ORIGINAL ARTICLE

Diagnostic performance of electrocardiographic criteria for left ventricular hypertrophy among various body mass index groups compared to diagnosis by cardiac magnetic resonance imaging

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Abstract

Background: Presence of left ventricular hypertrophy (LVH) increases the risk for cardiovascular event. Many electrocardiographic (ECG) criteria can be used to diagnose LVH; however, high body mass index (BMI) may reduce ECG amplitudes. The aim of this study was to investigate the diagnostic performance of ECG criteria for diagnosing LVH among various BMI groups compared to diagnosis by cardiac magnetic resonance (CMR) imaging.

Methods: Patients who were referred for CMR were enrolled. CMR and ECG were performed on the same day. Left ventricular function, volume, and mass were calculated from CMR. Standard ECG criteria were measured, including: Cornell voltage, Cornell product, Romhilt-Estes point score system, Sokolow-Lyon index, and Sokolow-Lyon-Rappaport index. Diagnostic performance of each ECG criterion was calculated and analyzed in the following four BMI groups: underweight (<18.5 kg/m²), normal (18.5–22.9 kg/m²), overweight (23–24.9 kg/m²), and obese (≥25 kg/m²).

Results: Of the 1,882 patients that were included, 67 were underweight, 459 were normal weight, 434 were overweight, and 922 were obese. LVH was diagnosed in 34 (50.7%) underweight, 144 (31.4%) normal weight, 100 (23.0%) overweight, and 181 (19.6%) obese patients. Overall specificity of ECG was high (0.89–0.95), and overall sensitivity was low (0.25–0.37). The specificity of each ECG criterion was similar among BMI groups; however, the sensitivity of ECG criteria demonstrated a decreasing trend in the higher BMI groups.

Conclusion: All ECG criteria demonstrated relatively high specificity and relatively low sensitivity. Although the specificity across groups remained similar, higher BMI was found to be associated with decreased sensitivity.

KEYWORDS

body mass index, diagnostic performance, electrocardiography, left ventricular hypertrophy, magnetic resonance imaging

1 | INTRODUCTION

Left ventricular hypertrophy (LVH) is a common consequence (Dzau & Braunwald, 1991) of uncontrolled hypertension, and it contributes

to increased cardiovascular events in both hypertensive patients (Jissho et al., 2010; Vakili, Okin, & Devereux, 2001) and in general population (Bikkina et al., 1994). The risk of developing a major adverse cardiac event increases commensurately with increases in left

ventricular (LV) mass (Krittayaphong et al., 2009). LVH reflects increased left ventricular mass, which contributes to increased myocardial oxygen demand, and which may cause inadequate blood supply to the myocardium and may also cause myocardial ischemia or infarction (Aguilar et al., 2004). Treatments that reduce LV mass are associated with lower morbidity and mortality (Koren, Ulin, Koren, Laragh, & Devereux, 2002; Verdecchia et al., 2003, 1998).

The most commonly used tool for diagnosis of LVH is 12-lead electrocardiography (ECG), which is simple, low-cost, and widely available (Estes & Jackson, 2009). Many ECG criteria have demonstrated varying levels of accuracy relative to their ability to diagnose LVH (Krittayaphong et al., 2013; Schlegel et al., 2010; Xie & Wang, 2010), including Cornell voltage (Casale, Devereux, Alonso, Campo, & Kligfield, 1987; Casale et al., 1985), Cornell product (Ishikawa et al., 2009), Romhilt-Estes point score system (Romhilt et al., 1969; Romhilt & Estes, 1968), Sokolow-Lyon index (Sokolow & Lyon, 1949), and Sokolow-Lyon-Rappaport index (Levy et al., 1990). Echocardiography is a commonly used comparative method due to its wide availability; however, echocardiography has significant inter-observer variability (Dai, Ayres, Harrist, Bricker, & Labarthe, 1999). Cardiac magnetic resonance (CMR) imaging is a gold standard investigation for assessing left ventricular volume, left ventricular mass, and left ventricular ejection fraction (LVEF) due to its high image resolution, its three-dimensional image acquisition, and the fact that it has less intra- and inter-observer variability compared to echocardiogram (Buchner et al., 2009; Mor-Avi et al., 2004; Myerson, Bellenger, & Pennell, 2002).

