ORIGINAL ARTICLE

Electrocardiography and cardiac magnetic resonance imaging in the detection of left ventricular hypertrophy: the impact of indexing methods

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ABSTRACT

BACKGROUND   Discrepancies between increased left ventricular mass (LVM) and electrocardiographic (ECG) criteria for the diagnosis of left ventricular hypertrophy (LVH) are described in the literature.

AIMS   This study aimed to evaluate the usefulness of ECG criteria in the diagnosis of LVH, as determined by cardiac magnetic resonance (CMR) imaging, using various LVM indexing methods.

METHODS   We included 53 patients who underwent CMR imaging and had electrocardiograms of appropriate quality available in their medical records. The majority of the study patients had cardiovascular diseases. We defined CMR-LVH as increased LVM, also assessed after LVM indexing to body surface area (LVM / BSA), height[1.7], height[2.7], or as the percentage of predicted LVM (%pLVM). To determine ECG-LVH, 10 different ECG-LVH criteria were used.

RESULTS   The prevalence of CMR-LVH ranged from 11% (for %pLVM) to 72% (for LVM / BSA). At the same time, for a single criterion, the prevalence of ECG-LVH ranged between 1.9% (for R wave amplitude in lead V_5/V_6 greater than 2.6 mV, Sokolow–Lyon product, and Gubner–Ungerleider criterion) and 45.3% (for Peguero–Lo Presti criterion), showing high sensitivity, from 55.3% (95% CI, 38.3–71.4) to 100% (95% CI, 54.1–100). The sensitivity of ECG-LVH criteria when all criteria were applied together ranged from 57.9% (95% CI, 40.8–73.7) to 100% (95% CI, 63.1–100). The best performance regarding the endpoint of CMR-LVH diagnosis after LVM indexing was achieved by the Peguero–Lo Presti and Cornell criteria (area under the curve, 0.621–0.876; *P*, 0.001–0.17).

CONCLUSIONS   The diagnosis of LVH strongly depends on ECG- and CMR-based definitions. The Peguero–Lo Presti criterion and the Cornell criteria, which are sex-specific, may provide the highest level of diagnostic accuracy and should be considered when screening patients with cardiovascular diseases for LVH.

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INTRODUCTION   Left ventricular hypertrophy (LVH) is associated with elevated left ventricular (LV) volumes, increased wall thickness, or may be a combination of these pathophysiological changes.[1] In patients with LVH, anatomical alterations are associated with changes in electrical properties of the heart.[2] The presence of LVH reflects an increased probability of morbidity and mortality.[3,4] Therefore, the proper diagnosis of LVH is of value in the medical decision-making process.

Multiple electrocardiographic (ECG) criteria for the diagnosis of LVH (ECG-LVH) have been proposed and some of them are widely used in

WHAT'S NEW?

The diagnosis of left ventricular hypertrophy (LVH) strongly depends on electrocardiographic and cardiac magnetic resonance imaging–based definitions. The incidence of LVH diagnosed with the use of cardiac magnetic resonance imaging–based criteria may range from 11% (for predicted left ventricular mass) to 72% (for left ventricular mass indexed to body surface area). Diagnosed using electrocardiographic criteria, the incidence of LVH may range from 1.9% (for R wave amplitude in lead V_5/V_6 greater than 2.6 mV, Sokolow–Lyon product, and Gubner–Ungerleider criterion) to 45.3% (for Peguero–Lo Presti criterion). The novel Peguero–Lo Presti criterion and the Cornell criteria, which are sex-specific, may provide the highest level of diagnostic accuracy. These criteria should be considered as part of the "cumulative criterion" when screening patients with cardiovascular diseases for LVH.

clinical practice.[4-8] The statement by the American Heart Association / American College of Cardiology Foundation / Heart Rhythm Society from 2009 included over 35 ECG-LVH criteria.[5] A more recent statement by the Working Group on Noninvasive Electrocardiology and Telemedicine of the Polish Cardiac Society recommended 13 different ECG-LVH criteria, depending on the presence of ventricular conduction disorders.[8] Voltage and non-voltage changes in QRS complexes are used for LVH screening in most of these criteria.[3] However, despite the clinical significance of ECG-LVH criteria, they are generally characterized by low sensitivity; therefore, novel or modified ECG-LVH criteria have been proposed.[6,9-12] The intra- and interobserver variability (according to the Shrout and Fleiss analysis with fixed effect) for selected ECG-LVH criteria was 0.94 and 0.8, respectively.[6] Discordance between increased LV mass (LVM) and ECG-LVH criteria is a disadvantage of using ECG-based criteria for LVH detection.[3] Using ECG-based criteria, some patients without LVH may be improperly diagnosed as having LVH. On the other hand, some patients may not fulfil current ECG-based definitions, despite the presence of LVH. This can be the case when using a single ECG-LVH criterion. Therefore, to increase accuracy of ECG-LVH diagnosis, the use of multiple ECG-LVH criteria is recommended.[5,8]

Currently, cardiac magnetic resonance (CMR) imaging is the gold standard in the diagnosis of LVH.[13] When used for the assessment of LVM, it has higher reproducibility and precision compared with echocardiography, as it provides good contrast at endocardial borders and there is no need for geometric assumptions.[14,15] The reproducibility of LVM measurement by CMR imaging reflected by a mean weighted intraobserver variability is 4.8 g, whereas interobserver variability is 9 g.[16] Furthermore, CMR imaging provides detailed images, which can reveal local wall thickening in specific LV segments.[15] Previous studies have shown the value of CMR imaging in the diagnostic workup of LVH, differentiation between ischemic and nonischemic

etiologies of myocardial disease, and improvement of clinical decision making and risk stratification.[15,17-21] However, CMR imaging has absolute and relative contraindications, which are similar to those of magnetic resonance imaging, and requires sufficient expertise for appropriate study interpretation. Additionally, there are other concerns regarding the optimal assessment of LVM. This is partially due to the fact that LVM depends on multiple factors, especially body size; thus, several methods to index LVM have been proposed.[22-26]

Our aim was to evaluate the usefulness of ECG-LVH criteria in the diagnosis of LVH, as determined by CMR imaging, using various LVM indexing (LVMi) methods.

