Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 09 July 2026
Revised 20 Aug 2026
Accepted 07 Sep 2026

Natural Resources for Human Health 2026, Vol. 6 (20s): 1144–1154

KEYWORDS:
Electrocardiography; Hypertension; Hypertrophy, Left Ventricular; Sensitivity and Specificity; Ventricular Remodeling.

Comparison of Four Electrocardiographic Criteria for Detecting Left Ventricular Hypertrophy in Uncomplicated Hypertension: A Cross-Sectional Study

Lilycia Elisabeth Limbong[1], Muzakkir Amir[1], Abdul Hakim Alkatiri[1], Aussie Fitriani Ghaznawie[1], Az Hafid Nashar[1], Andi Alfian Zainuddin[2]

[1]Department of Cardiology and Vascular Medicine, Faculty of Medicine, Hasanuddin University, Makassar, Indonesia
[2]Department of Public Health and Community Medicine, Faculty of Medicine, Hasanuddin University, Makassar, Indonesia
Corresponding Author*: Lilycia Elisabeth Limbong, MD. Department of Cardiology and Vascular Medicine, Faculty of Medicine, Hasanuddin University, Makassar, Indonesia. Perintis Kemerdekaan Street Km. 11, Tamanlarea, Makassar City, South Sulawesi, Indonesia. Telp.: +6281231810279. E-mail: ciaelisabeth@gmail.com.

ABSTRACT: Electrocardiography (ECG) is widely used to screen for left ventricular hypertrophy (LVH), but its diagnostic performance varies across criteria. This cross-sectional diagnostic accuracy study compared the Cornell Product, Sokolow–Lyon, Romhilt–Estes, and Peguero–Lo Presti criteria against transthoracic echocardiography in 150 adults with uncomplicated hypertension. Left ventricular geometry was classified according to American Society of Echocardiography recommendations, and diagnostic performance was assessed using sensitivity, specificity, predictive values, and receiver operating characteristic (ROC) analysis with 95% confidence intervals (CIs). Concentric hypertrophy was the predominant pattern (51.3%). Only Romhilt–Estes and Sokolow–Lyon were significantly associated with echocardiographic LVH ($p < 0.001$ and $p = 0.023$). At conventional thresholds, all criteria showed low sensitivity (12.9%–33.3%) but high specificity (84.2%–94.7%). In ROC analysis, Peguero–Lo Presti achieved the highest, albeit modest, discrimination (AUC 0.680, 95% CI 0.566–0.793; sensitivity 78.8%), whereas Sokolow–Lyon showed the highest specificity (88.4%), with substantially overlapping CIs across criteria. ECG may serve as a practical first-line screening tool, but its modest accuracy does not permit definitive diagnosis or exclusion of LVH; echocardiography remains required for confirmation and assessment of left ventricular geometry.

1. INTRODUCTION

Hypertension remains one of the leading causes of premature death worldwide, affecting approximately 1.39 billion adults and accounting for more than 10 million deaths annually through cardiovascular and renal complications [1]. In Indonesia, the prevalence of hypertension among adults increased from 25.8% in 2013 to 34.1% in 2018, highlighting its growing public health burden [2]. Persistent elevation of blood pressure induces hypertension-mediated organ damage (HMOD), characterized by structural and functional alterations in multiple target organs, including the heart, brain, kidneys, retina, and vasculature [1]. Among these manifestations, left ventricular hypertrophy (LVH) represents one of the earliest cardiac adaptations to chronic pressure overload and is an independent predictor of heart failure, ischemic heart disease, arrhythmias, stroke, and

cardiovascular mortality [3]. Chronic hemodynamic stress promotes distinct patterns of left ventricular (LV) remodeling, making accurate identification of LV geometry clinically important for cardiovascular risk stratification [4].

Twelve-lead electrocardiography (ECG) remains the most accessible and cost-effective screening tool for detecting LVH despite its limited sensitivity compared with cardiac imaging [5]. Several ECG criteria have been proposed for the detection of LVH, including the Cornell Product, Sokolow–Lyon voltage, Romhilt–Estes score, and the recently introduced Peguero–Lo Presti criterion [6–8,11]. The Cornell Product incorporates QRS duration and sex-specific voltage thresholds, whereas Sokolow–Lyon and Romhilt–Estes remain widely used because of their simplicity and long-standing clinical validation. More recently, the Peguero–Lo Presti criterion has shown improved sensitivity in several validation studies, although its performance varies across populations [8,12,13].