Various ECG criteria contain R, S, and/or QRS wave amplitudes as components of their criteria (Casale et al., 1985; Levy et al., 1990; Molloy, Okin, Devereux, & Kligfield, 1992; Romhilt & Estes, 1968; Sokolow & Lyon, 1949). However, there are many factors that influence ECG amplitudes, including chest wall thickness. Higher body mass index (BMI) was shown to be associated with lower ECG amplitudes in patients with similar LV mass (Nasir, Rubal, Jones, & Shah, 2012). Prior study showed the sensitivity of Cornell voltage product to be significantly lower in obese normotensive patients than in non-obese normotensive patients (Norman & Levy, 1996). However, data relating to the performance of ECG criteria for diagnosing LVH among four BMI groups is scarce. Accordingly, the aim of this study was to investigate the diagnostic performance of ECG criteria for diagnosing LVH among various BMI groups compared to diagnosis by CMR imaging.

2 | METHODS

2.1 | Study population

This study included patients >18 years of age that underwent both ECG and CMR on the same day at Faculty of Medicine Siriraj Hospital, Mahidol University, during the 2005–2009 study period. Siriraj Hospital is a 2,300-bed national tertiary referral hospital that is located in Bangkok, Thailand. Patients unable to complete the CMR examination or with known contraindication for CMR, such as pacemaker, internal defibrillator, or intracranial clip, were

excluded. Patients with unstable clinical conditions, claustrophobia, conduction abnormalities (e.g., Wolff-Parkinson-White syndrome), complete left bundle branch block, or right bundle branch block were also excluded. One hundred and eighty-four healthy volunteers that underwent CMR comprised the control group for this study. Control group CMR results were used to establish the diagnosis threshold for LVH by CMR. The protocol for this study was approved by the Siriraj Institutional Review Board (SIRB), and written informed consent was obtained from all study participants.

2.2 | CMR protocol

Cardiac magnetic resonance for left ventricular function, volume, and mass was performed using a Philips Gyroscan NT 1.5 T MRI Scanner (Philips Medical Systems, Best, the Netherlands). Cine images and spin echo images were performed using a steady-state free-precession (SSFP) technique. Images were acquired in 4-chamber, vertical long-axis, horizontal long-axis, and multiple-slice short-axis series. Functional images were developed according to the following parameters: echo time/repetition time/number of excitations = 1.8/3.7/2; 256 × 240 matrix; 390 × 312 mm field of view; 8 mm slice thickness; 1.52 × 1.21 reconstruction pixel; and, 70 degree flip angle.

2.3 | Analysis of CMR images

Cardiac magnetic resonance images were analyzed on a View Forum Workstation (Philips Medical Systems). Left ventricular volume was measured and calculated in end-systolic (left ventricular end-systolic volume, LVESV) and end-diastolic phase (left ventricular end-diastolic volume, LVEDV). Left ventricular mass (LVMASS) and LVEF were also calculated. Indices of LVEDV, LVESV, and LVMASS (LVEDVI, LVESVI, and LVMASSI) were calculated by index to body surface area.

Patients were considered to have LVH when their LVMASSI was above 95% of the LVMASSI (Solberg, 1987). Similarly, we used the 95th percentile for LVMASSI in the healthy population as the cut-off value for diagnosis of LVH by CMR (Krittayaphong, Saiviroonporn, Boonyasirinant, Nakyen, & Kangkagate, 2004).

2.4 | Analysis of 12-lead ECG results

Twelve-lead ECG was performed on the same day prior to CMR examination. ECG output data was recorded at a paper speed of 25 mm/s and 10 mm/mV with the patient resting in the supine position and breathing calmly. ECG results were interpreted by experienced investigators who were unaware of the patient's clinical information and CMR results. The following ECG criteria were used in this study: (a) Cornell voltage (Casale et al., 1987, 1985); (b) Cornell product (Ishikawa et al., 2009); (c) Romhilt-Estes point score system of at least five points (Romhilt et al., 1969; Romhilt & Estes, 1968); (d) Sokolow-Lyon index (Sokolow & Lyon, 1949); and (e) Sokolow-Lyon-Rappaport index (Levy et al., 1990). The

criteria for the diagnosis of LVH for each of the aforementioned ECG criteria are presented in Supporting Information Table S1.