METHODS **Study population** Our study included real-world patients, the majority of whom had cardiovascular diseases, underwent CMR imaging between 2011 and 2015 in the Department of Diagnostic Imaging at the University Hospital in Kraków (Poland), and had an ECG of appropriate quality for analysis in the available medical records. Clinical data obtained from a structured medical record review included baseline clinical and demographic characteristics and medication history.[19] Patients with right bundle branch block, left bundle branch block, left anterior fascicular block, or ventricular preexcitation were excluded from the current analysis. The study was approved by the local ethics committee.

Electrocardiographic analysis Standard 12-lead ECGs were recorded at a 25 mm/s paper speed and calibration of 10 mm/mV. The ECGs were then interpreted by a reader who was initially blinded to the patient's CMR imaging data. The duration of QRS complexes and the amplitudes of R and S waves were measured. We evaluated 10 different ECG-LVH criteria, including all standard criteria recommended in the statement by the Working Group on Noninvasive Electrocardiology and Telemedicine of the Polish Cardiac Society as well as the novel Peguero–Lo Presti criterion.[4,6-8,14] A "cumulative criterion" was defined as positive when at least 1 ECG-LVH criterion was fulfilled. The assessment of ECG-LVH and analyzed criteria are described in detail in FIGURE 1 and in Supplementary material, *Table S1*.

Cardiac magnetic resonance imaging Cardiac magnetic resonance imaging was performed using a 1.5 Tesla GE Signa HDxt scanner (General Electric, Milwaukee, Wisconsin, United States). The fast imaging employing steady-state acquisition cine technique was used to acquire images. Contrast-enhanced scans performed after gadolinium injection, as described and reported elsewhere,[19] were obtained in 48 study patients
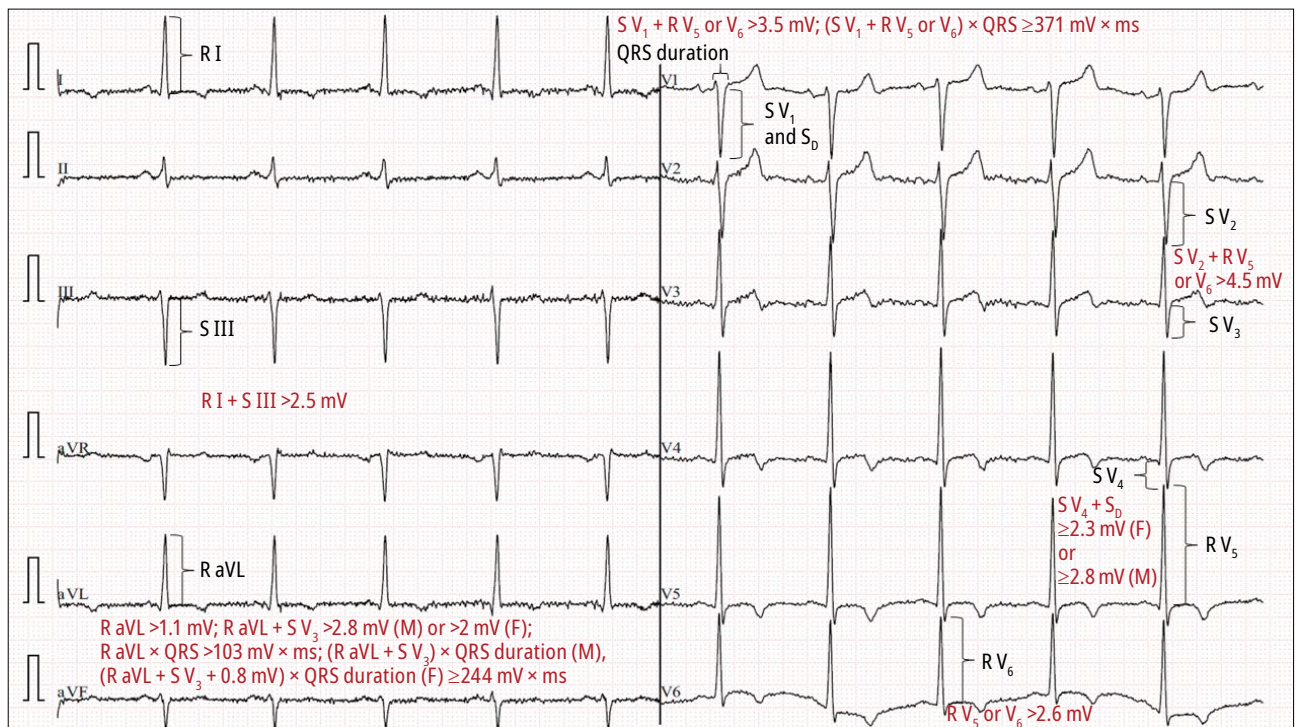
FIGURE 1 The electrocardiogram recording at a paper speed of 25 mm/s and calibration of 10 mm/mV showing the methodology of the electrocardiographic assessment of left ventricular hypertrophy. The electrocardiographic criteria for the diagnosis of left ventricular hypertrophy were based on previous studies.[4,6-8,14]

Abbreviations: F, female; M, male; R, R wave amplitude; S, S wave amplitude; S_D, the deepest S wave in any single lead

(90.6%). If appropriate, other techniques such as short tau inversion recovery, double inversion recovery, and triple inversion recovery were used. The American Heart Association model for LV segmentation was applied. Left ventricular mass was assessed using the QMass® MR analysis software, version 7.6 (Medis Medical Imaging Systems bv, Leiden, the Netherlands). We used 6 different criteria to diagnose LVH by CMR imaging (CMR-LVH). Here, LVH was defined as LVM >148 g for men or >96 g for women according to Petersen et al.[23] Left ventricular hypertrophy was also assessed after LVMi to body surface area (BSA) (LVM/BSA), height$^{1.7}$ (LVM/height$^{1.7}$), height$^{2.7}$ (LVM/height$^{2.7}$), or to the percentage of predicted LVM (%pLVM), according to cutoff values determined in the Multi-Ethnic Study of Atherosclerosis (MESA) (Supplementary material, *Table S1*).[22,24-26] Additionally, LVM/BSA with cutoff values indicating LVH proposed by Petersen et al[23] were used. Predicted LVM (pLVM) was calculated using the following MESA equations: pLVM = 8.17 × height (in meters)$^{0.561}$ × weight (in kilograms)$^{0.608}$ for men and pLVM = 6.82 × height (in meters)$^{0.561}$ × weight (in kilograms)$^{0.608}$ for women.