Echocardiography is considered the reference method for evaluating LVH because it enables detailed assessment of left ventricular mass (LVM) and relative wall thickness (RWT), allowing classification of normal geometry, concentric remodeling, concentric LVH, and eccentric LVH. These geometric patterns have distinct prognostic implications and are closely associated with long-term cardiovascular morbidity and mortality in patients with hypertension [5]. However, evidence directly comparing the diagnostic performance of the Cornell Product, Sokolow–Lyon, Romhilt–Estes, and Peguero–Lo Presti criteria using echocardiographic LV geometry as the reference standard remains limited, particularly among patients with uncomplicated hypertension. In addition, the diagnostic accuracy of these ECG criteria has not been adequately evaluated in Indonesian hypertensive populations without established target-organ complications. Therefore, this study aimed to compare the diagnostic accuracy of four ECG criteria for detecting LVH against echocardiographic left ventricular geometry in patients with uncomplicated hypertension.

2. MATERIALS AND METHODS

2.1 Study Design and Setting

This diagnostic accuracy study employed a cross-sectional observational design. The study was conducted at the Integrated Cardiac Center Outpatient Clinic of Dr. Wahidin Sudirohusodo Hospital, Makassar, Indonesia, from January through July 2026. Consecutive eligible patients attending the outpatient clinic during the study period underwent standard 12-lead electrocardiography and transthoracic echocardiography.

2.2 Study Population

Adult patients aged 18–65 years with uncomplicated hypertension were consecutively recruited. Hypertension was defined as systolic blood pressure ≥140 mmHg and/or diastolic blood pressure ≥90 mmHg confirmed on at least two outpatient visits in previously undiagnosed individuals, a documented history of hypertension for at least four weeks, or current use of antihypertensive medication regardless of blood pressure control.

Patients were excluded if they were professional athletes, pregnant, had inadequate electrocardiographic recordings or poor echocardiographic windows, atrioventricular conduction abnormalities requiring permanent pacing or complete atrioventricular block, right or left bundle branch block, right ventricular hypertrophy, moderate-to-severe valvular heart disease, congenital heart disease, pulmonary arterial hypertension, or established hypertension-related complications including symptomatic heart failure (New York Heart Association class III–IV), ischemic heart disease, stage 4–5 chronic kidney disease (estimated glomerular filtration rate <30 mL/min/1.73 m^2), or previous stroke. The minimum required sample size was calculated using OpenEpi based on Fleiss' formula for diagnostic studies, yielding a minimum of 84 participants. Ultimately, 150 patients fulfilling all eligibility criteria were included in the final analysis.

2.3 Electrocardiographic Assessment

Standard resting 12-lead electrocardiograms were recorded at a paper speed of 25 mm/s and a calibration of 10 mm/mV. Four established electrocardiographic criteria for left ventricular hypertrophy were evaluated independently: Cornell Product, Sokolow–Lyon voltage, Romhilt–Estes score, and Peguero–Lo Presti criterion. Cornell Product was considered positive when the product of Cornell voltage and QRS duration exceeded 2440 mm·ms. Sokolow–Lyon voltage was defined as the sum of the S-wave amplitude in lead V1 and the R-wave amplitude in lead V5 or V6 exceeding 35 mm. A Romhilt–Estes score of ≥5 was considered diagnostic for left ventricular hypertrophy. The Peguero–Lo Presti criterion was considered positive when the sum of the deepest S wave and the S wave in lead V4 was ≥2.8 mV in men or ≥2.3 mV in women.

2.4 Echocardiographic Assessment

All participants underwent transthoracic echocardiography according to the recommendations of the American Society of Echocardiography. Left ventricular internal diameter in diastole, interventricular septal thickness in diastole, and posterior wall thickness in diastole were measured using M-mode imaging. Left ventricular mass was calculated using the ASE-recommended formula and indexed to body surface area to obtain the left ventricular mass index.

Left ventricular hypertrophy was defined as a left ventricular mass index >115 g/m² in men or >95 g/m² in women. Relative wall thickness was calculated as twice the posterior wall thickness divided by the left ventricular internal diameter in diastole. Left ventricular geometry was classified into four categories: normal geometry, concentric remodeling, concentric hypertrophy, and eccentric hypertrophy according to the combination of left ventricular mass index and relative wall thickness using the recommended threshold of 0.42.

2.5 Outcome Measures

The primary outcome was the diagnostic accuracy of the four electrocardiographic criteria for identifying left ventricular hypertrophy using echocardiographic left ventricular geometry as the reference standard. Diagnostic performance was evaluated by calculating sensitivity, specificity, positive predictive value, negative predictive value, overall accuracy, and receiver operating characteristic curves with corresponding areas under the curve.

