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Limitations of Electrocardiography for Detecting Left Ventricular Hypertrophy or Concentric Remodeling in Athletes

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Dr. Victor Froelicher and Dr. David Hadley are developers and part owners of the ECG system used to acquire the digitized ECG data (Cardea 20/20 ECG System, Cardea Insight Inc., Bellevue, WA, USA). No other potential conflicts of interest are present for any co-author.

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Key words

ECG; echocardiography; pre-participation evaluation; athlete's heart; left ventricular mass

ABSTRACT

Background

Electrocardiography (ECG) is used to screen for left ventricular hypertrophy (LVH), but common ECG-LVH criteria have been found less effective in athletes. The purpose of this study was to comprehensively evaluate the value of ECG for identifying athletes with left ventricular hypertrophy and/or a concentric cardiac phenotype.

Methods

A retrospective analysis of 196 male division 1 college athletes routinely screened with ECG and echocardiography within The Stanford Athletic Cardiovascular Screening Program was performed. Left-ventricular mass and volume were determined using echocardiography. Left ventricular hypertrophy was defined as left ventricular mass $>102 \text{ g/m}^2$; a concentric cardiac phenotype as left ventricular mass/volume (M/V) $\geq 1.05 \text{ g/mL}$. Twelve-lead ECGs including high-resolution time intervals and QRS voltages were obtained. 37 previously published ECG-LVH criteria were applied, of which the majority have never been evaluated in athletes. C-statistics, including area under the receiver operating curve (AUC), and likelihood ratios were calculated.

Results

ECG lead voltages were poorly associated with left ventricular mass ($r=0.18-0.30$) and M/V ($r=0.15-0.25$). The proportion of athletes with ECG-LVH was 0-74% across criteria, with sensitivity and specificity ranging between 0-91% and 27-99.5%, respectively. The average AUC of the criteria in identifying the 11 athletes with left ventricular hypertrophy was 0.57 (95% CI 0.56-0.59), while the average AUC for identifying the eight athletes with a concentric phenotype was 0.59 (95% CI 0.56-0.62).

Conclusion

The diagnostic capacity of all ECG-LVH criteria were inadequate and therefore not clinically useful in screening for left ventricular hypertrophy or a concentric phenotype in athletes. This is probably due to the weak association between left ventricular mass and ECG voltage.

INTRODUCTION

Electrocardiography (ECG) is currently recommended as part of the athletic pre-participation screening protocol,^{1,2} and several studies have proven its role for screening for cardiomyopathies and channelopathies.³ The role of ECG for identifying left ventricular hypertrophy (LVH) remains more controversial, and the current guidelines for ECG interpretation in athletes consider an isolated finding of increased QRS-voltage a normal finding.² Although scarcely evaluated in athletes,⁴⁻⁶ this recommendation is logical considering the low diagnostic accuracy of the most commonly used ECG criteria for detecting left ventricular hypertrophy.^{7,8}

Several ECG based criteria have been proposed to assess left ventricular hypertrophy (ECG-LVH), focusing on either limb voltage, precordial voltage, or their combination. In addition, non-voltage parameters such as QRS-duration have been incorporated into ECG-LVH criteria and point scores as well as an ECG-based equation of left ventricular mass estimation have been developed. Currently, it is unknown how these different criteria compare for the detection of left ventricular hypertrophy in athletes.

Moreover, considering the physiological increase in left ventricular mass frequently reported in athletes,^{2,9} identifying those subjects with a non-proportional increase in left ventricular mass might be of greatest clinical value.^{10,11} This can be quantified as the left ventricular mass to volume ratio (M/V), which previously has been shown to distinguish physiological from pathological left ventricular remodeling in athletes.^{12,13} Whether any available ECG-LVH criteria can identify athletes with increased M/V has not been explored.

The main purpose of the current study was to compare 37 voltage and non-voltage ECG criteria for the detection of left ventricular hypertrophy in college athletes, as well as for identifying those athletes with a concentric cardiac phenotype, estimated by M/V.

METHODS

Cohort

Participants included male college athletes who had a digitized resting ECG and a routine echocardiographic examination as part of their annual pre-participation cardiovascular screening evaluation (PPE) at Stanford University between 2010-2016. Exclusion criteria were (i) abnormal ECG findings as per current guidelines,² (ii) probable electrode misplacement on retrospective ECG evaluation, (iii) inadequate echocardiographic image quality. All participants signed consent forms at the PPE and echocardiographic examination approved by the institutional review board at Stanford University (approval numbers 12245 and 25673, respectively).

ECG examination and interpretation

Standard 12-lead ECGs were acquired by experienced medical personnel within the Stanford Sports Cardiology PPE program and were read on-site by an experienced sports cardiologist. The ECG tracings were recorded at 25 mm/s and obtained with the athlete in the supine position during quiet respiration after a short period of rest. Detailed, digitized ECG data was collected and saved to a database using the Cardea 20/20™ Resting ECG Analysis System (Cardea Insight Inc., Bellevue, WA, USA), including time intervals with a precision of 1 ms, P-QRS-T amplitudes with a precision of 1 μ V (1/1000 mV) and time-voltage area of the P-wave, QRS-complex and ST-T complex. For data analysis, the greatest deflection of either R or r' and of either S and s' were used as R and S wave amplitude, respectively.

For the purpose of this study, all ECGs were re-read manually in November 2018 by the same experienced sports cardiologist, applying the most current guidelines.²

ECG criteria

We applied 37 available ECG criteria with published thresholds for detection of left ventricular hypertrophy. summarized in Figure 1 and detailed in eTable1 in Supplements. This included the current

criterion for ECG interpretation in athletes,² 24 criteria summarized in the current guidelines for ECG interpretation in cardiac chamber hypertrophy,⁷ eight criteria recently evaluated by our group for long-term cardiovascular mortality in a non-athletic population,¹⁴ and four additional criteria. We categorized each criteria as either of (I) voltage only criteria (n=30); (II) criteria including QRS-duration (n=4); (III) point score criteria (n=2) and (IV) mass equation criterion (n=1). The voltage only criteria were further sub-categorized as (Ia) limb lead (n=7); (Ib) precordial lead (n=15) or (Ic) limb+precordial lead voltage criteria (n=8).

