

Comparison of four electrocardiographic criteria for the detection of cardiac abnormalities in Singapore athletes

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ABSTRACT

Introduction: Sudden cardiac death in athletes is a rare occurrence, the most common cause being hypertrophic cardiomyopathy, which increases the risk of sustained ventricular tachycardia or ventricular fibrillation. Most of these young athletes are asymptomatic prior to the cardiac arrest. Several electrocardiogram criteria such as the European Society of Cardiology group 2 Criteria changes, Seattle Criteria, Refined Criteria, and most recently the 2017 International Criteria, have sought to improve the accuracy of identifying these at-risk athletes during pre-participation screening while minimising unnecessary investigations for the majority of athletes at low risk. We aimed to compare the above four criteria in our Singapore athlete population to identify which criterion performed the best in detecting cardiac abnormalities on echocardiography.

Method: Out of 1,515 athletes included in Changi General Hospital, Singapore registry between June 2007 and June 2014, the electrocardiograms of 270 athletes with further cardiac investigations were analysed. We compared the above four electrocardiographic criteria to evaluate which performed best for detecting cardiac abnormalities on echocardiography in our Southeast Asian athlete population.

Results: The European Society of Cardiology, Seattle, Refined and 2017 International Criteria had a sensitivity of 20%, 0%, 20% and 5%, respectively; a specificity of 64%, 93%, 84% and 97%, respectively; a positive predictive value of 4%, 0%, 9% and 11%, respectively; and a negative predictive value of 91%, 92%, 93% and 93%, respectively for detecting abnormalities on echocardiography.

Conclusion: The latest 2017 International Criteria performed the best as it had the highest specificity and positive predictive value, joint highest negative predictive value, and lowest false positive rate.

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INTRODUCTION

Sudden cardiac death in athletes during exercise is rare, with an estimated incidence of 1–2 per 100,000 people per year in young athletes,¹ and approximately 1 per 7,000 per year in adult athletes.² The predominant aetiology of these cases is cardiovascular in nature, with conditions such as hypertrophic cardiomyopathy (HCM), arrhythmogenic right ventricular cardiomyopathy and ion channelopathies among those implicated.³ These conditions increase the risk of malignant cardiac arrhythmias such as sustained ventricular tachycardia or ventricular fibrillation.

However, most of the affected individuals are young and asymptomatic prior to the event; consequently, the challenge is to detect these at-risk individuals who might benefit from competitive activity restriction while minimising unnecessary investigations for the majority of athletes that are at low risk.

The majority of cardiovascular causes that predispose individuals to sudden cardiac death could potentially be identified by a resting 12-lead electrocardiogram (ECG). The 12-lead ECG is one of the cornerstones of pre-participation screening, in conjunction with screening for cardiovascular-related symptoms, a family

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CLINICAL IMPACT

What is New

- Previous electrocardiographic criteria predominantly analysed athletes who were of Caucasian, Black and Arabic descent.
- This study analysed the four main criteria in Singapore's athlete population to determine which performed the best to detect structural heart abnormalities.

Clinical Implications

- Utilising the 2017 International Criteria to interpret electrocardiograms during pre-participation screening will help to reduce the burden of false-positive results, while minimising the risk of missing important cardiac conditions.

history of cardiovascular disease with an emphasis on premature sudden cardiac death or inheritable cardiac diseases, and a physical examination.⁴

Over the past 10 years, there have been several modifications to ECG interpretation to sieve out ECG changes that reflect normal physiological changes (the “athlete’s heart”) from pathological changes that reflect underlying heart disease. In 2009, Corrado et al. published the European Society of Cardiology (ESC) Criteria that listed out group 1 ECG changes—which were common and training-related—as well as group 2 ECG changes—which were uncommon and training-unrelated.⁵ This latter group warranted further investigations to rule out underlying cardiac disease. There have also been other publications with similar ECG criteria intending to distinguish normal from abnormal ECG findings.⁶ However, the rate of false-positive interpretations and unnecessary secondary investigations appeared unacceptably high especially in Black athletes.⁷