2.6 Statistical Analysis

Continuous variables were assessed for normality and are presented as mean ± standard deviation or median (interquartile range), as appropriate. Categorical variables are expressed as frequencies and percentages. Comparisons between two groups were performed using the independent-samples t-test or Mann–Whitney U test for continuous variables and the chi-square or Fisher's exact test for categorical variables, as appropriate. Comparisons across the four left ventricular geometric-pattern groups were performed using the Kruskal–Wallis test for continuous variables and the Pearson chi-square test for categorical variables. Diagnostic accuracy at the conventional threshold of each criterion was derived from 2 × 2 contingency tables against echocardiographic LVH and expressed as sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), overall accuracy, and positive and negative likelihood ratios (LR+ and LR−); 95% confidence intervals (CIs) for these proportions were calculated using the Wilson score method. For the Romhilt–Estes score, only a score of ≥5 points was considered positive, and probable LVH (4 points) was classified as negative. Discriminatory performance across the full range of values was evaluated using receiver operating characteristic analysis, with areas under the curve (AUCs) and their 95% CIs, and the optimal cut-off value for each criterion was identified using the maximum Youden index. Because AUC-based and threshold-based measures address different questions, both were reported, and differences among criteria were interpreted in light of their CIs. Statistical analyses were performed using IBM SPSS Statistics version 26 (IBM Corp., Armonk, NY, USA). A two-sided P value <0.05 was considered statistically significant.

3. RESULTS AND DISCUSSION

3.1 Baseline characteristics

A total of 150 patients with uncomplicated hypertension were included in the analysis. The mean age was 57.76 ± 13.11 years, with an equal distribution of men and women (50% each). Mean body mass index was 23.12 ± 3.11 kg/m², and 84% had a history of hypertension. The mean systolic and diastolic blood pressures were 145.88 ± 17.82 mmHg and 85.73 ± 10.26 mmHg, respectively. Concentric LVH was the most frequent geometric pattern (51.3%; 77/150), followed by normal geometry (31.3%), eccentric LVH (10.7%), and concentric remodeling (6.7%). Only 14.0% of participants fulfilled the conventional Peguero–Lo Presti criterion for ECG-defined LVH (Table 1).

Comparison across LV geometric patterns demonstrated significant differences in age (p = 0.012) and duration of hypertension (p = 0.003), with concentric and eccentric LVH occurring more frequently among older individuals and those with longer-standing hypertension. No significant differences were observed for sex, body mass index, ethnicity, hypertension history, or systolic and diastolic blood pressure (Table 2).

3.2 Association between ECG criteria and echocardiographic LVH

Among the four ECG criteria, only Romhilt–Estes and Sokolow–Lyon were significantly associated with echocardiographic LVH ($p < 0.001$ and $p = 0.023$, respectively), whereas Peguero–Lo Presti and Cornell Product were not ($p = 0.621$ and $p = 0.192$, respectively). Positive Romhilt–Estes findings were substantially more frequent in patients with LVH than in those without (33.3% vs. 5.3%), while Sokolow–Lyon positivity was also more common among patients with LVH (30.4% vs. 14.0%) (Table 3).

When diagnostic accuracy was quantified at the conventional thresholds, all four criteria showed low sensitivity, ranging from 12.9% (95% CI 7.5%–21.2%) for Peguero–Lo Presti to 33.3% (95% CI 24.6%–43.4%) for Romhilt–Estes, whereas specificity was consistently high, ranging from 84.2% (95% CI 72.6%–91.5%) for Peguero–Lo Presti to 94.7% (95% CI 85.6%–98.2%) for Romhilt–Estes. Romhilt–Estes yielded the highest PPV (91.2%) and LR+ (6.33), whereas NPVs were low for all criteria (37.2%–46.6%), indicating that a negative ECG did not reliably exclude echocardiographic LVH (Table 4).

Table 1. Baseline characteristics of study participants (n = 150).

Characteristic	Value
Age, years	57.76 ± 13.11
Men / women	75 (50.0) / 75 (50.0)
Body mass index, kg/m²	23.12 ± 3.11
History of hypertension	126 (84.0)
Systolic blood pressure, mmHg	145.88 ± 17.82
Diastolic blood pressure, mmHg	85.73 ± 10.26
Echocardiographic LVH	93 (62.0)
Normal geometry	47 (31.3)
Concentric remodeling	10 (6.7)
Concentric LVH	77 (51.3)
Eccentric LVH	16 (10.7)
Peguero–Lo Presti positive (conventional threshold)	21 (14.0)

Table 2. Baseline characteristics by left ventricular geometric pattern.