Statistical analysis Continuous variables were expressed as mean (SD) or median (interquartile range [IQR]). They were compared between the 2 study groups using the *t* test or the Mann–Whitney test, as appropriate. Categorical variables were presented as numbers and percentages and evaluated by the Pearson χ² test or the Fisher exact test. Correlations between 2 continuous variables were assessed using the Pearson or Spearman rank correlation, as appropriate. Proportions were compared to test for differences in positive LVH diagnoses based on ECG-LVH criteria. Receiver operating characteristics were analyzed to find the best variable to differentiate patients with and without LVH. Moreover, specificity, sensitivity, positive predictive value, negative predictive value, accuracy, and negative likelihood ratio were calculated for each tested ECG-LVH criterion. The McNemar test was used to evaluate the agreement between ECG-LVH criteria and the diagnosis of CMR-LVH. A *P* value less than 0.05 was considered significant. Statistical analyses were performed using the IBM SPSS Statistics software, version 25 (IBM Corp., Armonk, New York, United States). The Statistica (version 13.3; TIBCO Software, Inc., Palo Alto, California, United States) software was used to compare areas under the curves (AUCs) in the analyses of receiver operating characteristics (Hanley and McNeil formula). Confidence intervals were calculated, and proportions were compared using the MedCalc software (available at: https://www.medcalc.org/).

RESULTS The study group included 53 patients (17% women) at a median (IQR) age of 40 (28–59.5) years. Within this group, hypertension was present in 23 patients (43.4%), dyslipidemia in 19 (35.8%), diabetes in 5 (9.4%), atrial fibrillation in 8 (15.1%), history of smoking in

TABLE 1 Baseline characteristics of the study patients with and without left ventricular hypertrophy, based on indexed and nonindexed left ventricular mass

Variables	LVM >148 g (M) or >96 g (F) (n = 36)	LVM ≤148 g (M) or ≤96 g (F) (n = 17)	P value	LVM / BSA >72 g/m² (M) or >55 g/m² (F) (n = 38)	LVM / BSA ≤72 g/m² (M) or ≤55 g/m² (F) (n = 15)	P value
Demographic characteristics						
Age, y, median (IQR)	44 (32.3–59)	29 (24.5–63.5)	0.33	44.5 (29.8–60.3)	33 (25–46)	0.13
Female sex, n (%)	8 (22.2)	1 (5.9)	0.24[a]	8 (21.1)	1 (6.7)	0.42[a]
Cardiovascular diseases and risk factors, n (%)						
HF	23 (63.9)	6 (35.3)	0.05	24 (63.2)	5 (33.3)	<0.05
CAD	14 (38.9)	6 (35.3)	0.80	15 (39.5)	5 (33.3)	0.68
Diabetes	4 (11.1)	1 (5.9)	1[a]	4 (10.5)	1 (6.7)	1[a]
Hypertension	16 (44.4)	7 (41.2)	0.82	17 (44.7)	6 (40)	0.75
Dyslipidemia	15 (41.7)	4 (23.5)	0.20	16 (42.1)	3 (20)	0.13
History of smoking	9 (25)	5 (29.4)	0.73	11 (28.9)	3 (20)	0.51
AF	8 (22.2)	0	0.04[a]	7 (18.4)	1 (6.7)	0.42[a]
CMR parameters, mean (SD) or median (IQR)						
LVEF, %	43.3 (14.9)	55 (11.6)	0.006	43.2 (14.8)	56.7 (10)	0.002
LVEDV, ml	174.6 (163–232.9)	141 (122.7–188.9)	0.01	174.6 (159.1–235.4)	146 (122.5–189.6)	0.02
LVESV, ml	110.1 (80.2–145.5)	66.6 (55.6–73.9)	<0.001	98.6 (78–154.4)	65.6 (52.9–74.1)	0.001

a Fisher exact test (exact significance, 2-tailed).

Abbreviations: AF, atrial fibrillation; BSA, body surface area; CAD, coronary artery disease; CMR, cardiac magnetic resonance; LVEDV, left ventricular end-diastolic volume; LVESV, left ventricular end-systolic volume; HF, heart failure; IQR, interquartile range; LVEF, left ventricular ejection fraction; LVM, left ventricular mass; others, see FIGURE 1

TABLE 2 Electrocardiographic criteria for the diagnosis of left ventricular hypertrophy parameters in the study patients with and without left ventricular hypertrophy, based on nonindexed left ventricular mass