In 2013, Drezner et al. published the Seattle Criteria which added and removed some ECG criteria to the list of abnormal ECG findings, as well as redefining some criteria such as T wave inversion.⁸ Subsequent studies showed that the Seattle Criteria had a lower false-positive rate compared to the ESC Criteria.⁹ Despite this, the ESC and Seattle Criteria were still based predominantly on data derived from Caucasian athletes. As such, Sheikh et al. published the Refined Criteria in 2014 to take into account both Black and

White athletes.⁷ This Refined Criteria included a borderline category of ECG variants, which required the presence of 2 or more ECG criteria before recommending further investigation. It was later shown that the Refined Criteria outperformed the ESC and Seattle Criteria in Arabic, Black and Caucasian athletes.¹⁰

More recently, renowned experts in the field published the International Criteria in 2017, endorsed by international bodies on both sides of the Atlantic.¹¹ This recommendation largely built on the Refined Criteria and also introduced the concept of juvenile T wave changes, which were considered normal.

The above revisions to ECG interpretation criteria have advanced knowledge of ECG abnormalities in athletes among cardiologists all over the world. However, knowledge gaps remain in athletes of races, other than information of Caucasian, Black and Arabic descent. We had previously presented our data comparing the ESC, Seattle and Refined Criteria in Southeast Asian athletes and found that the Refined Criteria provided the optimum combination of sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) among the three criteria for detecting cardiac abnormalities on echocardiography.¹² In this study, we present updated data to compare the above three criteria, in addition to the latest 2017 International Criteria, when applied to our Southeast Asian athlete population.

METHOD

Setting

A total of 1,515 Singapore competitive athletes who underwent pre-participation screening between June 2007 and June 2014 at the Singapore Sport & Exercise Medicine Centre at Changi General Hospital were prospectively included into our registry. They were elite sports athletes, predominantly soccer players funded by Fédération Internationale de Football Association (FIFA) and the Singapore football leagues, participating at the national level. Transthoracic echocardiograms were performed in accordance with the American Society of Echocardiology guidelines either as part of the screening protocols of their sports organisation or on clinical grounds because of abnormal electrocardiograms (ECGs), the presence of symptoms or cardiac murmurs. Other investigations such as computed tomography coronary angiogram, cardiac magnetic resonance imaging and invasive coronary angiography were performed based on clinical indications to arrive at a final diagnosis. Another 270 athletes with further cardiac investigations were included in this analysis and their electronic

medical records reviewed in December 2015. The study was approved by the SingHealth Institutional Review Board in 2015.

Retrospective ECG analysis

The ECGs of all 270 elite athletes were interpreted retrospectively by 2 senior cardiologists (a sports cardiologist and an interventional cardiologist with an interest in sports cardiology) using the ESC Criteria, Seattle Criteria, Refined Criteria, and the 2017

International Criteria (Table 1). The ECG readers were blinded to the results of the cardiac tests during the analysis.

Statistical analysis

The data collected were summarised using frequency with proportion for categorical variables, mean with standard deviation (SD), and median with interquartile range (IQR) for parametric and non-parametric variables, respectively. The accuracy of ESC

Table 1. Summary table of the different electrocardiographic criteria.