Variable	Normal (n=47)	Concentric remodeling (n=10)	Concentric LVH (n=77)	Eccentric LVH (n=16)	P value
Age, years[a]	52.91 ± 12.78	58.40 ± 9.27	60.14 ± 12.97	60.13 ± 14.25	0.012*
Sex[b]					0.410
Men	20 (26.7)	4 (5.3)	39 (52.0)	12 (16.0)	
Women	27 (36.0)	6 (8.0)	38 (50.7)	4 (5.3)	
Body mass index category[b]					0.843
Underweight	5 (50.0)	1 (10.0)	3 (30.0)	1 (10.0)	
Normal	18 (31.6)	2 (3.5)	32 (56.1)	5 (8.8)	

Variable	Normal (n=47)	Concentric remodeling (n=10)	Concentric LVH (n=77)	Eccentric LVH (n=16)	P value
Overweight	15 (27.8)	4 (7.4)	29 (53.7)	6 (11.1)	
Obese	9 (31.0)	3 (10.3)	13 (44.8)	4 (13.8)	
Ethnicity[b]					0.647
Bugis	25 (33.3)	7 (9.3)	33 (44.0)	10 (13.3)	
Makassar	8 (26.7)	3 (10.0)	17 (56.7)	2 (6.7)	
Toraja	6 (42.9)	0 (0.0)	7 (50.0)	1 (7.1)	
Mandar	3 (37.5)	0 (0.0)	4 (50.0)	1 (12.5)	
Other	5 (21.7)	0 (0.0)	16 (69.6)	2 (8.7)	
History of hypertension[b]					0.486
Yes	38 (30.2)	10 (7.9)	64 (50.8)	14 (11.1)	
No	9 (37.5)	0 (0.0)	13 (54.2)	2 (8.3)	
Hypertension duration, years[b]					0.003*
<2	25 (51.0)	2 (4.1)	19 (38.8)	3 (6.1)	
2–9	20 (23.0)	5 (5.7)	52 (59.8)	10 (11.5)	
≥10	2 (14.3)	3 (21.4)	6 (42.9)	3 (21.4)	
Systolic blood pressure category[b]					0.205
<140 mmHg	14 (31.1)	4 (8.9)	18 (40.0)	9 (20.0)	
140–160 mmHg	28 (32.9)	4 (4.7)	47 (55.3)	6 (7.1)	
>160 mmHg	5 (25.0)	2 (10.0)	12 (60.0)	1 (5.0)	
Diastolic blood pressure category[b]					0.654
<90 mmHg	28 (32.2)	5 (5.7)	42 (48.3)	12 (13.8)	
90–100 mmHg	18 (32.1)	4 (7.1)	31 (55.4)	3 (5.4)	
>100 mmHg	1 (14.3)	1 (14.3)	4 (57.1)	1 (14.3)	

Values are presented as mean ± standard deviation or n (%). [a] Kruskal–Wallis test. [b] Pearson chi-square test. *p <0.05.

3.3 Association between ECG criteria and left ventricular geometry

Only the Romhilt–Estes criterion demonstrated a significant association with LV geometric patterns (p = 0.003). Positive findings were most frequently observed in patients with concentric LVH (35.1%) and eccentric LVH (25.0%), whereas patients with normal geometry or concentric remodeling were predominantly negative. No significant associations were observed for Peguero–Lo Presti, Sokolow–Lyon, or Cornell Product (all p > 0.05) (Table 5).

Table 3. Categorical association of ECG criteria with echocardiographic LVH.

ECG criterion	LVH (n=93)	No LVH (n=57)	P value
Romhilt–Estes positive	31 (33.3)	3 (5.3)	<0.001
Romhilt–Estes probable	6 (6.5)	2 (3.5)	
Romhilt–Estes negative	56 (60.2)	52 (91.2)	
Peguero–Lo Presti positive	12 (12.9)	9 (15.8)	0.621
Peguero–Lo Presti negative	81 (87.1)	48 (84.2)	
Sokolow–Lyon positive	28 (30.4)	8 (14.0)	0.023
Sokolow–Lyon negative	64 (69.6)	49 (86.0)	
Cornell Product positive	13 (14.0)	4 (7.0)	0.192
Cornell Product negative	80 (86.0)	53 (93.0)	

Values are presented as n (%). *P* values were calculated using the Pearson chi-square test. A two-sided *p* value <0.05 was considered statistically significant.

Table 4. Diagnostic accuracy of ECG criteria at conventional thresholds for echocardiographic LVH.

ECG criterion (threshold)	Sensitivity	Specificity	PPV	NPV	Accuracy	LR+ / LR−
Romhilt–Estes (≥5 points)	33.3 (24.6–43.4)	94.7 (85.6–98.2)	91.2 (77.0–97.0)	46.6 (37.7–55.6)	56.7 (48.7–64.3)	6.33 / 0.70
Sokolow–Lyon (>35 mm)[a]	30.4 (22.0–40.5)	86.0 (74.7–92.7)	77.8 (61.9–88.3)	43.4 (34.6–52.6)	51.7 (43.7–59.6)	2.17 / 0.81
Cornell Product (>2440 mm·ms)	14.0 (8.4–22.5)	93.0 (83.3–97.2)	76.5 (52.7–90.4)	39.8 (31.9–48.3)	44.0 (36.3–52.0)	1.99 / 0.93
Peguero–Lo Presti (≥2.8 mV men; ≥2.3 mV women)	12.9 (7.5–21.2)	84.2 (72.6–91.5)	57.1 (36.5–75.5)	37.2 (29.4–45.8)	40.0 (32.5–48.0)	0.82 / 1.03

Values are presented as % (95% CI) unless otherwise indicated. 95% CIs were calculated using the Wilson score method. Romhilt–Estes probable LVH (4 points) was classified as negative. [a] Sokolow–Lyon data were available for 149 participants (92 with LVH and 57 without LVH). PPV, positive predictive value; NPV, negative predictive value; LR+, positive likelihood ratio; LR−, negative likelihood ratio.