ECG-LVH criteria parameters	LVM >148 g (M) or >96 g (F) (n = 36)	LVM ≤148 g (M) or ≤96 g (F) (n = 17)	P value
R wave amplitude in V_5 or V_6, mV	1.2 (0.9–1.7)	1.2 (1–1.7)	0.82
S wave amplitude in V_1 + R wave amplitude in V_5 or V_6, mV	2.28 (1.7–2.7)	1.9 (1.5–2.4)	0.23
(S wave amplitude in V_1 + R wave amplitude in V_5 or V_6) × QRS duration, mV × ms	192 (132–251.8)	170.5 (128–214)	0.35
S wave amplitude in V_2 + R wave amplitude in V_5 or V_6, mV	2.7 (1)	2.5 (1.1)	0.50
R wave amplitude in aVL, mV	0.4 (0.2–0.7)	0.2 (0.1–0.4)	0.02
R wave amplitude in aVL × QRS duration, mV × ms	36 (16–56)	22 (8–33)	0.03
R wave amplitude in aVL + S wave amplitude in V_3, mV	1.5 (0.8)	1.16 (0.6)	0.08
(R wave amplitude in aVL + S wave amplitude in V_3) × QRS duration (M), (R wave amplitude in aVL + S wave amplitude in V_3 + 0.8 mV) × QRS duration (F), mV × ms	152 (73–215.6)	104 (58–140.3)	0.08
R wave amplitude in I + S wave amplitude in III, mV	0.8 (0.6–1.4)	0.65 (0.5–0.9)	0.07
S_D + S wave amplitude in V_4, mV	2.6 (1.7–3.2)	1.7 (1.5–2.4)	0.05

Data are presented as mean (SD) or median (interquartile range).

Abbreviations: ECG, electrocardiography; LVH, left ventricular hypertrophy; others, see FIGURE 1 and TABLE 1

TABLE 3 Electrocardiographic criteria for the diagnosis of left ventricular hypertrophy in the study patients with and without left ventricular hypertrophy, based on nonindexed left ventricular mass

Positive ECG-LVH criteria	LVM >148 g (M) or >96 g (F) (n = 36)		LVM ≤148 g (M) or ≤96 g (F) (n = 17)		McNemar test	P value
	TP	FN	FP	TN		
R wave amplitude in V_5 or V_6 >2.6 mV	1 (2.8)	35 (97.2)	0	17 (100)	<0.001	1[a]
S wave amplitude in V_1 + R wave amplitude V_5 or V_6 >3.5 mV	3 (8.3)	33 (91.7)	1 (5.9)	16 (94.1)	<0.001	1[a]
(S wave amplitude in V_1 + R wave amplitude in V_5 or V_6)×QRS duration ≥371 mV×ms	1 (2.8)	35 (97.2)	0	17 (100)	<0.001	1[a]
S wave amplitude in V_2 + R wave amplitude in V_5 or V_6 >4.5 mV	1 (2.8)	35 (97.2)	1 (5.9);	16 (94.1)	<0.001	0.54[a]
R wave amplitude in aVL >1.1 mV	3 (8.3)	33 (91.7)	0	17 (100)	<0.001	0.54[a]
R wave amplitude in aVL×QRS duration >103 mV×ms	4 (11.1)	32 (88.9)	0	17 (100)	<0.001	0.29[a]
R wave amplitude in aVL + S wave amplitude in V_3 >2.8 mV (M) or >2 mV (F)	2 (5.6)	34 (94.4)	0	17 (100)	<0.001	1[a]
(R wave amplitude in aVL + S wave amplitude in V_3)×QRS duration (M), (R wave amplitude in aVL + S wave amplitude in V_3 + 0.8 mV)×QRS duration (F) ≥244 mV×ms	5 (13.9)	31 (86.1)	0	17 (100)	<0.001	0.16[a]
R wave amplitude in I + S wave amplitude in III >2.5 mV	1 (2.8)	35 (97.2)	0	17 (100)	<0.001	1[a]
S_D + S wave amplitude in V_4 ≥2.3 mV (F) or ≥2.8 mV (M)	21 (58.3)	15 (41.7)	3 (17.6)	14 (82.4)	0.01	0.005
At least 1 positive ECG-LVH criterion	22 (61.1)	14 (38.9)	4 (23.5)	13 (76.5)	0.03	0.01

Data are presented as number (percentage).

a Fisher exact test (exact significance, 2-tailed)

Abbreviations: FN, false negative; FP, false positive; TN, true negative; TP, true positive; others, see FIGURE 1 and TABLES 1 and 2

14 (26.4%), coronary artery disease in 20 (37.7%), and heart failure in 29 (54.7%). The mean (SD) left ventricular ejection fraction was 47% (14.9%), the median (IQR) left ventricular end-diastolic volume was 172.5 (146.2–220.1) ml, and the median (IQR) left ventricular end-systolic volume was 91.7 (66.1–121.5) ml. Late gadolinium enhancement was observed in 41 patients (85%) in whom gadolinium contrast was administered. The baseline characteristics of patients with or without LVH based on non-indexed LVM and LVM indexed for BSA, according to cutoff values proposed by Petersen et al,[23] are shown in TABLE 1. For other LVMi methods, no significant differences in baseline characteristics were found between patients with and without LVH (data not shown).

The prevalence of CMR-LVH was 67.9% for nonindexed LVM, 71.7% for LVM / BSA, 17% for LVM / height[1.7], 15.1% for LVM / height[2.7], 15.1% for LVM / BSA (MESA), and 11.3% for %pLVM. For a single criterion, the prevalence of ECG-LVH ranged from 1.9% (for R wave amplitude in leads V_5/V_6 >2.6 mV, the Sokolow–Lyon product, and the Gubner–Ungerleider criterion) to 45.3% (for the Peguero–Lo Presti criterion). Also, ECG-LVH

was diagnosed in 3.8% of patients using the Cornell voltage and for S wave amplitude in V_2 + R wave amplitude in lead V_5 or V_6 >4.5 mV. For R wave amplitude in lead aVL >1.1 mV, ECG-LVH was detected in 5.7% of the study patients, while for the Sokolow–Lyon voltage and R wave amplitude in lead aVL × QRS duration >103 mV × ms, it was detected in 7.5% of the patients. For the Cornell product, ECG-LVH was observed in 9.4% of the patients, and for at least 1 positive ECG-LVH criterion, the prevalence of ECG-LVH was 49.1%.