2.5 | Statistical analysis

SPSS Statistics version 20 (SPSS, Inc., Chicago, IL, USA) was used to perform all data analyses. Continuous data are reported as

mean $\pm$ standard deviation (SD), and categorical data are reported as number and percentage. Continuous data were compared using independent t-test or analysis of variance (ANOVA), and categorical data were compared using chi-square test. Sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and accuracy were calculated. Patients were classified into four groups according to BMI: underweight (BMI: $<18.5 \text{ kg/m}^2$), normal

TABLE 1 Baseline demographic and clinical characteristics

Characteristics	Total (n = 1,882)	Underweight (n = 67)	Normal (n = 459)	Overweight (n = 434)	Obese (n = 922)	p-Value
Male gender	994 (52.8%)	36 (53.7%)	247 (53.8%)	249 (57.4%)	462 (50.1%)	0.088
Age (years)	64.5 $\pm$ 11.3	66.2 $\pm$ 16.1	65.2 $\pm$ 12.0	64.5 $\pm$ 11.2	64.1 $\pm$ 10.6	<0.001
Weight (kg)	65.2 $\pm$ 12.3	45.3 $\pm$ 4.5	54.7 $\pm$ 6.5	62.5 $\pm$ 6.3	73.1 $\pm$ 10.9	<0.001
Height (cm)	160.4 $\pm$ 8.4	161.2 $\pm$ 7.1	160.5 $\pm$ 8.4	161.1 $\pm$ 8.0	160.0 $\pm$ 8.7	0.123
BSA (m ²)	1.7 $\pm$ 0.2	1.4 $\pm$ 0.1	1.6 $\pm$ 0.1	1.7 $\pm$ 0.1	1.8 $\pm$ 0.2	<0.001
BMI (kg/m ²)	25.3 $\pm$ 4.1	17.4 $\pm$ 0.9	21.2 $\pm$ 1.2	24.0 $\pm$ 0.6	28.5 $\pm$ 3.1	<0.001
SBP (mmHg)	137.8 $\pm$ 23.8	144.0 $\pm$ 30.8	138.0 $\pm$ 25.9	138.3 $\pm$ 22.7	137.0 $\pm$ 22.8	<0.001
DBP (mmHg)	75.7 $\pm$ 13.3	75.8 $\pm$ 15.6	75.5 $\pm$ 13.3	76.9 $\pm$ 12.5	75.3 $\pm$ 13.5	0.265
Current smoker	374 (19.9%)	17 (25.4%)	101 (22.0%)	80 (18.4%)	176 (19.1%)	0.320
Hypercholesterolemia	1,206 (64.1%)	42 (62.7%)	276 (60.1%)	284 (65.4%)	604 (65.5%)	0.228
Diabetes mellitus	663 (35.2%)	18 (26.9%)	130 (28.3%)	139 (32.0%)	376 (40.8%)	<0.001
Hypertension	1,177 (62.5%)	35 (52.2%)	246 (53.6%)	258 (59.4%)	638 (69.2%)	<0.001
History of MI	272 (14.5%)	16 (23.9%)	76 (16.6%)	65 (15.0%)	115 (12.5%)	0.024
History of angina	92 (4.9%)	4 (6.0%)	21 (4.6%)	24 (5.5%)	43 (4.7%)	0.861
History of PCI	182 (9.7%)	10 (14.9%)	42 (9.2%)	41 (9.4%)	89 (9.7%)	0.515
History of CABG	116 (6.2%)	5 (7.5%)	29 (6.3%)	30 (6.9%)	52 (5.6%)	0.784
History of DOE	863 (45.9%)	37 (55.2%)	214 (46.6%)	181 (41.7%)	431 (46.7%)	0.123
Medications						
Beta blocker	944 (50.2%)	34 (50.7%)	220 (47.9%)	221 (50.9%)	469 (50.9%)	0.751
CCB	424 (22.5%)	14 (20.9%)	102 (22.2%)	85 (19.6%)	223 (24.2%)	0.292
Nitrate	679 (36.1%)	33 (49.3%)	162 (35.3%)	154 (35.5%)	330 (35.8%)	0.153
ASA	1,174 (62.4%)	40 (59.7%)	278 (60.6%)	264 (60.8%)	592 (64.2%)	0.456
Clopidogrel	68 (3.6%)	6 (9.0%)	12 (2.6%)	23 (5.3%)	27 (2.9%)	0.009
ACEI	612 (32.5%)	23 (34.3%)	145 (31.6%)	120 (27.6%)	324 (35.1%)	0.049
ARB	163 (8.7%)	6 (9.0%)	26 (5.7%)	41 (9.4%)	90 (9.8%)	0.073
Statins	1,057 (56.2%)	40 (59.7%)	222 (48.4%)	250 (57.6%)	545 (59.1%)	0.002
CMR variables						
LVH	459 (24.4%)	34 (50.7%)	144 (31.4%)	100 (23.0%)	181 (19.6%)	<0.001
LVEF (%)	60.5 $\pm$ 18.5	49.0 $\pm$ 19.5	56.6 $\pm$ 20.0	59.9 $\pm$ 18.8	63.5 $\pm$ 16.8	<0.001
Abnormal wall motion	686 (36.5%)	40 (59.7%)	197 (42.9%)	158 (36.4%)	291 (31.6%)	<0.001
LVEDVI (ml/m ²)	75.7 $\pm$ 35.3	99.8 $\pm$ 48.1	84.8 $\pm$ 41.3	76.7 $\pm$ 37.7	69.0 $\pm$ 26.9	<0.001
LVESVI (ml/m ²)	35.5 $\pm$ 35.9	56.5 $\pm$ 49.2	44.1 $\pm$ 41.4	36.4 $\pm$ 37.8	29.2 $\pm$ 28.6	<0.001
LVMASSI (g/m ²)	55.6 $\pm$ 20.8	65.9 $\pm$ 25.5	58.4 $\pm$ 22.8	55.5 $\pm$ 20.8	53.5 $\pm$ 18.9	<0.001