Table 5. Categorical association of ECG criteria with left ventricular geometry.

ECG criterion	Normal (n=47)	Concentric remodeling (n=10)	Concentric LVH (n=77)	Eccentric LVH (n=16)	P value
Romhilt–Estes positive	2 (4.3)	1 (10.0)	27 (35.1)	4 (25.0)	0.003
Romhilt–Estes probable	2 (4.3)	0 (0.0)	4 (5.2)	2 (12.5)	
Peguero–Lo Presti positive	7 (14.9)	2 (20.0)	12 (15.6)	0 (0.0)	0.377
Sokolow–Lyon positive	6 (12.8)	2 (20.0)	23 (30.3)	5 (31.3)	0.144
Cornell Product positive	2 (4.3)	2 (20.0)	13 (16.9)	0 (0.0)	0.058

Values are presented as n (%). *P* values were calculated using the Pearson chi-square test. A two-sided *p* value <0.05 was considered statistically significant.

3.4 Diagnostic performance of ECG criteria

Receiver operating characteristic analysis demonstrated significant discriminatory ability for all four ECG criteria in detecting echocardiographic LVH (all p < 0.05). Peguero–Lo Presti achieved the highest discriminatory performance (AUC 0.680, 95% CI 0.566–0.793) and the greatest sensitivity (78.8%), whereas Sokolow–Lyon showed the highest specificity (88.4%). Cornell Product and Romhilt–Estes demonstrated intermediate performance with AUCs of 0.647 (95% CI 0.536–0.758) and 0.628 (95% CI 0.515–0.741), respectively, while Sokolow–Lyon had an AUC of 0.663 (95% CI 0.554–0.773) (Table 6). However, all AUCs were in the modest range (0.628–0.680), and their 95% CIs overlapped substantially; therefore, the differences in overall discrimination among the four criteria were small and should be interpreted with caution. The sensitivities and specificities shown in Table 6 refer to the data-derived optimal cut-offs and therefore differ from those obtained at the conventional thresholds (Table 4). The ROC estimates in Tables 6 and 7 are reported as originally derived by the study team; because this analysis could not be reproduced on the final dataset (n = 150), the sensitivities and specificities at the optimal cut-offs may reflect a different analytic sample and should be regarded as exploratory (see Limitations).

Table 6. ROC performance of ECG criteria for echocardiographic LVH.

ECG score	AUC (95% CI)	Optimal cut-off	Sensitivity (%)	Specificity (%)	P value
Peguero–Lo Presti	0.680 (0.566–0.793)	≥14.5	78.8	55.8	0.003
Romhilt–Estes	0.628 (0.515–0.741)	≥1.5	63.5	62.8	0.032
Cornell Product	0.647 (0.536–0.758)	≥890	75.0	53.5	0.014
Sokolow–Lyon	0.663 (0.554–0.773)	≥35.5	38.5	88.4	0.006

AUC, area under the receiver operating characteristic curve; CI, confidence interval. *Cut-off units: Peguero–Lo Presti and Sokolow–Lyon, mm (10 mm = 1 mV); Cornell Product, mm·ms; Romhilt–Estes, points. P* values were derived from receiver operating characteristic analysis and test whether the AUC differs from 0.50. A two-sided *p* value <0.05 was considered statistically significant.

When LV geometry was evaluated, none of the ECG criteria significantly predicted concentric remodeling or eccentric LVH. In contrast, concentric LVH was predicted by Peguero–Lo Presti (AUC 0.699, 95% CI 0.591–0.808; p = 0.001), Sokolow–Lyon (AUC 0.697, 95% CI 0.592–0.801; p = 0.001), and Cornell Product (AUC 0.630, 95% CI 0.519–0.742; p = 0.029), whereas Romhilt–Estes did not demonstrate significant discriminatory ability. Peguero–Lo Presti yielded the highest sensitivity (82.6%) and Cornell Product the highest specificity (69.4%) for identifying concentric LVH (Table 7). Because concentric remodeling and eccentric LVH were infrequent in this cohort, the estimates for these patterns were imprecise, as reflected by their wide CIs, and should be considered exploratory.

Table 7. ROC performance of ECG criteria for left ventricular geometric patterns.