Before indexation, median (IQR) R wave amplitude in lead aVL and median (IQR) R wave amplitude in lead aVL × QRS duration were higher in patients with LVH as determined by CMR imaging, compared with patients without LVH (0.4 [0.2–0.7] mV vs 0.2 [0.1–0.4] mV; P = 0.02 and 36 [16–56] mV × ms vs 22 [8–33] mV × ms; P = 0.03, respectively) (TABLE 2). After LVMi, values used to calculate the Peguero–Lo Presti, Cornell voltage, Cornell voltage–duration product, and Sokolow–Lyon product criteria performed better than parameters calculated in other ECG-LVH criteria and were generally higher in patients with LVH as compared with those without LVH (Supplementary material, *Tables S2–S6*).

TABLE 4 Electrocardiographic criteria in the diagnostic workup of left ventricular hypertrophy and their sensitivity and specificity. Data are shown for indexed and nonindexed left ventricular mass (continued on the next page).

ECG-LVH criteria	Indexed and nonindexed LVM	Sensitivity	Specificity
R wave amplitude in V_5 or V_6 >2.6 mV	LVM	2.8 (0.1–14.5)	100 (80.5–100)
	LVM / BSA (MESA)	0 (0–36.9)	97.8 (88.2–99.9)
	LVM / BSA	2.6 (0.1–13.8)	100 (78.2–100)
	LVM / height$^{1.7}$	0 (0–33.6)	97.7 (88–99.9)
	LVM / height$^{2.7}$	0 (0–36.9)	97.8 (88.2–99.9)
	%pLVH	0 (0–45.9)	97.9 (88.7–100)
S wave amplitude in V_1 + R wave amplitude in V_5 or V_6 >3.5 mV	LVM	8.3 (1.8–22.5)	94.1 (71.3–99.85)
	LVM / BSA (MESA)	25 (3.2–65.1)	95.6 (84.9–99.5)
	LVM / BSA	7.9 (1.7–21.4)	93.3 (68.1–99.8)
	LVM / height$^{1.7}$	22.2 (2.8–60)	95.5 (84.5–99.4)
	LVM / height$^{2.7}$	25 (3.2–65.1)	95.6 (84.9–99.5)
	%pLVH	33.3 (4.3–77.7)	95.7 (85.5–99.5)
(S wave amplitude in V_1 + R wave amplitude in V_5 or V_6) × QRS duration ≥371 mV × ms	LVM	2.8 (0.1–14.5)	100 (80.5–100)
	LVM / BSA (MESA)	12.5 (0.3–52.7)	100 (92.1–100)
	LVM / BSA	2.6 (0.1–13.8)	100 (78.2–100)
	LVM / height$^{1.7}$	11.1 (0.3–48.3)	100 (92–100)
	LVM / height$^{2.7}$	12.5 (0.3–52.7)	100 (92.1–100)
	%pLVH	16.7 (0.4–64.1)	100 (92.5–100)
S wave amplitude in V_2 + R wave amplitude in V_5 or V_6 >4.5 mV	LVM	2.8 (0.1–14.5)	94.1 (71.3–99.9)
	LVM / BSA (MESA)	0 (0–36.9)	95.6 (84.9–99.5)
	LVM / BSA	5.3 (0.6–17.8)	100 (78.2–100)
	LVM / height$^{1.7}$	0 (0–33.6)	95.5 (84.5–99.4)
	LVM / height$^{2.7}$	0 (0–36.9)	95.6 (84.9–99.5)
	%pLVH	0 (0–45.9)	95.7 (85.5–99.5)
R wave amplitude in aVL >1.1 mV	LVM	8.3 (1.8–22.5)	100 (80.5–100)
	LVM / BSA (MESA)	12.5 (0.3–52.7)	95.6 (84.9–99.5)
	LVM / BSA	7.9 (1.7–21.4)	100 (78.2–100)
	LVM / height$^{1.7}$	11.1 (0.3–48.3)	95.5 (84.5–99.4)
	LVM / height$^{2.7}$	12.5 (0.3–52.7)	95.6 (84.9–99.5)
	%pLVH	16.7 (0.4–64.1)	95.7 (85.5–99.5)
R wave amplitude in aVL × QRS duration >103 mV × ms	LVM	11.1 (3.1–26.1)	100 (80.5–100)
	LVM / BSA (MESA)	25 (3.2–65.1)	95.6 (84.9–99.5)
	LVM / BSA	10.5 (2.9–24.8)	100 (78.2–100)
	LVM / height$^{1.7}$	22.2 (2.8–60)	95.5 (84.5–99.4)
	LVM / height$^{2.7}$	25 (3.2–65.1)	95.6 (84.9–99.5)
	%pLVH	33.3 (4.3–77.7)	95.7 (85.5–99.5)
R wave amplitude in aVL + S wave amplitude in V_3 >2.8 mV (M) or >2 mV (F)	LVM	5.6 (0.7–18.7)	100 (80.5–100)
	LVM/BSA (MESA)	12.5 (0.3–52.7)	97.8 (88.2–99.9)
	LVM / BSA	5.3 (0.6–17.8)	100 (78.2–100)
	LVM / height$^{1.7}$	11.1 (0.3–48.3)	97.7 (88–99.9)
	LVM / height$^{2.7}$	12.5 (0.3–52.7)	97.8 (88.2–99.9)
	%pLVH	16.7 (0.4–64.1)	97.9 (88.7–100)