Note. Data presented as mean $\pm$ standard deviation or number and percentage.

A p-value < 0.05 indicates statistical significance (bold and italic values).

ACEI: angiotensin converting enzyme inhibitor; ARB: angiotensin receptor blocker; ASA: acetylsalicylic acid; BMI: body mass index; BSA: body surface area; CABG: coronary artery bypass graft; CCB: calcium channel blocker; DBP: diastolic blood pressure; DOE: dyspnea on exertion; LVEDVI: left ventricular end-diastolic volume index; LVEF: left ventricular ejection fraction; LVESVI: left ventricular end-systolic volume index; LVH: left ventricular hypertrophy; LVMASSI: left ventricular mass index; MI: myocardial infarction; PCI: percutaneous coronary intervention; SBP: systolic blood pressure.

weight (BMI: 18.5–22.9 kg/m²) group, overweight (BMI: 23.0–24.9 kg/m²) and obese (BMI: ≥25 kg/m²) group. Chi-square test for trend was used to evaluate sensitivity and specificity trends among different BMI groups when using the same ECG criteria. Non-parametric test for related samples was used to compare the sensitivity and specificity of each ECG criterion in the same BMI group. A *p*-value < 0.05 was considered to be statistically significant.

3 | RESULTS

3.1 | Demographic data

Two thousand two hundred and twenty-six (2,226) patients were referred for CMR during 2005–2009. After the exclusion of 344 patients, the remaining 1,882 patients were enrolled in this study. The baseline demographic and clinical characteristics of each BMI group are given in Table 1. Sixty-seven (3.6%) patients were in the underweight group, 459 (24.4%) patients were in the normal weight group, 434 (23.1%) patients were in the overweight group, and 922

(49.0%) patients were in the obese group. LVH was diagnosed in 459 patients (24.4%), including 34 underweight patients (50.7%), 144 normal weight patients (31.4%), 100 overweight patients (23.0%), and 181 obese patients (19.6%). The higher BMI groups had a significantly higher prevalence of diabetes mellitus and hypertension. The lower BMI groups had a significantly higher prevalence of history of myocardial infarction and abnormal wall motion on CMR.