Pattern and ECG score	AUC (95% CI)	Optimal cut-off	Sensitivity (%)	Specificity (%)	P value
Concentric remodeling: Peguero–Lo Presti	0.678	≥15.5	88.9	46.5	0.079

	(0.515–0.842)				
Concentric remodeling: Romhilt–Estes	0.387 (0.192–0.582)	≥4.5	11.1	82.6	0.266
Concentric remodeling: Cornell Product	0.430 (0.213–0.647)	≥1450	33.3	61.6	0.493
Concentric remodeling: Sokolow–Lyon	0.428 (0.259–0.598)	≥21.0	55.6	36.0	0.481
Concentric LVH: Peguero–Lo Presti	0.699 (0.591–0.808)	≥14.5	82.6	55.1	0.001
Concentric LVH: Romhilt–Estes	0.583 (0.467–0.699)	≥1.5	63.0	59.2	0.163
Concentric LVH: Cornell Product	0.630 (0.519–0.742)	≥1450	45.7	69.4	0.029
Concentric LVH: Sokolow–Lyon	0.697 (0.592–0.801)	≥21.0	76.1	49.0	0.001
Eccentric LVH: Peguero–Lo Presti	0.410 (0.170–0.650)	≥19.5	33.3	70.8	0.463
Eccentric LVH: Romhilt–Estes	0.685 (0.533–0.838)	≥2.5	66.7	68.5	0.130
Eccentric LVH: Cornell Product	0.566 (0.418–0.713)	≥1450	50.0	62.9	0.592
Eccentric LVH: Sokolow–Lyon	0.355 (0.147–0.563)	≥21.0	50.0	36.0	0.236

AUC, area under the receiver operating characteristic curve; CI, confidence interval. *Cut-off units: Peguero–Lo Presti and Sokolow–Lyon, mm (10 mm = 1 mV); Cornell Product, mm·ms; Romhilt–Estes, points. P* values were derived from receiver operating characteristic analysis and test whether the AUC differs from 0.50. A two-sided *p* value <0.05 was considered statistically significant.

3.5 Discussion

This study demonstrated that the diagnostic performance of the evaluated ECG criteria varied according to the analytic approach and LV geometric pattern. Romhilt–Estes and Sokolow–Lyon were associated with echocardiographic LVH at their conventional thresholds, whereas Peguero–Lo Presti provided the numerically highest, albeit modest, overall discrimination on ROC analysis. This apparent discrepancy is methodologically plausible because categorical analyses assess performance at a fixed threshold, while ROC analysis evaluates discrimination across a range of values, as described by Hanley and McNeil (1982) [10].

The higher discriminatory ability of Peguero–Lo Presti is consistent with the original study by Peguero et al. (2017) [11], as well as validation studies in Asian populations by Shao et al. (2019) [12]. Meta-analyses by Yu et al. (2021) and Sun et al. (2018) also suggested higher sensitivity for Peguero–Lo Presti than for conventional voltage criteria [8,13]. More recently, Marcato et al. (2022) compared Peguero–Lo Presti, Sokolow–Lyon, Cornell, and Romhilt–Estes against echocardiography and similarly found

that Peguero–Lo Presti had the best sensitivity and overall accuracy, whereas Sokolow–Lyon had the highest specificity [14]. These findings support the use of Peguero–Lo Presti as an initial screening criterion when reducing missed LVH is the principal objective, particularly when a locally derived cut-off is applied. Of note, at its conventional threshold, Peguero–Lo Presti identified only 12.9% of patients with echocardiographic LVH in our cohort, suggesting that the higher sensitivity reported previously may not be reproduced in this population without threshold recalibration.

Nevertheless, the superiority of Peguero–Lo Presti should not be assumed to be universal. Faggiano et al. (2024) noted that the available evidence remains heterogeneous across populations, reference standards, and LVH phenotypes [15]. Differences in body composition, sex distribution, hypertension severity, antihypertensive treatment, and ECG acquisition may influence diagnostic performance. Therefore, the present findings add evidence from an Indonesian hypertensive population and support the need for local validation of optimal thresholds rather than universal application of a single cut-off.

Sokolow–Lyon showed the greatest specificity, indicating that a positive result may provide stronger support for structural LVH, whereas a negative result cannot reliably exclude it. This pattern is in line with the systematic review by Pewsner et al. (2007) and with Marcato et al. (2022) [14,16]. In clinical practice, Sokolow–Lyon may therefore be more useful to strengthen suspicion of LVH than to rule it out.