When ECG-LVH criteria were analyzed as categorical variables, we observed that only the Peguero–Lo Presti and at least 1 positive ECG-LVH criterion were more frequently positive in patients with CMR-LVH diagnosed based on nonindexed LVM compared with the remainder of patients (58.3% vs 17.6%; $P = 0.005$ and 61.1% vs 23.5%; $P = 0.01$, respectively) (TABLE 3). Importantly, before and after LVMi, different criteria were more accurate in patients with LVH as determined by CMR imaging compared with patients without LVH. After LVMi, the Peguero–Lo Presti criterion and at least 1 positive ECG-LVH criterion were more frequently positive in patients with CMR-LVH diagnosed based on the cutoff criteria for CMR-LVH, considering all LVMi methods (Supplementary material, Tables S7–S11). In addition, for %pLVM, LVM / BSA (MESA), LVM / height$^{1.7}$, and LVM / height$^{2.7}$ indexing methods, the Cornell product was more frequently positive in patients with CMR-LVH than in those without CMR-LVH. When applying the comparison of proportion to these 3 differentiation criteria, the Peguero–Lo Presti criterion and at least 1 positive ECG-LVH criterion differed from the Cornell product (difference for LVM / BSA [MESA], 62.5%; 95% CI, 17–86.3; $P = 0.009$; difference for LVM / height$^{1.7}$, 55.6%; 95% CI, 9–78.8; $P = 0.02$; difference for LVM / height$^{2.7}$, 50%; 95% CI, 2.9–75.9; $P = 0.046$), whereas there was a trend in difference in the case of %pLVM (50%; 95% CI, 0.006–81.2; $P = 0.06$). At the same time, the Peguero–Lo Presti criterion and at least 1 positive ECG-LVH criterion did not differ (data not shown). The McNemar test revealed that the majority of ECG-LVH criteria were in agreement with CMR-LVH when %pLVM as an LVMi method was used. None of the ECG-LVH criteria were in agreement with CMR-LVH when defined with nonindexed LVM and LVM / BSA with cutoff values proposed by Petersen et al[23] (TABLE 3 and Supplementary material, Table S8).

The Sokolow–Lyon product, S wave amplitude in lead V_2 + R wave amplitude in lead V_5 / V_6, R wave amplitude in lead aVL × QRS duration, Cornell voltage, and Peguero–Lo Presti voltage parameters correlated with LVM ($R = 0.27$, $P <0.05$; $R = 0.33$, $P = 0.01$; $R = 0.27$, $P <0.05$; $R = 0.36$, $P = 0.008$; and $R = 0.46$, $P = 0.001$, respectively; Supplementary material, Table S12). The Sokolow–Lyon voltage, Sokolow–Lyon product, S wave amplitude in lead V_2 + R wave amplitude in lead V_5 / V_6, R wave amplitude in lead aVL, R wave amplitude in lead aVL × QRS duration, Cornell voltage, Cornell voltage–duration product, Gubner-Ungerleider criterion, and Peguero–Lo Presti criterion parameters correlated with indexed LVM (Supplementary material, Table S12).

Sensitivities of ECG criteria for LVH were highest when all criteria were applied together (at least 1 ECG-LVH criterion was positive) and

TABLE 4 Electrocardiographic criteria in the diagnostic workup of left ventricular hypertrophy and their sensitivity and specificity. Data are shown for indexed and nonindexed left ventricular mass (continued from the previous page).

ECG-LVH criteria	Indexed and nonindexed LVM	Sensitivity	Specificity
(R wave amplitude in aVL + S wave amplitude in V$_3$)×QRS duration (M), (R wave amplitude in aVL + S wave amplitude in V$_3$ + 0.8 mV)×QRS duration (F) ≥244 mV×ms	LVM	13.9 (4.7–29.5)	100 (80.5–100)
	LVM / BSA (MESA)	37.5 (8.5–75.5)	95.6 (84.9–99.5)
	LVM / BSA	13.2 (4.4–28.1)	100 (78.2–100)
	LVM / height$^{1.7}$	33.3 (7.5–70.1)	95.5 (84.5–99.4)
	LVM / height$^{2.7}$	37.5 (8.5–75.5)	95.6 (84.9–99.5)
	%pLVH	50 (11.8–88.2)	95.7 (85.5–99.5)
R wave amplitude in I + S wave amplitude in III >2.5 mV	LVM	2.8 (0.1–14.5)	100 (80.5–100)
	LVM / BSA (MESA)	0 (0–36.9)	97.8 (88.2–99.9)
	LVM / BSA	2.6 (0.1–13.8)	100 (78.2–100)
	LVM / height$^{1.7}$	0 (0–33.6)	97.7 (88–99.9)
	LVM / height$^{2.7}$	0 (0–36.9)	97.8 (88.2–99.9)
	%pLVH	0 (0–45.9)	97.9 (88.7–100)
S$_D$ + S wave amplitude in V$_4$ ≥2.3 mV (F) or ≥2.8 mV (M)	LVM	58.3 (40.8–74.5)	82.4 (56.6–96.2)
	LVM / BSA (MESA)	100 (63.1–100)	64.4 (48.8–78.1)
	LVM / BSA	55.3 (38.3–71.4)	80 (51.9–95.7)
	LVM / height$^{1.7}$	88.9 (51.8–99.7)	63.6 (47.8–77.6)
	LVM / height$^{2.7}$	87.5 (47.4–99.7)	62.2 (46.5–76.2)
	%pLVH	100 (54.1–100)	61.7 (46.4–75.5)
At least 1 positive ECG-LVH criterion	LVM	61.1 (43.5–76.9)	76.5 (50.1–93.2)
	LVM / BSA (MESA)	100 (63.1–100)	60 (44.3–74.3)
	LVM / BSA	57.9 (40.8–73.7)	73.3 (44.9–92.2)
	LVM / height$^{1.7}$	88.9 (51.8–99.7)	59.1 (43.3–73.7)
	LVM / height$^{2.7}$	87.5 (47.4–99.7)	57.8 (42.2–72.3)
	%pLVH	100 (54.1–100)	57.5 (42.2–71.7)

Data are presented as percentage (95% CI).

Abbreviations: MESA, Multi-Ethnic Study of Atherosclerosis; others, see FIGURE 1 and TABLES 1 and 2

ranged from 57.9 (95% CI, 40.8–73.7) to 100 (95% CI, 63.1–100), depending on LVMi methods used. For a single criterion, the Peguero–Lo Presti criterion showed the highest sensitivity as compared with other ECG-LVH criteria and ranged from 55.3 (95% CI, 38.3–71.4) to 100 (95% CI, 54.1–100), according to various LVM indexing methods. However, specificity of these criteria was generally lower compared with other criteria and ranged from 57.5 (95% CI, 42.2–71.7) to 76.5 (95% CI, 50.1–93.2) for at least 1 positive ECG-LVH criterion and from 61.7 (95% CI, 46.4–75.5) to 82.4 (95% CI, 56.6–96.2) for the Peguero–Lo Presti criterion (TABLE 4). Positive predictive value, negative predictive value, accuracy, and the negative likelihood ratio of all the analyzed ECG-LVH criteria are shown in Supplementary material, *Table S13*.