ECG abnormality	European Society of Cardiology Criteria	Seattle Criteria	Refined Criteria	2017 International Criteria
Left atrial enlargement	Negative portion of the P wave in lead V1 ≥ 0.1 mV in depth and ≥ 40 ms in duration	Prolonged P wave duration of >120 ms in lead I or II with negative portion of the P wave ≥ 1 mm in depth and ≥ 40 ms in duration in lead V1	As per ESC	As per Seattle Criteria
Right atrial enlargement	P wave amplitude ≥ 2.5 mm in lead II, III, or aVF	As per ESC	As per ESC	As per ESC
Left QRS axis deviation	-30° to -90°	As per ESC	As per ESC	As per ESC
Right QRS axis deviation	$>115^\circ$	$>120^\circ$	As per ESC	As per Seattle Criteria
Right ventricular hypertrophy	Sum of R wave in V1 and S wave in V5 or V6 ≥ 10.5 mm	Sum of R wave in V1 and S wave in V5 >10.5 mm and right axis deviation $>120^\circ$	As per ESC	Not applicable
Complete left bundle branch block (LBBB)	QRS ≥ 120 ms, predominantly negative QRS complex in lead V1 (QS or rS), and upright monophasic R wave in leads I and V6	As per ESC	As per ESC	As per ESC
Complete right bundle branch block (RBBB)	RSR pattern in anterior precordial leads with QRS duration ≥ 120 ms	Not applicable	As per ESC	As per ESC
Intraventricular conduction delay	Any QRS duration >120 ms including RBBB and LBBB	Any QRS duration ≥ 140 ms or complete LBBB	As per ESC	Any QRS duration ≥ 140 ms
Pathological Q wave	>4 mm deep in any lead except III, aVR	>3 mm deep or >40 ms duration in ≥ 2 leads except III and aVR	≥ 40 ms in duration or $\geq 25\%$ of the height of the ensuing R wave	Q/R ratio ≥ 0.25 or ≥ 40 ms in duration in ≥ 2 contiguous leads (excludes III and aVR)
Significant T wave inversion	≥ 2 mm in ≥ 2 adjacent leads (deep) or “minor” in ≥ 2 leads	>1 mm in depth in ≥ 2 leads V2–6, II and aVF, or I and aVL (excludes III, aVR, and V1)	As per Seattle Criteria	Negative portion of T wave ≥ 1 mm in depth in ≥ 2 contiguous leads (excludes aVR, III and V1). But excludes: 1. Black athletes of African-Caribbean descent with J-point elevation and convex ST segment elevation followed by TWI in V2–4 2. Athletes <16 years with TWI in V1–3 3. Biphasic TWI in only V3
ST segment depression	≥ 0.5 mm deep in ≥ 2 leads	As per ESC	As per ESC	≥ 0.5 mm in depth in ≥ 2 contiguous leads

Table 1. Summary table of the different electrocardiographic criteria. (Cont'd)

ECG abnormality	European Society of Cardiology Criteria	Seattle Criteria	Refined Criteria	2017 International Criteria
ST segment depression	≥0.5mm deep in ≥2 leads	As per ESC	As per ESC	≥0.5mm in depth in ≥2 contiguous leads
Ventricular pre-excitation	PR interval <120ms with or without delta wave	PR interval <120ms with delta wave	As per Seattle Criteria	PR interval <120ms with a delta wave (slurred upstroke in the QRS complex) and QRS duration ≥120ms
Epsilon wave	Not applicable	Not applicable	Not applicable	Distinct low amplitude signal (small positive deflection or notch) between the end of the QRS complex and onset of the T wave in leads V1–3
Prolonged QT interval	QTc>440ms for males, >460ms for females	QTc ≥470ms for males, ≥480ms for females. Marked QT prolongation: QTc≥500ms	QTc≥470ms for males, ≥480ms for females	As per Seattle Criteria
Brugada Type 1 pattern	Not defined	Not defined	Not defined	Coved pattern: Initial ST elevation ≥2mm with downsloping ST segment elevation followed by a negative symmetric T wave in ≥1 leads in V1–3
Profound sinus bradycardia	Not applicable	<30 beats per minute or sinus pauses ≥3sec	Not applicable	As per Seattle Criteria
Profound 1st degree atrioventricular block	Not applicable	Not applicable	Not applicable	PR interval ≥400ms
Mobitz Type II 2nd degree atrioventricular block	Not applicable	Not applicable	Not applicable	Intermittently non-conducted P waves with a fixed PR interval
3rd degree atrioventricular block	Not applicable	Not applicable	Not applicable	Complete heart block
Multiple premature ventricular complexes	Not applicable	≥2 premature ventricular complexes per 10 second tracing	As per Seattle Criteria	As per Seattle Criteria
Atrial tachyarrhythmias	Not defined	Not defined	Not defined	Supraventricular tachycardia, atrial fibrillation, atrial flutter
Ventricular tachyarrhythmias	Not defined	Not defined	Not defined	Couplets, triplets, non-sustained ventricular tachycardia

ESC: European Society of Cardiology; LBBB: left bundle branch block; RBBB: right bundle branch block

recommendations, Seattle Criteria, Refined Criteria and the 2017 International Criteria to detect cardiac abnormality was assessed from sensitivity and specificity test by using echocardiography as the gold standard. Statistical analysis was performed using SPSS Statistics software version 20.0 (IBM Corp, Armonk, US).

