26.1	0.003	42.6 ± 13.3	0.004
Absent	146.0 ± 38.6		72.9 ± 14.9		34.5 ± 8.2	
Sokolow-Lyon index						
Present	169.6 ± 46.5	0.0004	83.9 ± 32.9	0.007	39.7 ± 11.8	0.01
Absent	145.5 ± 39.0		73.0 ± 15.1		34.5 ± 8.3	
Gubner-Ungerleider						
Present	151.4 ± 39.2	0.76	75.7 ± 17.5	0.71	36.9 ± 8.0	0.41
Absent	148.2 ± 40.8		74.2 ± 16.7		35.1 ± 9.0	
Romhilt-Estes score ≥5						
Present	176.4 ± 52.6	0.01	89.1 ± 24.8	0.045	40.2 ± 12.5	0.16
Absent	147.2 ± 39.8		73.7 ± 16.1		35.0 ± 8.8	
Romhilt-Estes score ≥4						
Present	172.0 ± 45.8	<0.0001	84.3 ± 20.6	0.0002	39.0 ± 10.6	0.004
Absent	143.9 ± 38.1		72.4 ± 15.2		34.4 ± 8.5	

BSA, body surface area; LVH, left ventricular hypertrophy; LVM, left ventricular mass; LVM/BSA, left ventricular mass index by BSA; LVM/height^{2,7}, left ventricular mass index by height^{2,7}.

Table 4

Diagnostic test characteristics of seven electrocardiographic measures of left ventricular hypertrophy as compared to computed tomography-based left ventricular hypertrophy

	Sensitivity	Specificity	Accuracy	LR+	LR-
L_{VH}_{BSA}					
Cornell voltage index	22% (5/23)	97% (300/310)	92% (305/333)	6.7	0.8
Cornell voltage duration product	39% (9/23)	92% (288/310)	89% (297/333)	5.5	0.7
Cornell/strain index	39% (9/23)	94% (292/310)	90% (301/333)	6.7	0.6
Sokolow-Lyon index	35% (8/23)	90% (278/310)	86% (286/333)	3.4	0.7
Gubner-Ungerleider	4% (1/23)	95% (294/310)	89% (295/333)	0.8	1.0
Ronhilt-Estes score ≥ 5	13% (3/23)	97% (300/310)	91% (303/333)	4.0	0.9
Ronhilt-Estes score ≥ 4	43% (10/23)	86% (267/310)	83% (277/333)	3.1	0.7
L_{VH}_{height}^{2,7}					
Cornell voltage index	17% (4/24)	96% (298/309)	91% (302/333)	4.7	0.9
Cornell voltage duration product	33% (8/24)	93% (286/309)	88% (294/333)	4.5	0.7
Cornell/strain index	33% (8/24)	94% (290/309)	89% (298/333)	5.4	0.7
Sokolow-Lyon index	25% (6/24)	89% (275/309)	84% (281/333)	2.3	0.8
Gubner-Ungerleider	4% (1/24)	95% (293/309)	88% (294/333)	0.8	1.0
Ronhilt-Estes score ≥ 5	8% (2/24)	96% (298/309)	90% (300/333)	2.3	1.0
Ronhilt-Estes score ≥ 4	33% (8/24)	85% (264/309)	82% (272/333)	2.3	0.8

L_{VH}, left ventricular hypertrophy; LR+, likelihood ratio of a positive test; LR-, likelihood ratio of a negative test.

Table 5

Association of ECG measures of left ventricular hypertrophy as compared to computed tomography-based left ventricular hypertrophy

	Unadjusted OR (95%CI)	P	Adjusted model ^a OR (95%CI)	P
LVH _{BSA}				
Cornell voltage index	8.3 (2.6–27.0)	0.0004	8.1 (2.5–26.7)	0.0006
Cornell voltage duration product	8.4 (3.3–21.6)	<0.0001	7.7 (3.0–20.1)	<0.0001
Cornell/strain index	10.4 (4.0–27.3)	<0.0001	9.5 (3.6–25.2)	<0.0001
Sokolow–Lyon index	4.6 (1.8–11.8)	0.001	4.3 (1.7–11.1)	0.003
Gubner–Ungerleider	0.8 (0.1–6.6)	0.86	0.9 (0.1–7.1)	0.91
Romhilt–Estes score ≥5	4.5 (1.1–17.7)	0.03	5.4 (1.3–22.4)	0.02
Romhilt–Estes score ≥4	4.8 (2.0–11.6)	0.0005	4.9 (1.9–12.6)	0.0008
LVH _{height2.7}				
Cornell voltage index	5.4 (1.6–18.5)	0.007	5.2 (1.5–18.2)	0.01
Cornell voltage duration product	6.2 (2.4–16.1)	0.0002	5.6 (2.1–14.7)	0.0005
Cornell/strain index	7.6 (2.9–20.1)	<0.0001	6.8 (2.5–18.2)	<0.0001
Sokolow–Lyon index	2.7 (1.0–7.3)	0.05	2.4 (0.9–6.6)	0.10
Gubner–Ungerleider	0.8 (0.1–6.3)	0.83	0.9 (0.1–6.9)	0.89
Romhilt–Estes score ≥5	2.5 (0.5–11.8)	0.26	2.8 (0.6–14.1)	0.21
Romhilt–Estes score ≥4	2.9 (1.2–7.3)	0.02	2.8 (1.1–7.2)	0.03

CI, confidence interval; LVH, left ventricular hypertrophy; OR, odds ratio.

^a Multivariable models were adjusted for age and sex, except for the sex-specific Cornell voltage index, Cornell voltage duration product, and Cornell/strain index, which were adjusted for age only.

Table 6

Incremental predictive value of ECG left ventricular hypertrophy parameters beyond history of hypertension for predicting computed tomography-based left ventricular hypertrophy

	−2 log likelihood	Δ−2 log likelihood	C statistic	P
LVH_{BSA}				
HTN	161.0	(Reference)	0.63	–
HTN + Cornell voltage index	152.5	8.5	0.70	0.004
HTN + Cornell voltage duration product	147.0	14.0	0.72	0.0002
HTN + Cornell/strain index	144.7	16.3	0.73	<0.0001
HTN + Sokolow–Lyon index	153.1	7.9	0.69	0.005
HTN + Gubner–Ungerleider	160.9	0.1	0.64	0.75
HTN + Romhilt–Estes score ≥5	157.2	3.85	0.68	0.0497
HTN + Romhilt–Estes score ≥4	150.8	10.2	0.75	0.001
LVH_{height2.7}				
HTN	147.5	(Reference)	0.76	–
HTN + Cornell voltage index	143.5	4.0	0.78	0.046
HTN + Cornell voltage duration product	139.4	8.0	0.80	0.005
HTN + Cornell/strain index	137.7	9.8	0.81	0.002
HTN + Sokolow–Lyon index	145.2	2.3	0.78	0.13
HTN + Gubner–Ungerleider	147.2	0.3	0.76	0.61
HTN + Romhilt–Estes score ≥5	146.2	1.3	0.77	0.26
HTN + Romhilt–Estes score ≥4	143.3	4.2	0.79	0.04

HTN, hypertension; LVH, left ventricular hypertrophy.