The R wave amplitude in lead aVL (AUC, 0.694; $P = 0.02$) and R wave amplitude in lead aVL × QRS duration (AUC, 0.686; $P = 0.03$) were the only predictors of CMR-LVH when LVM was not indexed (FIGURE 2, TABLE 5). There was no difference in AUC between these 2 criteria ($P = 0.55$). After LVMi, the Cornell voltage–duration product, Peguero–Lo Presti criterion, and Cornell voltage were the best predictors of CMR-LVH (TABLE 5 and Supplementary material, *Figures S1–S5*). There was no difference in AUC between these 3 ECG-LVH criteria (data not shown).

DISCUSSION In this study, we showed that LVH strongly depends on ECG- and CMR imaging–based definitions. Methods of LVMi and specific ECG-LVH criteria significantly contribute to LVH diagnosis. Left ventricular mass indexing (except for LVM / BSA indexing according to cutoff values proposed by Petersen et al[23]) was associated with a lower rate of CMR-LVH. These data confirm the need to use appropriate indexation methods during LVM assessment.

Our observations are in line with those of previous studies, which have shown that ECG-LVH criteria generally have low sensitivity yet high specificity for LVH diagnosis.[3,27,28] The diagnostic efficiency of ECG-LVH criteria differs depending on the study, with a sensitivity of approximately 50% and a specificity of nearly 90%.[29] The sensitivity of ECG-LVH criteria is related to the characteristics of the study group, including the frequency of LVH.[9,30] In a hypertensive population, the sensitivity of ECG-LVH criteria (Gubner–Ungerleider, Sokolov–Lyon voltage, Cornell criteria, and Romhilt–Estes score) ranged from 0% to 68%, whereas specificity ranged from 53% to 100%.[9] Our observations support previous findings regarding the assessment of individual ECG-LVH criteria, indicating the relatively high sensitivity of the Cornell product and Peguero–Lo Presti criterion in the diagnosis of ECG-LVH.[6,31,32] The low sensitivity of ECG-LVH criteria may also result from the strict threshold values of ECG-LVH criteria, while the electrical activity of the heart observed on ECG, which reflects LVH, depends on multiple factors, including body weight, sex, race, and age.[12,27,33] Of note, the Cornell and the Peguero–Lo Presti criteria are sex-specific, which may be an important factor contributing to their better clinical performance.

Importantly, we have shown that the sensitivity of ECG-LVH detection using the Peguero–Lo Presti criterion was also similar to using all ECG-LVH criteria together ("cumulative criterion"), which ranged from 57.9% to 100% (according to various LVMi methods). Moreover, the specificity of the Peguero–Lo Presti criterion was similar to that of the "cumulative criterion" approach. Taken together, it appears that the inclusion of the Peguero–Lo Presti criterion in
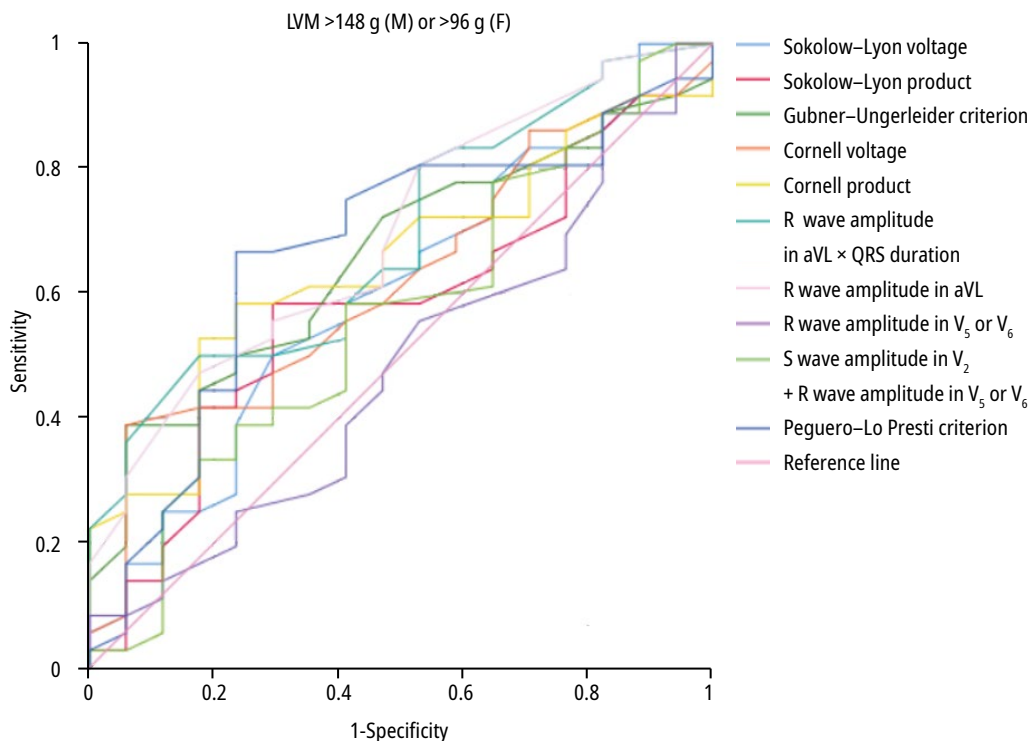
LVM >148 g (M) or >96 g (F)

Legend:
- Sokolow–Lyon voltage
- Sokolow–Lyon product
- Gubner–Ungerleider criterion
- Cornell voltage
- Cornell product
- R wave amplitude in aVL × QRS duration
- R wave amplitude in aVL
- R wave amplitude in V_5 or V_6
- S wave amplitude in V_2 + R wave amplitude in V_5 or V_6
- Peguero–Lo Presti criterion
- Reference line