Echocardiographic determination of left ventricular mass and M/V

All subjects had an echocardiographic examination within 30 days from the ECG recording, of which 81% was performed the same day. Echocardiography was performed with subjects in the lateral decubitus position using a commercially available system (iE33; Philips Medical Imaging, Andover, MA, USA) with images analyzed on Xcelera workstations. The echocardiographic protocol included 2-D and color Doppler in parasternal and apical views. Left ventricular mass (LVM) and volume were calculated using the area-length method in end-diastole from short-axis images and left ventricular length was measured in the apical 4-chamber view (eFigure 1 in Supplement). Mass to volume ratio was derived by dividing left ventricular mass by left ventricular volume. Left ventricular mass was indexed by body surface area (BSA; $LVM[BSA]$) as well as by allometrically scaled body surface area and height ($LVM[BSA^{1.5}]$ and $LVM[height^{2.7}]$). The presence of left ventricular hypertrophy per echocardiography was determined using current echocardiographic guidelines¹⁵; $LVM[BSA] > 102 \text{ g/m}^2$. A concentric cardiac phenotype was defined as a M/V in the upper 95th percentile of the cohort.

Statistical analyses

SPSS software, v25.0 (IBM Corp, Armonk, NY, USA) was used for database management and statistical analysis. R Studio v1.1.456 (R Studio Inc., Vienna, Austria) was used to calculate the numeric sums of each combined criterion and to determine which criteria each athlete fulfilled. These scripts are included in eMethods. Continuous data were expressed as mean $\pm$ SD, categorical data as number of observations and frequency. We evaluated differences between groups with Student's t-test for continuous variables and Chi² test for categorical variables and P-values < 0.05 were considered statistically significant. The physiological association between single lead voltage as well as summed voltages within each criterion and indexed and unindexed left ventricular mass and M/V were explored using bivariate correlation analysis, where negative deflections (Q and S waves) were transferred to their absolute (positive) values. We calculated the odds ratios for having left ventricular hypertrophy by echocardiography and selected

ECG criteria, respectively, based on anthropometric and demographic variables using binary logistic regression.

Area under the receiving operating curve (AUC) with 95% confidence interval (CI) was calculated for each ECG criterion with its corresponding, suggested cut-off value, using (i) echocardiographic left ventricular hypertrophy as per guidelines, (ii) M/V in upper 95th percentile or (i) and (ii) in combination as outcome variable, respectively. An AUC with a 95% CI overlapping 0.5 was considered non-discriminatory. The methodology and calculations of each diagnostic metric is detailed in eTable 2, assuming a pre-test probability equal to the prevalence of each entity.

RESULTS

196 male athletes were included after excluding two subjects with a pathological ECG (one with anterior pathological Q-wave, one with pathological lateral T-wave inversion), three subjects with lead misplacement and four subjects where echocardiographic images did not allow reliable left ventricular mass estimation.

Left ventricular mass and M/V by echocardiography

LVM[BSA] and M/V were normally distributed (figure 2a+b), with average values of 81 ± 12 g/m² and 0.87 ± 0.10 g/mL, respectively. The upper 95th percentile of LVM[BSA] was 102 g/m², identical to the threshold in echocardiographic guidelines for defining left ventricular hypertrophy.¹⁵ and 11 athletes displayed echocardiographic left ventricular hypertrophy. Four of the eight athletes in the upper 95th percentile for M/V (1.05 g/mL) also had left ventricular hypertrophy (figure 2c+d).

Proportion of athletes with positive ECGs

There was a large difference between ECG-LVH criteria in the number of athletes with a positive ECG, ranging from 0 to 74% (figure 3a). In particular, with the original version of the Sum of 12 leads and Sum of 12-leads-product criteria, 68% and 74% of athletes, respectively, had a positive ECG.

Forty-nine (25%) athletes fulfilled the ECG-LVH criterion in current athletic guidelines (S V1 + R V5/V6 >35 mm).² As seen in table 1, these subjects were on average leaner (body mass index 25 ± 4 vs. 28 ± 5 kg/m², $p < 0.001$) and included a larger proportion of Afro-American athletes (47% vs. 27%, $p < 0.001$) and basketball players (24% vs. 3%, $p < 0.001$).

By sports, 18% of American football, 25% of volleyball and 75% of basketball players fulfilled the guideline criterion. Accordingly, the odds ratio for being positive for ECG-LVH as per current guidelines was 4.3 (95% CI 1.0-18.2) for basketball players and 0.3 (0.1-1.0) for subjects with a body mass index >30 kg/m² in a multivariable logistic regression model (eTable 3). In contrast, having left

ventricular hypertrophy per echocardiography (i.e. an LVM[BSA] >102 g/m²) was not associated with ECG-LVH per current guidelines (β =2.7, 95% CI 0.8-9.2, p =0.12).

Association between left ventricular mass and ECG voltage

Unindexed left ventricular mass was correlated with R-wave amplitude in aVL, I, V5 and V6 (Pearson r =0.18 – 0.30, eTable 4). Indexing left ventricular mass by body surface area or allometrically with either BSA^{1.5} or height^{2.7} had little impact on the strength of these correlations.

In general, the correlations were similarly weak between indexed and unindexed left ventricular mass, M/V and ECG measures when the latter were combined as within different criteria (eTable 5). The only exception was the Framingham adjusted Cornell criteria¹⁶, accounting for age, sex and body mass index, where the correlation to unindexed left ventricular mass was nominally stronger (r =0.50, p <0.001).

Diagnostic ability of ECG criteria for detecting left ventricular hypertrophy or/and a high M/V

Left ventricular hypertrophy

As seen in figure 3b, the greatest AUC of any criterion for detecting the 11 subjects with left ventricular hypertrophy was 0.69 (95% CI 0.52-0.86) for the combined Sokolow-Lyon criteria; the only criterion with a AUC 95% CI not overlapping 0.50. The average AUC of all criteria was 0.57 (95% CI 0.56-0.59). There was a wide range in both sensitivity and specificity among criteria for detecting left ventricular hypertrophy (Figure 4 and eTable 5). The highest positive likelihood ratio for any criterion was 8.4 for having an S-wave in V1 >23mm, resulting in a post-test probability of having left ventricular hypertrophy of 33% (eFigure 3).

Mass to volume ratio (M/V)

The diagnostic ability of the ECG criteria to identify the eight athletes with a M/V in the upper 95th percentile (i.e. ≥ 1.05 g/mL) is detailed in eTable 6 and Figure 4. The average AUC was 0.59 (95% CI 0.56-0.62) and four criteria had an AUC >0.70, all with a 95% CI not-overlapping 0.50; Romhilt-Estes point score (AUC 0.74); Perugia point score (AUC 0.71); modified sum of 12 leads (AUC 0.74);

modified sum of 12 leads-product (AUC 0.72). No criterion had a post-test probability >20% if ECG-LVH positive (eFigure 3).