3.2 | Diagnostic performance of ECG criteria for LVH diagnosis

Sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and accuracy of each ECG criterion are shown in Table 2. Overall sensitivity and specificity of each ECG criterion is presented in Figure 1. The overall specificity of ECG for diagnosing LVH was higher than the overall sensitivity. The three parameters with the highest sensitivity were Cornell product, Romhilt-Estes point score system, and Sokolow-Lyon-Rappaport index—all of which were greater than 0.360 (*p* > 0.05).

TABLE 2 Diagnostic performance of five evaluated ECG criteria

Criteria	BMI group	Sensitivity	Specificity	PPV	NPV	Accuracy
Cornell voltage	Overall	0.29 (0.25–0.33)	0.94 (0.93–0.96)	0.62 (0.56–0.69)	0.80 (0.78–0.82)	0.78 (0.77–0.80)
Cornell voltage	Underweight	0.41 (0.26–0.58)	0.97 (0.85–0.99)	0.93 (0.70–0.99)	0.62 (0.48–0.74)	0.69 (0.57–0.79)
Cornell voltage	Normal	0.33 (0.26–0.41)	0.94 (0.91–0.96)	0.73 (0.61–0.82)	0.76 (0.71–0.80)	0.75 (0.71–0.79)
Cornell voltage	Overweight	0.26 (0.18–0.35)	0.93 (0.90–0.96)	0.54 (0.40–0.67)	0.88 (0.77–0.84)	0.78 (0.74–0.82)
Cornell voltage	Obesity	0.24 (0.18–0.31)	0.95 (0.93–0.96)	0.53 (0.42–0.67)	0.84 (0.81–0.86)	0.81 (0.78–0.83)
Cornell product	Overall	0.37 (0.33–0.42)	0.93 (0.92–0.94)	0.64 (0.58–0.69)	0.82 (0.80–0.84)	0.80 (0.78–0.81)
Cornell product	Underweight	0.47 (0.32–0.63)	0.94 (0.80–0.98)	0.89 (0.67–0.970)	0.63 (0.49–0.75)	0.70 (0.58–0.80)
Cornell product	Normal	0.40 (0.32–0.48)	0.94 (0.91–0.96)	0.75 (0.64–0.83)	0.77 (0.728–0.812)	0.77 (0.73–0.81)
Cornell product	Overweight	0.34 (0.26–0.44)	0.934 (0.90–0.96)	0.61 (0.48–0.72)	0.83 (0.78–0.86)	0.80 (0.76–0.83)
Cornell product	Obesity	0.35 (0.28–0.42)	0.93 (0.91–0.95)	0.54 (0.45–0.63)	0.85 (0.83–0.88)	0.82 (0.79–0.838)
Romhilt	Overall	0.37 (0.33–0.42)	0.89 (0.87–0.90)	0.52 (0.46–0.57)	0.81 (0.79–0.83)	0.76 (0.74–0.78)
Romhilt	Underweight	0.50 (0.34–0.66)	0.94 (0.80–0.98)	0.90 (0.69–0.97)	0.65 (0.50–0.77)	0.72 (0.60–0.81)
Romhilt	Normal	0.40 (0.33–0.48)	0.88 (0.84–0.91)	0.60 (0.50–0.70)	0.76 (0.72–0.80)	0.73 (0.69–0.77)
Romhilt	Overweight	0.36 (0.27–0.46)	0.87 (0.82–0.90)	0.44 (0.34–0.55)	0.82 (0.78–0.86)	0.75 (0.71–0.79)
Romhilt	Obesity	0.33 (0.26–0.40)	0.90 (0.88–0.92)	0.44 (0.36–0.53)	0.85 (0.82–0.87)	0.79 (0.76–0.81)
Sokolow	Overall	0.25 (0.21–0.29)	0.95 (0.94–0.96)	0.62 (0.55–0.69)	0.80 (0.78–0.82)	0.80 (0.76–0.80)
Sokolow	Underweight	0.35 (0.22–0.52)	0.91 (0.76–0.97)	0.80 (0.55–0.93)	0.58 (0.44–0.70)	0.627 (0.51–0.73)
Sokolow	Normal	0.24 (0.18–0.32)	0.95 (0.92–0.97)	0.67 (0.54–0.79)	0.73 (0.69–0.77)	0.73 (0.68–0.76)
Sokolow	Overweight	0.28 (0.20–0.38)	0.93 (0.90–0.95)	0.55 (0.41–0.68)	0.81 (0.77–0.85)	0.78 (0.74–0.82)
Sokolow	Obesity	0.21 (0.16–0.28)	0.96 (0.95–0.98)	0.59 (0.46–0.70)	0.83 (0.81–0.86)	0.82 (0.79–0.84)
Rappaport	Overall	0.37 (0.33–0.42)	0.91 (0.89–0.92)	0.560 (0.50–0.61)	0.818 (0.80–0.84)	0.78 (0.76–0.80)
Rappaport	Underweight	0.53 (0.37–0.69)	0.79 (0.62–0.89)	0.72 (0.52–0.86)	0.62 (0.47–0.75)	0.66 (0.54–0.76)
Rappaport	Normal	0.40 (0.32–0.49)	0.89 (0.85–0.92)	0.62 (0.52–0.72)	0.77 (0.73–0.81)	0.74 (0.70–0.78)
Rappaport	Overweight	0.37 (0.28–0.47)	0.89 (0.85–0.92)	0.50 (0.39–0.61)	0.82 (0.78–0.86)	0.77 (0.73–0.81)
Rappaport	Obesity	0.32 (0.26–0.39)	0.93 (0.90–0.94)	0.51 (0.42–0.60)	0.85 (0.82–0.87)	0.81 (0.78–0.83)