FIGURE 2 The area under the curve of electrocardiographic criteria for the diagnosis of left ventricular hypertrophy parameters representing the predictive performance for left ventricular hypertrophy, based on nonindexed left ventricular mass

Abbreviations: see FIGURE 1 and TABLE 1

TABLE 5 Area under the curve analyses according to various left ventricular hypertrophy definitions based on indexed and nonindexed left ventricular mass

ECG-LVH criteria parameters	LVM >148 g (M) or >96 g (F)	%pLVM >1.31	LVM/BSA (MESA) >106.2 g/m² (M) or >84.6 g/m² (F)	LVM/BSA >72 g/m² (M) or >55 g/m² (F)	LVM/height¹·⁷ ≥80 g/m¹·⁷ (M) or ≥60 g/m¹·⁷ (F)	LVM/height²·⁷ >45.1 g/m²·⁷ (M) or >38 g/m²·⁷ (F)
R wave amplitude in V_5 or V_6, mV	0.480 (0.82)	0.388 (0.38)	0.451 (0.66)	0.562 (0.48)	0.455 (0.67)	0.394 (0.35)
S wave amplitude in V_1 + R wave amplitude in V_5/V_6, mV	0.602 (0.23)	0.651 (0.23)	0.628 (0.25)	0.666 (0.06)	0.631 (0.22)	0.596 (0.39)
(S wave amplitude in V_1 + R wave amplitude in V_5/V_6) × QRS duration, mV × ms	0.580 (0.35)	0.690 (0.13)	0.668 (0.13)	0.630 (0.14)	0.693 (0.07)	0.650 (0.18)
S wave amplitude in V_2 + R wave amplitude in V_5/V_6, mV	0.565 (0.45)	0.644 (0.26)	0.696 (0.08)	0.603 (0.25)	0.643 (0.18)	0.599 (0.38)
R wave amplitude in aVL, mV	0.694 (0.02)	0.729 (0.07)	0.599 (0.38)	0.646 (0.10)	0.636 (0.20)	0.663 (0.15)
R wave amplitude in aVL × QRS duration, mV × ms	0.686 (0.03)	0.727 (0.07)	0.607 (0.34)	0.644 (0.11)	0.648 (0.17)	0.665 (0.14)
R wave amplitude in aVL + S wave amplitude in V_3, mV	0.621 (0.16)	0.816 (0.01)	0.819 (0.004)	0.621 (0.17)	0.756 (0.02)	0.738 (0.03)
(R wave amplitude in aVL + S wave amplitude in V_3) × QRS duration (M), (R wave amplitude in aVL + S wave amplitude in V_3 + 0.8 mV) × QRS duration (F), mV × ms	0.648 (0.09)	0.853 (0.005)	0.835 (0.003)	0.639 (0.12)	0.831 (0.002)	0.811 (0.005)
R wave amplitude in I + S wave amplitude in III, mV	0.657 (0.07)	0.699 (0.12)	0.576 (0.49)	0.566 (0.46)	0.620 (0.26)	0.642 (0.21)
S_D + S wave amplitude in V_4, mV	0.667 (0.05)	0.846 (0.006)	0.876 (0.001)	0.682 (0.04)	0.799 (0.005)	0.779 (0.01)

Data are presented as the area under the curve (*P* value).

Abbreviations: see FIGURE 1 and TABLES 1 and 2

the "cumulative criterion" is advantageous when comparing proportions and AUC results for single parameters. Furthermore, owing to its high sensitivity, using the Peguero–Lo Presti criterion as an individual criterion appears to be a good screening test for LVH in real-world patients with cardiovascular diseases. However, it should be noted that the Peguero–Lo Presti criterion was related to a significant number of false-positive results in our study cohort. Moreover, Sun et al[12] have shown that the novel Peguero–Lo Presti criterion may not be a better ECG-LVH criterion in Asian populations as compared with the previously used criteria. Thus, more studies comparing this criterion to the previously used ECG-LVH criteria in various groups of patients are needed.

Left ventricular hypertrophy is generally defined as an increased LVM; however, LVM is not the only factor influencing QRS changes, such as QRS voltage and duration.[34] Myocardial ischemia, remodeling, including cardiomyocyte hypertrophy or fibrosis, and changes in the electrical properties of the myocardium, such as the presence of conduction blocks, are factors determining QRS characteristics.[29,35] These factors, at least in part, contribute to the observed discrepancies between ECG-LVH and CMR-LVH. Cardiac magnetic resonance imaging, reflecting myocardial structural alterations, and ECG, indicating the electrical properties of the myocardium, could be used together in a comprehensive myocardial assessment and, combined, may better predict cardiovascular outcomes.

Limitations Our study had several limitations, which should be acknowledged. Electrocardiography and CMR imaging were not always performed on the same day. However, the median (IQR) interval between ECG recording and CMR imaging was 1 (0–4) day. We excluded patients having an ECG of inappropriate quality for analysis, which could have influenced selection of the study participants. Our study cohort was small in size; however, even in this group, we could determine differences in the tested ECG-LVH criteria and suggest potentially the most significant ECG-LVH criteria. The majority of the study patients had previously diagnosed cardiovascular diseases and/or late gadolinium enhancement, which could affect QRS characteristics as well as sensitivity and specificity of the analyzed ECG-LVH criteria. However, we did not aim to propose new cutoff values of established ECG-LVH criteria in our study. Our observations should be confirmed in a larger group of patients. Finally, our results may not be fully applicable in a general population without comorbidities.

Conclusions The diagnosis of LVH strongly depends on ECG- and CMR imaging–based definitions. In clinical practice, the proper identification of true positive and true negative cases of LVH based solely on ECG-LVH criteria may be misleading. The Peguero–Lo Presti criterion and the Cornell criteria, which are sex-specific, may provide the highest level of diagnostic accuracy and should be considered in screening patients with cardiovascular diseases for LVH.

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