The difference in AUC for each criterion's ability to identify left ventricular hypertrophy and a high M/V, respectively is contrasted in eFigure 4. In particular, the Romhilt-Estes score had higher AUC for identifying subjects with a high M/V than those with left ventricular hypertrophy (M/V AUC: 0.74 vs. left ventricular hypertrophy AUC: 0.56).

The combination of left ventricular hypertrophy and a concentric phenotype

The ability of the ECG criteria to identify the four subjects with both echocardiographic left ventricular hypertrophy and high M/V was generally superior to identifying left ventricular hypertrophy or high M/V alone. Three criteria, all precordial, had an AUC >0.75; max of (R + S) in any precordial lead >35 mm (AUC 0.87, 95% CI 0.78-0.95); S V1 + R V5 >35 mm (AUC 0.76, 95% CI 0.51-1.00) and S V1 + R V5/V6 >35 mm (AUC 0.76, 95% CI 0.51-1.00). Having an R + S wave >35 mm in any precordial lead identified all four athletes with a specificity of 73%. The positive likelihood ratio of this criteria was 27.8, while the low prevalence (2%) constrained the post-test probability of having a combination of left ventricular hypertrophy and high M/V at 37%.

DISCUSSION

This study demonstrates that QRS-amplitudes on surface ECG can not be used as a marker of left ventricular mass in male athletes, and none of the 37 ECG-LVH criteria evaluated are clinically useful for discriminating athletes with abnormally high left ventricular mass or with a concentric cardiac phenotype. A few precordial lead ECG criteria performed reasonably well in identifying athletes with a combination of left ventricular hypertrophy and high M/V (i.e. concentric hypertrophy), which is a novel albeit exploratory finding that could be of substantial clinical value and invites further studies.

The cardiac phenotype of athletes ('athlete's heart') has been extensively studied during the past three decades.^{9, 17, 18} Our understanding of the physiological cardiac adaptations occurring with high-level exercise training has increased in parallel with the evolution of cardiac imaging techniques,¹⁹ and large-scale athletic screening programs on a national level.^{18, 20} The purpose of the PPE of athletes is primarily to identify athletes with underlying heart disease in order to prevent sudden cardiac death.^{1, 2} Cardiac imaging is not however, part of the routine PPE for a majority of athletes and the decision on the need of further follow-up investigations relies on the personal and family history, physical examination and – in most cases – a resting 12-lead ECG.¹ International efforts have been made to improve the accuracy of this process, in particular for the interpretation of the ECG in athletes.^{2, 21} Thus, a correct understanding of the potential and limitations of the ECG to detect structural and electrical abnormalities in athletes are essential for every physician involved in the clinical evaluation of this group of subjects.

Left ventricular hypertrophy imposes a certain clinical dilemma, as increased left ventricular mass is the hallmark of 'athlete's heart' while also being associated with hypertrophic cardiomyopathy, the most frequent inherited cardiac disease found in athletes.²² Accordingly, the current guidelines for ECG interpretation in athletes state that fulfillment of a traditional QRS-voltage criterion for ECG-LVH should not by itself merit for further investigation.² As only a few ECG criteria have previously been evaluated in athletes,^{4-6, 23} and considering the addition of more recently proposed ECG-LVH criteria,^{14, 24, 25} we hypothesized that there could be criteria more suitable to use in the PPE setting. However, our

results clearly show that neither of the voltage, voltage + non-voltage or non-voltage criteria evaluated are useful in identifying subjects with abnormally high left ventricular mass in this group of subjects. The only criterion with an AUC not overlapping 0.50 was the combined Sokolow-Lyon criterion. Although many criteria had a specificity of $\geq 90\%$, the sensitivity was in most cases $< 50\%$, which is similar to previous evaluations in athletes^{4, 5} army recruits²⁶ as well as in hypertensive heart disease with left ventricular hypertrophy.^{24, 27} Due to the low prevalence (5.6%) of left ventricular hypertrophy in the cohort, the post-test probabilities for all ECG-LVH criterion were low.

The poor diagnostic ability of the ECG-LVH criteria were not surprising considering the lack of strong correlations between QRS voltage and left ventricular mass. Four single lead QRS-amplitudes (aVL, I, V5, V6), all reflecting the depolarization of the lateral heart wall, correlated weakly to left ventricular mass. Indexing left ventricular mass by allometrically scaled body surface area or height, or body surface area per ratio standard had little impact on the magnitude of the correlation coefficients, nor did summarizing voltages from several leads. This indicates that the heart mass, approximated by left ventricular mass, has little impact on the surface ECG voltage in male athletes and that this can not be explained primarily by inter-individual differences in body surface area or height. Of note, the only criterion where the correlation of voltage sums exceeded a magnitude of $r > 0.40$ was the Framingham Adjusted Cornell criteria, which adjust for body mass index and age as continuous variables as well as provides sex specific thresholds. It is possible that factors associated with a high body mass index may influence the diagnostic ability to detect left ventricular hypertrophy in athletes, as previously reported in obese patients with hypertension.²⁸ This could reflect an insulating effect of adipose tissue, epicardial and pericardial fat depositions, or increased distance from the heart to chest electrodes.⁷

Ultimately, the purpose of any ECG-LVH criteria used at the PPE setting would be to identify athletes with underlying cardiac pathology or high risk thereof.^{1, 2} The threshold in current echocardiographic guidelines for defining left ventricular hypertrophy in a general population is an LVM[BSA] of $> 102 \text{ g/m}^2$,¹⁵ which corresponded to the upper 95th percentile in the current cohort.

Considering the range in physiological cardiac remodeling reported in athletes,¹¹ this might not represent an optimal threshold to identify athletes with a higher risk of pathology. Therefore, we also evaluated the ECG-criteria in their ability in identifying subjects with a more concentric cardiac phenotype, which has been shown to distinguish physiological from pathological remodeling in athletes^{12, 13} and to be associated with later development of cardiac functional impairment in hypertensive patients.²⁹ In addition, we recently found M/V to be positively, and independently associated with higher systolic blood pressure in athletes,³⁰ indicating a clinical relevance and possible underlying mechanism for the concentric remodeling in this group. Several of the ECG-LVH criteria performed slightly better in detecting subjects with a high M/V ratio than those with isolated left ventricular hypertrophy. which to our knowledge never has been evaluated previously. In particular, the Romhilt-Estes point score (incorporating QRS-voltage, ST-T strain pattern, ventricular activation time, left atrial abnormalities, QRS-axis and -duration) had an AUC of 0.74 for identifying high M/V as compared to 0.56 for left ventricular hypertrophy. Intriguingly, all four athletes with a combination of left ventricular hypertrophy and high M/V ratio (i.e. concentric hypertrophy) fulfilled the criterion of having an R + S-wave >35 mm in any precordial lead, with a specificity of 73% and an AUC of 0.87. Clinically, this group of subjects is the most important to identify, as concentric hypertrophy more often is associated with pathological remodeling in athletes, than left ventricular hypertrophy alone. This finding prompts for validation in larger cohorts.