Romhilt–Estes was the only criterion associated with LV geometric patterns. Unlike purely voltage-based criteria, this score incorporates repolarization abnormalities, left atrial enlargement, QRS duration, and delayed intrinsicoid deflection. These components may capture electrical remodeling accompanying structural changes, particularly in concentric LVH. This observation is consistent with the concept that chronic pressure overload produces structural and electrical remodeling simultaneously, as described by Ganau et al. (1992) and Cuspidi et al. (2012) [9,17]. Overall, the findings support a complementary interpretation of ECG criteria in hypertensive patients. Peguero–Lo Presti may be preferred when sensitivity is prioritized, Sokolow–Lyon may increase diagnostic confidence when positive, and Romhilt–Estes may provide additional information on electrical remodeling. Echocardiography remains necessary to confirm LVH and to characterize LV geometry accurately.

Screening performance must be distinguished from definitive diagnosis. ECG criteria are intended to identify patients who warrant further evaluation rather than to establish or exclude structural LVH. In the present study, all AUCs were below 0.70 and NPVs at conventional thresholds were low (37.2%–46.6%), meaning that a substantial proportion of patients with echocardiographic LVH would be missed if ECG were used alone. Conversely, the high specificity and PPV of Romhilt–Estes and Sokolow–Lyon indicate that a positive result increases the likelihood of LVH, but imaging is still required to confirm the diagnosis and define LV geometry. ECG should therefore be regarded as a triage tool: a positive ECG should prompt echocardiography, and a negative ECG should not preclude echocardiography when clinical suspicion of hypertension-mediated cardiac damage is high. In addition, predictive values depend on disease prevalence; the high prevalence of LVH in this referral-based sample (62.0%) may have increased PPVs and lowered NPVs compared with those expected in primary care populations.

This study has several limitations. First, its cross-sectional design captured ECG and echocardiographic findings at a single time point; therefore, the temporal relationship between electrical and structural remodeling and the prognostic value of each criterion could not be assessed. Second, the study was conducted at a single tertiary referral center, and enrolled outpatients attending a cardiac clinic, a setting with a high prevalence of LVH (62.0%). This may have introduced spectrum bias, influenced the predictive values, and limited the generalizability of the findings to primary care settings and to populations with different ethnic, demographic, and clinical characteristics. In addition, a substantial proportion of participants had established hypertension and may have been receiving antihypertensive therapy, which can modify both ECG voltages and left ventricular mass. Third, cardiac magnetic resonance imaging, the reference standard for left ventricular mass assessment, was not available; therefore, echocardiography was used as the reference method. Fourth, the optimal cut-off values were derived and evaluated in the same sample without internal or external validation, which may overestimate diagnostic performance, and no formal pairwise statistical comparison of AUCs (e.g., the DeLong test) was performed. Also, the ROC-derived estimates presented in Tables 6 and 7 could not be re-verified against the final analytic dataset of 150 patients; the sensitivity and specificity values at the optimal cut-offs may therefore not correspond exactly to the full cohort, and these exploratory estimates should be interpreted with caution. Finally, the relatively small number of participants with concentric remodeling and eccentric hypertrophy may have reduced the statistical power for subgroup analyses and limited the precision of diagnostic performance

estimates for these geometric patterns. Future multicenter studies with larger sample sizes and external validation are warranted to confirm these findings and refine the diagnostic thresholds of the evaluated electrocardiographic criteria.

4. CONCLUSION

Among patients with uncomplicated hypertension, electrocardiographic criteria demonstrated heterogeneous diagnostic performance for detecting left ventricular hypertrophy and abnormal left ventricular geometry. Peguero–Lo Presti had the numerically highest, albeit modest, discriminatory ability and sensitivity at its data-derived cut-off, whereas Sokolow–Lyon had the highest specificity; however, the 95% CIs of the AUCs overlapped, and all criteria showed low sensitivity at conventional thresholds. ECG remains an accessible initial screening tool, but it should not be used for the definitive diagnosis or exclusion of LVH; echocardiography is essential for confirmation of LVH and characterization of left ventricular geometry.

ACKNOWLEDGEMENTS

The authors thank all participants and the staff of the Integrated Cardiac Center, Dr. Wahidin Sudirohusodo Hospital, Makassar, Indonesia, for their support during data collection.

AUTHOR CONTRIBUTIONS

L.E.L.: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Writing – Original Draft.

M.A.: Conceptualization, Methodology, Supervision, Writing – Review & Editing.

A.H.A.: Methodology, Validation, Supervision, Writing – Review & Editing.

A.F.G.: Methodology, Investigation, Validation, Writing – Review & Editing.

A.H.N.: Methodology, Supervision, Writing – Review & Editing.

A.A.Z.: Methodology, Formal Analysis, Supervision, Writing – Review & Editing.

All authors reviewed and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

ETHICS STATEMENT

This study was approved by the Ethics Committee of the Faculty of Medicine, Hasanuddin University (Approval No. 936/UN4.6.4.5.31/PP36/2026). The study was conducted in accordance with the Declaration of Helsinki and applicable local regulations. Written informed consent was obtained from all participants before enrolment.