Note. Sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and accuracy are presented as the calculated value (95% confidence interval).

Rappaport: Sokolow-Lyon-Rappaport index; Romhilt: Romhilt-Estes point score system at score ≥5 for diagnosis of LVH; Sokolow: Sokolow-Lyon index.

FIGURE 1 Overall sensitivity (a) and specificity (b) of ECG criteria (* $p < 0.05$)

The three parameters with the highest specificity were Cornell voltage, Cornell product, and Sokolow-Lyon index—all of which were greater than 0.90 ($p > 0.05$).

The sensitivity and specificity of the five investigated ECG criteria compared among the four different BMI groups are shown in Figure 2. Chi-square test for trend revealed no significant difference in the specificity of each ECG criterion when compared among the four BMI groups, except for Sokolow-Lyon-Rappaport index ($p = 0.006$). In contrast, chi-square test for trend showed the sensitivities of Cornell voltage, Romhilt-Estes point score system, and Sokolow-Lyon-Rappaport index to be significantly decreased when BMIs increased. No statistically significant difference was observed for Cornell product or Sokolow-Lyon index.

Additional analysis was performed that compared the sensitivity and specificity of each ECG criteria between patients with overweight or obese status ($\text{BMI} \geq 23 \text{ kg/m}^2$) and patients with normal or underweight status. The results of that analysis are shown in Figure 3. The three most highly sensitive ECG criteria in patients with overweight or obese status were Cornell product,

Romhilt-Estes point score system, and Sokolow-Lyon-Rappaport index. The three most highly specific ECG criteria were Cornell voltage, Cornell product, and Sokolow-Lyon index.

4 | DISCUSSION

The present study set forth to investigate the effect of BMI on the diagnostic performance of ECG criteria. To do so, we divided study participants into the following four BMI groups: underweight, normal, overweight, and obese. The results showed a similar specificity, but a decrease in sensitivity in the increasing BMI groups. The three criteria with the highest sensitivity were Cornell product, Romhilt-Estes point score system, and Sokolow-Lyon-Rappaport index. The three criteria with the highest specificity were Cornell voltage, Cornell product, and Sokolow-Lyon index.