Limitations

First, due to the low number of females with echocardiographic examinations, we only included male athletes because of established differences in cardiac remodeling between sexes. Our results are limited to male athletes at a college age. Younger athletes might present with more juvenile ECG patterns and older athletes may have underlying cardiovascular disease and hypertension, possibly modifying the LVM-ECG-voltage relationship. Second, we used echocardiography as the method for determining left ventricular mass in favor of cardiac magnetic resonance imaging. Although this method may be increasingly utilized in a PPE setting in the future, sports physicians currently rely on echocardiography

for the evaluation of athletes, with echocardiographic normative values being more established. Third, including subjects with known pathological remodeling, such as hypertrophic cardiomyopathy could have yielded additional insights into the difference between physiological and pathological remodeling. However, this group of subjects often present with electrophysiological alterations in addition to remodeling and have lower than expected R and S wave amplitudes because of replacement of myocytes with fibrosis and fat deposits.

Conclusion

The correlations between left ventricular mass and ECG voltage are weak in male athletes, and none of the 37 evaluated ECG criteria are able to identify athletes with left ventricular hypertrophy or a high M/V ratio with sufficient discriminatory capacity (AUC) to be useful in evaluating athletes.

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FIGURES

All figures also submitted as separate files in their raw, line-art format (.EPS).

	Ia. Limb lead(s)	Ib. Precordial lead(s)
Single lead	<ul style="list-style-type: none"> • R I >15 mm • R aVL >11 mm • R aVF >20 mm • Q or S aVR >19 mm • R or S in any limb lead >19 mm 	<ul style="list-style-type: none"> • S V1 >23 mm • S V2 >25 mm • R V5 >33 mm • R V6 >25 mm • R in any precordial lead >26 mm • R + S in any precordial lead >35 mm
Multiple leads	<ul style="list-style-type: none"> • R I + S III >25 mm • (R I - S I) + (S III - R III) >16 mm 	<ul style="list-style-type: none"> • S V1 + R V5 >35 mm • S V1 + R V5/V6 >35 mm • S V2 + R V4/V5 >45 mm • S V2 + R V5/V6 >45 mm • S V1/V2 + R V6 >40 mm • S V1/V2 + R V5/V6 >35 mm • R V5/V6 >26 mm • R V6 : V5-ratio >1.0 • Either of: S V1 >23 mm; R V5 >33 mm; R V6 >25 mm
Ic. Limb + Precordial leads		
<ul style="list-style-type: none"> • R aVL + S V3 >28 mm (males); >20 mm (females) • R aVL + S V3 adjusted for BMI/age >28 mm (males); >20 mm (females) • Sum of QRS in aVF, V2, V6 >93 mm (≤30 years); >59 mm (>30 years) • Sum of (R+[S or Q]) in all 12 leads ≥179 mm • Sum of (max of Q, R or S) in all 12 leads ≥179 mm • Max S any lead + S V4 ≥28 mm (males), ≥23 mm (females) • Either of: R aVL >11 mm; S V1+R V5 >35 mm; R V5/V6 >26 mm • Either of: R aVL >12 mm; R I/II/III/aVF >20 mm; R V5/V6 >26 mm 		
II. Including QRS-duration		
<ul style="list-style-type: none"> • QRS-duration >114 ms (males); >97 ms (females) • (R aVL + S V3) * QRS-dur, ≥2436 mm/ms • Sum of (R+[S or Q]) in all 12 leads * QRS-duration ≥17472 mm/ms • Sum of (max of Q, R or S) in all 12 leads * QRS-duration ≥17472 mm/ms 		
III. Point Score criteria		
<ul style="list-style-type: none"> • Number positive: Voltage; STT V5-V6; LAA P in V1; QRS-axis; QRS-dur ≥4 • Either of (3): Voltage; STT V5-V6; Score above ≥4 		
IV. LV mass Equation		
<ul style="list-style-type: none"> • Rautaharju LV mass Equation 		

Figure 1. (Two-column figure)

Summary of the 37 different ECG criteria for detecting left ventricular hypertrophy applied in the 196 male athletes of the current report. For details and references, see eTable 1.

Figure 2. (two-column figure)

Distribution of echocardiographic measures in 196 male athletes and number of subjects with left ventricular hypertrophy and a high mass to volume ratio (M/V). The upper 95th percentile of left ventricular mass (LVM) indexed by body surface area (LVM[BSA]) was 102 g/m² and thus corresponded to the threshold defining left ventricular (LV) hypertrophy in echocardiographic guidelines. In panel D, the linear regression line ($\beta = 0.03$) with 95% confidence interval is shown ($R^2 = 0.14$, $p < 0.001$).

(A) Percent of athletes positive for left ventricular hypertrophy (LVH) per 37 different ECG-LVH criteria

(B) Area under the receiver operating curve (AUC) for correctly identifying 11 athletes with echocardiographic LVH

Figure 3. (two-column figure)

Proportion of the 196 male athletes with ECG-LVH using 37 different criteria (A) and the diagnostic characteristics for each criterion (B). The criteria are grouped by category as defined in

figure 1 and text. For detailed explanation of each criterion with the respective threshold and reference, readers are referred to eTable 1.

Figure 4. (two-column figure)

Diagnostic characteristics of different ECG-LVH criteria for correctly identifying the 11 athletes with left ventricular hypertrophy (A) and the 8 athletes with a concentric cardiac phenotype (B).

Sensitivity and specificity are noted on left y-axis and area under the receiving operator curve (AUC) on the right y-axis. and AUC for each criterion, sorted descending from left to right by specificity.

Supplementary material

Hedman et al.

“Limitations of Electrocardiography for Detecting Left Ventricular Hypertrophy or
Concentric Remodeling in Athletes”.

Supplemental Table 1. Different ECG criteria for detecting left ventricular hypertrophy.