RESULTS

Of the 270 athletes included in the study, their ages ranged from 11 to 55 years, with the median age being

19. A total of 218 athletes were under the age of 35 years, accounting for 81% of our study cohort. It was a predominantly male population (87.8%), comprising Malay (43.3%), Chinese (36.7%), Indian (8.1%) and other (11.9%) ethnicities. The athletes competed predominantly in soccer. The demographics are presented in Table 2.

The study showed that 94 (34.8%) of the athletes had ECG abnormalities consistent with ESC group 2 changes, 17 (6.3%) consistent with the Seattle Criteria, 45 (16.7%) consistent with the Refined Criteria, and only 9 (3.3%)

Table 2. Study population demographics.

Demographics	n=270
Median age (range), years	19.0 (11.0–55.0)
Age ≤35 years, n (%)	218 (81)
Male, n (%)	237 (87.8)
Races, n (%)	
Chinese	99 (36.7)
Malay	117 (43.3)
Indian	22 (8.1)
Others	32 (11.9)
Sporting discipline, n (%)	
Soccer	201 (74.4)
Long distance running	25 (9.3)
Swimming	12 (4.4)
Bowling	6 (2.2)
Badminton	5 (1.9)
Netball	5 (1.9)
Track and field	4 (1.5)
Golf	3 (1.1)
Sailing	2 (0.7)
Triathlon	2 (0.7)
Cycling	1 (0.4)
Floorball	1 (0.4)
Gymnastics	1 (0.4)
Squash	1 (0.4)
Table tennis	1 (0.4)

consistent with the 2017 International Criteria. Fig. 1 shows the percentage of each ECG abnormality detected by each of the 4 major criteria.

The 2017 International Criteria resulted in much fewer T wave inversions and Q waves being classified as abnormal when compared to the ESC group 2 Criteria. T wave inversions were reduced from 36 (ESC group 2 major and minor T wave inversions) to just 4 in the 2017 International Criteria, with a similar reduction in Q waves from 15 to 4, respectively. In addition, the ESC group 2 Criteria picked up 13 athletes with right ventricular hypertrophy ECG changes, whereas the 2017 International Recommendations did not label these 13 cases as being abnormal since the ECG changes were all in isolation.

There was a total of 20 patients with abnormalities detected on echocardiography. Table 3 lists these 20 patients with their corresponding ECG findings, whether they satisfied any of the 4 ECG criteria, and their final diagnosis after completion of investigations.

Table 4 lists the sensitivities, specificities, positive and negative predictive values, false positive and negative rates for the ESC, Seattle, Refined and 2017 International