In the present study, the overall specificity was high (0.888–0.951), and the overall sensitivity was low (0.246–0.373) for all ECG criteria, which corresponds with the results reported from previous studies (Buchner et al., 2009; Norman & Levy, 1996; Rodrigues et al., 2016).

FIGURE 2 Sensitivity (a) and specificity (b) of ECG criteria among BMI groups (* $p < 0.05$)

Norman and Levy (1996) used echocardiography as the gold standard, and they found Cornell product to have a higher sensitivity than Cornell voltage. They also showed that the sensitivity of Cornell product decreases in obesity after fixing the specificity at 95%. Similarly, we found that obesity decreased the sensitivity not only for Cornell voltage, but also for Romhilt-Estes point score system and Sokolow-Lyon-Rappaport index. The sensitivity of Cornell product was slightly higher than the sensitivity of Cornell voltage in our study ($p > 0.05$).

Rodrigues et al. (2016) compared different ECG criteria for LVH in obese and non-obese patients and found that obesity decreased both sensitivity and specificity. Our study showed a similar result for sensitivity, but obesity had no effect on specificity. The Rodrigues et al. study recruited patients from hypertensive population who had undergone CMR as part of the investigation for secondary causes of hypertension, and to quantify hypertensive end-organ damage. In contrast, we recruited from a population of patients who had undergone CMR for any clinical purpose. This difference would naturally result in differences between studies relative to patients' characteristics and underlying heart diseases.

The lower sensitivity in the high BMI groups was attributed to an increased amount of subcutaneous adipose tissue that increases the distance between the ECG recording electrodes and the heart

(Horton, Sherber, & Lakatta, 1977; Nasir et al., 2012). It is, therefore, possible that undetected LVH could exist in overweight and obese patients, and this could adversely affect risk stratification, self-awareness, and treatment strategy. Further study to adjust ECG criteria for diagnosis of LVH in higher BMI groups, and to improve the diagnostic performance of those criteria should be considered.

In overweight and obese population, our results revealed Cornell product, Romhilt-Estes point score system, and Sokolow-Lyon-Rappaport index to be the most sensitive ECG criteria, and Cornell voltage, Cornell product, and Sokolow-Lyon index to be the most specific ECG criteria for diagnosing LVH. Cornell product should, therefore, be regarded as the ECG criteria of choice in overweight and obese population. This recommendation is consistent with that proposed by Okin, Jern, Devereux, Kjeldsen, and Dahlöf (2000). The main strength of this study compared to the aforementioned studies is the large size of our study population, and the fact that we used CMR as the gold standard for assessment of LVH.

4.1 | Limitations

First, the patients included in the present study were patients who underwent CMR for clinical purposes at Siriraj Hospital, which means that a higher prevalence of LVH and other cardiac abnormalities would

FIGURE 3 Comparison of sensitivities (a) and specificities (b) among the evaluated ECG criteria for each BMI group (* $p < 0.05$)

be observed in our study population than the prevalence of these conditions that would be found in normal population. Therefore, further study in general population needs to be conducted to confirm the generalizability of these findings. Second, increasing BMI may not always indicate increased subcutaneous adipose tissue (Etchison et al., 2011). For example, athletes and body builders have higher BMIs due to a higher percentage of lean muscle mass. Further investigation using skinfold thickness (Durnin & Womersley, 1974) or dual-energy X-ray absorptiometry (DEXA; Kelly, Berger, & Richardson, 1998) should be conducted to determine the effect of subcutaneous tissue and its association with ECG diagnostic performance.

5 | CONCLUSION

All of the ECG criteria evaluated in this study demonstrated relatively high specificity and relatively low sensitivity. Although the specificity across groups remained similar, higher BMI was found to be significantly associated with decreased sensitivity. The results of this study suggest Cornell product as the ECG criteria of choice in overweight or obese population due to its relatively higher sensitivity and specificity compared to the other evaluated ECG criteria.

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CONFLICT OF INTEREST

Both authors declare no personal or professional conflicts of interest relating to any aspect of this study.

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