Lead(s)	Threshold/Cut-off	Reference(s) ^a	Also known as
Ia. Limb lead voltage only			
Single lead (n=5)			
R I	>15 mm	Gubner & Ungerlieder, 1943. ¹	
R aVL	>11 mm	Sokolow & Lyon, 1949. ²	
R aVF	>20 mm	Goldberger, 1949. ³	
Q or S aVR	>19 mm	Schack et al. 1950. ⁴	
R or S in any limb lead	>19 mm	Romhilt et al. 1969. ⁵	
Multiple leads (n=2)			
(R I-S I) + (S III-R III)	>16 mm	Lewis, 1914. ⁶	Lewis index
R I + S III	>25 mm	Gubner & Ungerlieder, 1943. ¹	
Ib. Precordial lead voltage only			
Single lead (n=6)			
S V1	>23 mm	Wilson et al. 1944. ⁷	
S V2	>25 mm	Mazzoleni et al. 1964. ⁸	
R V5	>33 mm	Wilson et al. 1944. ⁷	
R V6	>25 mm	Wilson et al. 1944. ⁷	
R + S any precordial lead	>35 mm	Grant, 1957. ⁹	
R any precordial lead	>26 mm	McPhie, 1958. ¹⁰	
Multiple leads (n=9)			
S V1 + R V5	>35 mm	Sokolow & Lyon, 1949. ²	The International Criteria for ECG Interpretation in Athletes
S V1 + R V5/V6	>35 mm	Sharma et al. 2018. ¹¹	
S V2 + R V4/V5	>45 mm	Wolff, 1956. ¹²	
S V2 + R V5/V6	>45 mm	Romhilt et al. 1969. ⁵	
S V1/V2 + R V5/V6	>40 mm	Murphy et al. 1984. ¹³	
S V1/V2 + R V6	>40 mm	Grant, 1957. ⁹	
R V5/V6	>26 mm	Sokolow & Lyon, 1949. ²	
S V1, RV5, R V6	Either of: SV1 >23 mm, RV5 >33 mm, RV6 >25 mm	Wilson et al. 1944. ⁷	
R V6 : R V5 (ratio)	>1.0	Holt & Spodick, 1962. ¹⁴	
Ic. Limb and precordial leads (n=8)			
SV1+RV5, RV5/V6, RaVL	Either of: SV1+RV5 >35 mm, RV5/V6 >26 mm, RaVL >11 mm	Sokolow & Lyon, 1949. ²	Combined Sokolow&Lyon criteria
RV5/V6, RI/II/III/aVF, RaVL	Either RV5/V6 >26 mm or any of RI/II/III/aVF >20 mm or RaVL >12 mm	Blackburn, 1969. ¹⁵	Minnesota Code
Sum of QRS in aVF, V2, V6	>93 mm (≤30 years) >59 mm (>30 years)	Manning & Smiley, 1964. ¹⁶	
R aVL + S V3	>28 mm (males) >20 mm (females)	Casale et al. 1985. ¹⁷	Cornell Criteria
R aVL + S V3, adj. for sex/BMI/age	>28 mm (males) >20 mm (females)	Norman et al. 1993. ¹⁸	Framingham Adjusted Cornell Criteria

Sum of [R+Q/S wave) in all 12 leads]	≥179 mm	Siegel & Roberts, 1982; Molloy et al. 1992. ^{19, 20}	Sum of 12 leads
Sum of [R or Q/S wave (largest) in all 12 leads]	≥179 mm	Siegel & Roberts, 1982; Ha et al. 2018. ^{20, 21}	Modified sum of 12 leads
Max S wave in any lead + SV4	≥28 mm (males) ≥23 mm (females)	Peguero et al. 2017. ²²	Peguero-Lo Presti
II. Including QRS-duration (n=4)			
QRS-duration	>114 ms (males) >97 ms (females)	Carlsson et al. 2006. ²³	
(R aVL + S V3) * QRS-dur	≥2436 mm/ms (+ 8 mm for females)	Molloy et al. 1992. ¹⁹	Cornell-Voltage-Product
Sum of [R+S wave in all 12 leads] * QRS-dur	≥17472 mm/ms	Molloy et al. 1992. ¹⁹	Sum of 12 leads-product
Sum of [R or S wave (largest) in all 12 leads] * QRS-dur	≥17472 mm/ms	Molloy et al. 1992; Ha et al. 2018. ^{19, 21}	Modified sum of 12 leads-product
III. Point scores (n=2)			
Voltage / STT V5-V6 / LAA P in V1 / axis /QRS-dur	Point score ≥4	Romhilt & Estes, 1968. ²⁴	Romhilt-Estes Score
Voltage-STT V5-V6-RomhiltEstes	Either of positive = TRUE	Schillaci et al. 1994. ²⁵	Perugia Score
IV. LV mass equation (n=1)			
R V5, S V1, max(SIII, QIII), Tneg(V6), Tpos(aVR), QRS-dur	≥131 g/m ² (all men)		
R V5, max(S V5, Q V5), max(SI, QI), Tpos(V1), Tneg(aVF), Tpos(V6)	≥110 g/m ² (white female)	Rautaharju et al. 1988. ²⁶	Rautaharju Mass Equation
R aVL, (R V6, S V2), R V2, max(S V5, Q V5), Tneg(aVL), QRS-dur	≥110 g/m ² (black female)		

a) See Online-Only bibliography for full reference. Bibliography numbers do not match main manuscript. In instances where several sources are cited, threshold values are derived from second publication or a modified definition is used compared to original publication.

Supplemental Table 2. Formulas used for calculations of predictive values, likelihood ratios and post-test probabilities.

Predictive values	
Positive predictive value (PPV)	Negative predictive value (NPV)
$\frac{\text{Sensitivity} * \text{Prevalence}}{(\text{Sensitivity} * \text{Prevalence}) + (1 - \text{Specificity}) * (1 - \text{Prevalence})}$	$\frac{\text{Specificity} * (1 - \text{Prevalence})}{(1 - \text{Sensitivity}) + \text{Specificity} * (1 - \text{Prevalence})}$
Positive likelihood ratio (LR+)	Negative likelihood ratio (LR-)
$\frac{\text{Sensitivity}}{(1 - \text{Specificity})}$	$\frac{(1 - \text{Sensitivity})}{\text{Specificity}}$
Pre-test probability (prevalence)*	Pre-test odds
$\frac{\text{Number with outcome}}{(\text{Total number of subjects})}$	$\frac{\text{Prevalence}}{(1 - \text{Prevalence})}$
Post-test odds if positive test	Post-test odds if negative test
$\text{Pre test odds} * \text{Positive likelihood ratio}$	$\text{Pre test odds} * \text{Negative likelihood ratio}$
Post-test probability if positive test	Post-test probability if negative test
$\frac{\text{Post test odds if positive test}}{(1 + \text{Post test odds if positive test})}$	$\frac{\text{Post test odds if negative test}}{(1 + \text{Post test odds if negative test})}$

*) Outcome in the current study determined by echocardiography as either left ventricular hypertrophy (LVH) or concentric remodelling (mass to volume ratio ≥ 1.05 g/mL).