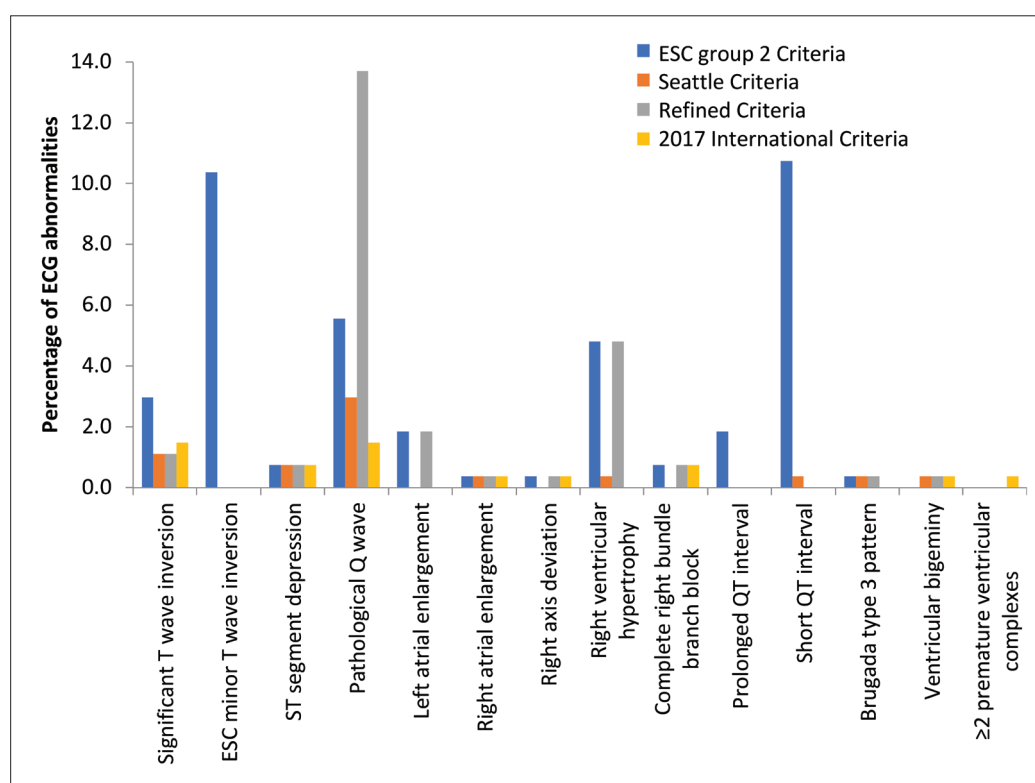


Fig. 1. Electrocardiographic abnormalities detected by each criterion.

ECG: electrocardiogram; ESC: European Society of Cardiology

The columns show the percentage of electrocardiographic abnormalities detected by each of the four criteria (European Society of Cardiology group 2 Criteria in blue, Seattle Criteria in red, Refined Criteria in green and the 2017 International Criteria in purple) in the study population of 270 athletes.

Table 3. List of patients with abnormal echocardiographic finding with their corresponding electrocardiogram (ECG) findings, abnormal ECG criterion satisfied, and final diagnosis.

Patient	ECG findings	Abnormal criterion	Final diagnosis
1	Sinus bradycardia		Previous myocarditis
2	Sinus bradycardia, early repolarisation, Q wave in lead III	Refined	Ischaemic heart disease
3	Sinus bradycardia, early repolarisation, QRS fragmentation, T wave inversion	European Society of Cardiology (ESC)	Ischaemic heart disease
4	Sinus bradycardia, Q wave in lead aVF	Refined	Dilated aortic root
5	Sinus bradycardia, early repolarisation		Pulmonary hypertension
6	Early repolarisation		Mitral valve prolapse
7	Sinus bradycardia, early repolarisation, left ventricular hypertrophy by Sokolov-Lyon criteria		Patent foramen ovale
8	Sinus bradycardia, early repolarisation, QRS fragmentation, left ventricular hypertrophy by Sokolov-Lyon criteria		Perimembranous ventricular septal defect and ventricular septal aneurysm
9	Early repolarisation, left ventricular hypertrophy by Sokolov-Lyon criteria		Atrial septal defect
10	Early repolarisation, QRS fragmentation, first degree heart block		Atrial septal defect
11	Low atrial rhythm, early repolarisation, QRS fragmentation, non-specific ST segment/T wave changes		Ventricular septal defect
12	Sinus bradycardia, early repolarisation, left ventricular hypertrophy by Sokolov-Lyon criteria		Mitral valve prolapse
13	Sinus bradycardia, Q wave in lead aVL	Refined	Left ventricular non-compaction
14	Sinus bradycardia, early repolarisation, left ventricular hypertrophy by Sokolov-Lyon criteria		Patent foramen ovale
15	Sinus bradycardia, non-specific ST segment/T wave changes		Mitral valve prolapse
16	Early repolarisation		Pulmonary stenosis with dilated pulmonary artery
17	Q wave in inferior leads, QRS fragmentation, RVH, left ventricular hypertrophy by Sokolov-Lyon criteria	ESC + Refined + 2017 International Criteria	Pulmonary hypertension
18	Sinus bradycardia, early repolarisation, left ventricular hypertrophy by Sokolov-Lyon criteria		Mitral valve prolapse
19	Left atrial enlargement, left ventricular hypertrophy by Cornell criteria, isolated premature ventricular complex	ESC	Mitral valve prolapse
20	Sinus bradycardia, early repolarisation, T wave inversions	ESC	Mitral valve prolapse and dilated aortic root