DATA AVAILABILITY STATEMENT

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

REFERENCES

[1] Unger T, Borghi C, Charchar F, et al. 2020 International Society of Hypertension Global Hypertension Practice Guidelines. Hypertension. 2020;75(6):1334-1357. doi:10.1161/HYPERTENSIONAHA.120.15026

[2] Badan Penelitian dan Pengembangan Kesehatan, Kementerian Kesehatan Republik Indonesia. Laporan Nasional Riskesdas 2018. Jakarta: Lembaga Penerbit Badan Penelitian dan Pengembangan Kesehatan; 2019.

[3] Huang X, Hu L, Long Z, Wang X, Wu J, Cai J. Hypertensive Heart Disease: Mechanisms, Diagnosis and Treatment. Rev Cardiovasc Med. 2024;25(3):93. doi:10.31083/J.RCM2503093

[4] Muiesan ML, Salvetti M, Monteduro C, et al. Left ventricular concentric geometry during treatment adversely affects cardiovascular prognosis in hypertensive patients. Hypertension. 2004;43(4):731-738. doi:10.1161/01.HYP.0000121223.44837.DE

[5] Miceli F, Presta V, Citoni B, et al. Conventional and new electrocardiographic criteria for hypertension-mediated cardiac organ damage: A narrative review. J Clin Hypertens (Greenwich). 2019;21(12):1863-1871. doi:10.1111/jch.13726.

[6] Tadic M, Cuspidi C. Electrocardiographic criteria for cardiac remodeling in hypertensive patients. The Journal of Clinical Hypertension. 2019;21(3):379. doi:10.1111/JCH.13478
[7] Romhilt DW, Estes EH. A point-score system for the ECG diagnosis of left ventricular hypertrophy. Am Heart J. 1968;75(6):752-758. doi:10.1016/0002-8703(68)90035-5
[8] Yu Z, Song J, Cheng L, et al. Peguero-Lo Presti criteria for the diagnosis of left ventricular hypertrophy: A systematic review and meta-analysis. PLoS One. 2021;16(1). doi:10.1371/JOURNAL.PONE.0246305
[9] Cuspidi C, Sala C, Negri F, Mancia G, Morganti A. Prevalence of left-ventricular hypertrophy in hypertension: an updated review of echocardiographic studies. J Hum Hypertens. 2012;26(6):343-349. doi:10.1038/JHH.2011.104
[10] Hanley JA, McNeil BJ. The Meaning and Use of the Area under a Receiver Operating Characteristic (ROC) Curve1. Radiology. 1982;143:29-36.
[11] Peguero JG, Lo Presti S, Perez J, Issa O, Brenes JC, Tolentino A. Electrocardiographic Criteria for the Diagnosis of Left Ventricular Hypertrophy. J Am Coll Cardiol. 2017;69(13):1694-1703. doi:10.1016/j.jacc.2017.01.037
[12] Shao Q, Meng L, Tse G, et al. Newly proposed electrocardiographic criteria for the diagnosis of left ventricular hypertrophy in a Chinese population. Ann Noninvasive Electrocardiol. 2019;24(2):e12602. doi:10.1111/anec.12602.
[13] Sun GZ, Wang HY, Ye N, Sun YX. Assessment of Novel Peguero-Lo Presti Electrocardiographic Left Ventricular Hypertrophy Criteria in a Large Asian Population: Newer May Not Be Better. Canadian Journal of Cardiology. 2018;34(9):1153-1157. doi:10.1016/j.cjca.2018.05.013
[14] Marcato JP, Senra Santos F, Gama Palone A, Lenci Marques G. Evaluation of Different Criteria in the Diagnosis of Left Ventricular Hypertrophy by Electrocardiogram in Comparison With Echocardiogram. Cureus. 2022;14(6). doi:10.7759/CUREUS.26376
[15] Faggiano A, Gherbesi E, Tadic M, Carugo S, Grassi G, Cuspidi C. Do We Need New Electrocardiographic Criteria for Left Ventricular Hypertrophy? The Case of the Peguero-Lo Presti Criterion. A Narrative Review. Am J Hypertens. 2024;37(3):155-162. doi:10.1093/AJH/HPAD117
[16] Pewsner D, Jüni P, Egger M, Battaglia M, Sundström J, Bachmann LM. Accuracy of electrocardiography in diagnosis of left ventricular hypertrophy in arterial hypertension: systematic review. BMJ. 2007;335(7622):711-714. doi:10.1136/BMJ.39276.636354.AE
[17] Ganau A, Devereux RB, Roman MJ, et al. Patterns of left ventricular hypertrophy and geometric remodeling in essential hypertension. J Am Coll Cardiol. 1992;19(7):1550-1558. doi:10.1016/0735-1097(92)90617-V