Supplemental Figure 1. Schematic illustration of the measurements and calculations used to determine left ventricular mass (LVM) and mass to volume ratio (M/V).

Supplemental Table 3. Logistic regression for categorical variables associated with electrocardiographic left ventricular hypertrophy with international ECG criteria for athletes (in 49 out of 196 athletes).

	Univariate		Multivariable	
	β (95% CI)	p	β (95% CI)	p
BMI >30 kg/m ²	0.2 (0.1-0.7)	0.007	0.3 (0.1-1.0)	0.041
Afro-American	2.5 (1.3-4.8)	0.009	-	-
Caucasian	0.4 (0.2-0.8)	0.010	-	-
Football	0.3 (0.1-0.6)	<0.001	-	-
Basketball	11.6 (3.5-38.0)	<0.001	4.3 (1.0-18.3)	0.049

BMI, body mass index; BSA, body surface area; BP, blood pressure.

Supplemental Table 4. Bivariate correlations between ECG leads and left ventricular mass indexed by different anthropometric measures and by left-ventricular volume in 196 male athletes.

Limb leads	LVM	LVM[BSA]	LVM[BSA ^{1.5}]	LVM[Height ^{2.7}]	M/V
aVL	.24 ^{†*} (R)	.20 [†] (R)	.15 [*] (R)	.27 ^{†*} (R)	.15 [*] (R)
I	.30 ^{†*} (R)	.26 ^{†*} (R)	.21 [†] (R)	.34 ^{†*} (R)	.25 ^{†*} (R)
aVR	-	-	-	-	-
II	-	.16 [*] (R)	.22 [†] (R)	-	.17 [*] (R)
aVF	-	-	.17 [*] (R)	-	-
III	-	-	-	-	-
Chest leads	LVM	LVM[BSA]	LVM[BSA ^{1.5}]	LVM[Height ^{2.7}]	M/V
V1	-	.19 [†] (S)	.21 [†] (S)	-	-
V2	-	.19 [†] (S)	.22 [†] (S)	-	-
V3	-	-	.16 [*] (S)	-	-
V4	-	-	.16 [*] (R)	-	-
V5	.18 [*] (R)	.30 ^{†*} (R)	.33 ^{†*} (R)	-	-
V6	.27 ^{†*} (R)	.30 ^{†*} (R)	.27 ^{†*} (R)	0.15 [*] (R)	-

*) p<0.05; †) p<0.01; ‡) p≤0.001. Note that for each lead, the highest correlation coefficient (Pearson r) for absolute, positive value of either of S- or R wave is presented as noted in parenthesis and corresponds to its physiological association with LV depolarization.

Example lead 1

Example lead 2

Sum of 12 leads;
R + (S or Q) amplitude in all 12 leads ≥ 179 mm

Modified sum of 12 leads;
Max of [R or (S or Q)] amplitude in all 12 leads ≥ 179 mm

Supplemental Figure 2. Different definitions of the Sum of 12 leads criterion used in this manuscript.

Blue color reflects the originally described method for summarizing the voltage in the 12 leads,(29) where the absolute values of the peak negative and positive deflections are first summarized in each lead. In the modified version,(31) the maximal absolute deflection in each lead are summarized from all 12 leads. Note that the threshold for left ventricular hypertrophy (≥ 179 mm) is identical with each of the two criteria.

Supplemental Table 5. Diagnostic precision of different ECG criteria for detecting the 11 out of 196 male athletes with left ventricular hypertrophy as defined per current echocardiography guidelines.

Lead(s)		N pos. (%)	AUC (95% CI)	Sens .	Spec.	PPV	NPV	LR+	LR-
Limb lead voltage (7)									
One lead (5)									
Gubner 1943	R I >15 mm	0	0.50 (0.32-.68)	-	-	-	-	-	-
Sokolov 1949	R aVL >11 mm	1 (0.5%)	0.50 (0.32-0.67)	0%	99.5%	0%	94%	.0	1.0
Goldberger 1949	R aVF >20 mm	18 (9%)	0.55 (0.36-0.73)	18%	91%	11%	95%	2.1	0.9
Schack 1950	Q or S aVR >19 mm	0	0.50 (0.32-0.68)	-	-	-	-	-	-
Romhilt 1968	R or S in any limb lead >19 mm	38 (19%)	0.54 (0.36-0.72)	27%	81%	8%	95%	1.4	0.9
>1 lead (2)									
Lewis 1914	(R I-S I) + (S III-R III) >16 mm	56 (29%)	0.54 (0.36-0.72)	36%	72%	7%	95%	1.3	0.9
Gubner 1943	R I + S III >25 mm	1 (0.5%)	0.50 (0.32-0.67)	0%	99.5%	0%	94%	.0	1.0
Precordial lead voltage (14)									
One lead (6)									
Wilson 1944	S V1 >23 mm	3 (2%)	0.54 (0.35-0.73)	9%	99%	33%	95%	8.4	0.9
Mazzoleni 1964	S V2 >25 mm	29 (15%)	0.57 (0.38-.75)	27%	86%	10%	95%	1.9	0.9
Wilson 1944	R V5 >33 mm	4 (2%)	0.49 (0.32-0.66)	0%	98%	0%	94%	.0	1.0
Wilson 1944	R V6 >25 mm	7 (4%)	0.53 (0.35-0.71)	9%	97%	14%	95%	2.8	0.9
Grant 1957	R + S any precordial lead >35 mm	55 (28%)	0.64 (0.46-0.82)	55%	74%	11%	96%	2.1	0.6
McPhie 1958	R any precordial lead >26 mm	53 (27%)	0.65 (0.47-0.82)	55%	75%	11%	97%	2.2	0.6
>1 lead (8)									
Sokolov 1949	S V1 + R V5 >35 mm	48 (24%)	0.61 (0.43-0.79)	46%	77%	10%	96%	2.0	0.7

Sharma 2018	S V1 + R V5/V6 >35 mm	49 (25%)	0.61 (0.43-0.79)	46%	76%	10%	96%	1.9	0.7
Wolff 1956	S V2 + R V4/V5 >45 mm	52 (27%)	0.55 (0.37-0.73)	36%	74%	8%	95%	1.4	0.9
Romhilt 1969	S V2 + R V5/V6 >45 mm	41 (21%)	0.58 (0.40-0.77)	36%	80%	10%	95%	1.8	0.8
Murphy 1984	S V1/V2 + R V5/V6 >40 mm	68 (35%)	0.65 (0.48-0.82)	64%	67%	10%	97%	1.9	0.5
Grant 1957	S V1/V2 + R V6 >40 mm	35 (18%)	0.60 (0.41-0.78)	36%	83%	11%	96%	2.2	0.8
Sokolov 1949	R V5/V6 >26 mm	28 (14%)	0.67 (0.48-0.85)	46%	88%	18%	96%	3.7	0.6
Wilson 1944	Either of: S V1 >23 mm, RV5 >33 mm, R V6 >25 mm	12 (6%)	0.56 (0.37-0.75)	18%	95%	17%	95%	3.4	0.9
Holt 1962	R V6:R V5 (ratio) >1.0	7 (4%)	0.53 (0.35-0.71)	9%	97%	14%	95%	2.8	0.9
Limb and precordial leads (8)									
Sokolov 1949	Either of: SV1+RV5 >35 mm, RV5/V6 >26 mm, RaVL >11 mm	53 (27%)	0.69 (0.52-0.86)	64%	75%	13%	97%	2.6	0.5
Blackburn 1969	RV5/V6 >26 mm, RI/II/III/aVF >20 mm, RaVL >12 mm	50 (25%)	0.61 (0.42-0.79)	46%	76%	10%	96%	1.9	0.7
Manning 1964	Sum of QRS in aVF, V2, V6 >93 mm (≤30 years), >59 mm (>30 years)	1 (0.5%)	0.50 (0.32-0.67)	0%	99.5%	0%	94%	.0	1.0
Casale 1985	R aVL + S V3 >28 mm (males), >20 mm (females)	6 (3%)	0.53 (0.35-0.72)	9%	97%	17%	95%	3.4	0.9
Norman 1993	R aVL + S V3, adj. for BMI/age >28 mm (males), >20 mm (females)	18 (9%)	0.55 (0.36-0.73)	18%	91%	11%	95%	2.1	0.9
Siegel 1982, Malloy 1992	Sum of (R+S or Q) in all 12 leads ≥179 mm	134 (68%)	0.62 (0.47-0.77)	91%	33%	7%	98%	1.4	0.3
Siegel 1982, Ha 2017	Sum of (max of Q, R or S) in all 12 leads ≥179 mm	57 (29%)	0.64 (0.46-0.81)	55%	72%	11%	96%	2.0	0.6
Peguero 2017	Max S any lead + S V4, ≥28 mm (males), ≥23 mm (females)	69 (35%)	0.65 (0.48-0.82)	64%	67%	10%	97%	1.9	0.6
Non-voltage (1)									
Carlsson 2006	QRS-duration, >114 ms (males), >97 ms (females)	20 (10%)	0.49 (0.32-0.67)	9%	90%	5%	94%	0.9	1.0
Voltage + non-voltage (4)									
Romhilt 1968	Score ≥4: Voltage / STT V5-V6 / LAA P in V1 / axis /QRS-dur	31 (16%)	0.56 (0.38-0.75)	27%	85%	10%	95%	1.8	0.9

Schillaci 1994	Either of pos.: Voltage-STT V5-V6-RomhiltEstes ≥ 4	43 (22%)	0.63 (0.44-0.81)	46%	80%	12%	96%	2.2	0.7
Molloy 1962, Okin 1995	(R aVL + S V3) * QRS-dur, ≥ 2436 mm/ms	20 (10%)	0.59 (0.40-0.78)	27%	91%	15%	95%	3.0	0.8
Molloy 1962	Sum of 12 leads * QRS-dur, ≥ 17472 mm/ms	146 (74%)	0.59 (0.43-0.74)	91%	27%	7%	98%	1.2	0.3
Molloy 1962 Ha 2017	Sum of 12 leads (Vic) * QRS-dur, ≥ 17472 mm/ms	66 (34%)	0.66 (0.49-0.83)	64%	68%	11%	97%	2.0	0.5

Mass equation/prediction (1)

Rautaharju 1988	≥ 131 g/m ² (men), ≥ 110 g/m ² (female), R V5, S V1, max(SIII, QIII), Tneg(V6), Tpos(aVR), QRS-dur	32 ^a (18%)	0.60 (0.41-0.79)	36%	84%	12%	96%	2.2	0.8
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a) Rautaharju score not calculated for 15 athletes of other than Caucasian or Afro-American ethnicity. Current echocardiographic guidelines (Lang et al. 2015) define LVH in males as a LVM[BSA] > 102 g/m². AUC, area under the curve; Sens/Spec, sensitivity/specificity; PPV/NPV, positive and negative predictive value; LR+/LR-, positive and negative likelihood ratio. Red colour indicates 95% CI not overlapping 0.50.

(A) Post-test probability of left ventricular hypertrophy (LVM[BSA] >102 g/m²) based on positive or negative ECG for LVH

(B) Post-test probability of a concentric phenotype (M/V ≥ 1.05 g/mL) based on positive or negative ECG for LVH

Supplemental Figure 3. Post-test probability of left ventricular hypertrophy (LVH, panel A) and a concentric phenotype (M/V ≥ 1.05 g/mL, panel B) based on a positive or negative ECG based on ECG criterion's ECG-LVH threshold.

Note that for a few criteria, a positive test decreased the probability of LVH or high M/V. The pre-test probability of disease was set to the prevalence of LVH (5.6%) and high M/V (4.1%) and is represented by the horizontal, dashed line.

Supplemental Table 6. Diagnostic precision of different ECG criteria for detecting the 8 out of 196 male athletes with a mass to volume ratio in the upper 95th percentile.

	Lead(s)	N (%) pos.	AUC	Sens	Spec	PPV	NPV	LR+	LR-
Limb lead voltage (7)									
One lead (5)									
Gubner 1943	R I >15 mm	0	0.50 (0.30-0.71)	-	-	-	-	-	-
Sokolov 1949	R aVL >11 mm	1 (0.5%)	0.50 (0.29-0.71)	0%	100 %	0%	96%	.0	1.0
Goldberger 1949	R aVF >20 mm	18 (9%)	0.52 (0.31-0.73)	13%	91%	6%	96%	1.4	1.0
Schack 1950	Q or S aVR >19 mm	0	0.50 (0.31-0.71)	-	-	-	-	-	-
Romhilt 1968	R or S in any limb lead >19 mm	38 (19%)	0.66 (0.45-0.87)	50%	82%	11%	97%	2.8	0.6
>1 lead (2)									
Lewis 1914	(R I-S I) + (S III-R III) >16 mm	56 (29%)	0.68 (0.48-0.88)	63%	73%	9%	98%	2.3	0.5
Gubner 1949	R I + S III >25 mm	1 (0.5%)	0.50 (0.29-0.69)	0%	100 %	0%	96%	.0	1.0
Precordial lead voltage (14)									
One lead (6)									
Wilson 1944	S V1 >23 mm	3 (2%)	0.49 (0.29-0.69)	0%	98%	0%	96%	.0	1.0
Mazzoleni 1964	S V2 >25 mm	29 (15%)	0.68 (0.47-0.90)	50%	87%	14%	98%	3.8	0.6
Wilson 1944	R V5 >33 mm	4 (2%)	0.49 (0.29-0.69)	0%	98%	0%	96%	.0	1.0
Wilson 1944	R V6 >25 mm	7 (4%)	0.48 (0.28-0.68)	0%	96%	0%	96%	.0	1.0
Grant 1957	R + S any precordial lead >35 mm	55 (28%)	0.68 (0.48-0.88)	63%	73%	9%	98%	2.4	0.5
McPhie 1958	R any precordial lead >26 mm	53 (27%)	0.56 (0.34-0.77)	38%	73%	6%	97%	1.4	0.9
>1 lead (9)									
Sokolov 1949	S V1 + R V5 >35 mm	48 (24%)	0.63 (0.42-0.84)	50%	77%	8%	97%	2.1	0.7
Sharma 2018	S V1 + R V5/V6 >35 mm	49 (25%)	0.63 (0.42-0.84)	50%	76%	8%	97%	2.1	0.7

Wolff 1956	S V2 + R V4/V5 >45 mm	52 (27%)	0.69 (0.49-0.88)	63%	75%	10%	98%	2.5	0.5
Romhilt 1969	S V2 + R V5/V6 >45 mm	41 (21%)	0.59 (0.37-0.80)	38%	80%	7%	97%	1.9	0.8
Murphy 1984	S V1/V2 + R V5/V6 >35 mm	68 (35%)	0.65 (0.45-0.84)	63%	44%	7%	98%	1.9	0.6
Grant 1957	S V1/V2 + R V6 >40 mm	35 (18%)	0.67 (0.45-0.88)	50%	84%	11%	98%	3.0	0.6
Sokolov 1949	R V5/V6 >26 mm	28 (14%)	0.56 (0.41-0.83)	25%	86%	7%	96%	1.8	0.9
Wilson 1944	Either of: S V1 >23 mm, RV5 >33 mm, R V6 >25 mm	12 (6%)	0.47 (0.28-0.66)	0%	94%	0%	96%	.0	1.1
Holt 1962	R V6:R V5 (ratio) >1.0	7 (4%)	0.48 (0.28-0.68)	0%	96%	0%	96%	.0	1.0
Limb and precordial leads (8)									
Sokolov 1949	Either of: SV1+RV5 >35 mm, RV5/V6 >26 mm, RaVL >11 mm	53 (27%)	0.62 (0.41-0.83)	50%	74%	8%	97%	1.9	0.7
Blackburn 1969	RV5/V6 >26 mm, RI/II/III/aVF >20 mm, RaVL >12 mm	50 (25%)	0.69 (0.49-0.89)	63%	76%	10%	98%	2.6	0.5
Manning 1964	Sum of QRS in aVF, V2, V6 >93 mm (≤30 years), >59 mm (>30 years)	1 (0.5%)	0.50 (0.29-0.70)	0%	100%	0%	96%	.0	1.0
Casale 1985	R aVL + S V3 >28 mm (males), >20 mm (females)	6 (3%)	0.48 (0.29-0.68)	0%	97%	0%	96%	.0	1.0
Norman 1993	R aVL + S V3, adj. for BMI/age >28 mm (males), >20 mm (females)	18 (9%)	0.65 (0.42-0.87)	38%	92%	17%	97%	4.7	0.7
Siegel 1982, Malloy 1992	Sum of (R+S or Q) in all 12 leads ≥179 mm	134 (68%)	0.60 (0.42-0.78)	88%	32%	5%	98%	1.3	0.4
Siegel 1982, Ha 2017	Sum of (max of Q, R or S) in all 12 leads ≥179 mm	57 (29%)	0.74 (0.56-0.92)	75%	73%	11%	99%	2.8	0.3
Peguero 2017	Max S any lead + S V4, ≥28 mm (males), ≥23 mm (females)	69 (35%)	0.64 (0.44-0.84)	63%	66%	7%	98%	1.8	0.6
Non-voltage (1)									
Carlsson 2006	QRS-duration, >114 ms (males), >97 ms (females)	20 (10%)	0.45 (0.26-0.63)	0%	89%	0%	95%	.0	1.1
Voltage + non-voltage (4)									
Romhilt 1968	Score ≥4: Voltage / STT V5-V6 / LAA P in V1 / axis /QRS-dur	31 (16%)	0.74 (0.54-0.95)	63%	86%	16%	98%	4.5	0.4

Schillaci 1994	Either of pos.: Voltage-STT V5-V6-RomhiltEstes ≥ 4	43 (22%)	0.71 (0.51-0.91)	63%	80%	12%	98%	3.1	0.5
Molloy 1962, Okin 1995	(R aVL + S V3) * QRS-dur, ≥ 2436 mm/ms	20 (10%)	0.58 (0.36-0.80)	25%	90%	10%	97%	2.6	0.8
Molloy 1962	Sum of 12 leads * QRS-dur, ≥ 17472 mm/ms	146 (74%)	0.57 (0.38-0.75)	88%	26%	5%	98%	1.2	0.5
Molloy 1962 Ha 2017	Sum of 12 leads (Vic) * QRS-dur, ≥ 17472 mm/ms	66 (34%)	0.72 (0.54-0.89)	75%	68%	9%	98%	2.4	0.4
Mass equation/prediction (1)									
	≥ 131 g/m ² (men), ≥ 110 g/m ² (female),	32 ^a	0.54						
Rautaharju 1988	R V5, S V1, max(SIII, QIII), Tneg(V6), Tpos(aVR), QRS-dur	(18%)	(0.33-0.75)	25%	83%	6%	96%	1.5	0.9

a) Rautaharju score not calculated for 15 athletes of other than Caucasian or Afro-American ethnicity. Current echocardiographic guidelines (Lang et al. 2015) define LVH in males as a LVM[BSA] >102 g/m². AUC, area under the curve; Sens/Spec, sensitivity/specificity; PPV/NPV, positive and negative predictive value; LR+/LR-, positive and negative likelihood ratio. Red colour indicates 95% CI not overlapping 0.50.

Supplemental Figure 4. Difference in area under the receiver operating curve (AUC) for each ECG criterion's ability to identify athletes with left ventricular hypertrophy (LVH, n=11) and those with a mass to volume ratio (M/V) in the upper 95th percentile (n=8), respectively.

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