criteria. The 2017 International Criteria had a sensitivity of 5%, a specificity of 96.8%, a positive predictive value of 11.1%, and a negative predictive value of 92.7% for detecting abnormalities detected by echocardiography.

The mean duration of follow up was 4.9 ± 1.8 years. During follow-up, none of the 270 athletes had any adverse events such as sudden cardiac death, unexplained syncope (3 had vasovagal syncope and 1 had syncope secondary to heatstroke) or acute myocardial infarction.

Unrelated to his sporting activity, a 56-year-old athlete (patient number 2 in Table 3) had percutaneous coronary intervention performed to his distal left circumflex artery.

DISCUSSION

In this study involving pre-participation screening of competitive and leisure athletes, we compared the ESC, Seattle, Refined and 2017 International Criteria in detecting cardiac abnormalities in Southeast Asian athletes. To the best of our knowledge, these are

Table 4. Sensitivity and specificity using different electrocardiographic criteria to detect cardiac abnormalities in the entire study population (95% confidence interval).

	European Society of Cardiology group 2 Criteria	Seattle Criteria	Refined Criteria	2017 International Criteria
Sensitivity, %	20.0 (5.7–43.7)	0 (0–16.8)	20.0 (5.7–43.7)	5.0 (0.1–24.9)
Specificity, %	64.0 (57.7–70.0)	93.2 (89.3–96.0)	83.6 (78.4–88.0)	96.8 (93.8–98.6)
Positive predictive value, %	4.3 (1.1–10.5)	0 (0–19.5)	8.9 (2.5–21.2)	11.1 (0.3–48.2)
Negative predictive value, %	90.9 (85.7–94.7)	92.1 (88.1–95.1)	92.9 (88.7–95.9)	92.7 (88.9–95.6)
False positive rate, %	36.0 (30.0–42.3)	6.8 (4.0–10.7)	16.4 (12.0–21.6)	3.2 (1.4–6.2)
False negative rate, %	80.0 (56.3–94.3)	100 (83.2–100)	80.0 (56.3–94.3)	95.0 (75.1–99.9)

the first such published data in Southeast Asian athletes and build upon our knowledge base for athletes around the world.

There was a significant reduction in the number of abnormal T wave inversions and pathological Q waves using the 2017 International Criteria due to stricter criteria. The ESC group 2 changes considered deep T wave inversions as $\geq 2\text{mm}$ in ≥ 2 adjacent leads, and minor T wave inversions as $< 2\text{mm}$ in ≥ 2 adjacent leads. Using these criteria, there were 8 deep and 28 minor T wave inversions in our study. On the other hand, although the 2017 International Criteria considered abnormal T wave inversions as just $\geq 1\text{mm}$ in ≥ 2 contiguous leads, it excluded leads aVR, III and V1 from consideration, as well as regarded juvenile T wave inversions in V1–3 as normal findings.¹³ Similarly, the ESC group 2 and Seattle Criteria considered pathological Q waves based on an absolute depth on the Q wave, while the Refined Criteria introduced the concept of a Q/R ratio of ≥ 0.25 to compensate for issues such as physiological left ventricular hypertrophy or thin individuals. The 2017 International Criteria further necessitated that abnormal Q waves had to be present in ≥ 2 contiguous leads, excluding leads III and aVR, before further investigations are warranted. These reductions, predominantly in athletes with normal cardiac investigations, contributed significantly to the improved specificity of the 2017 International Criteria in our study.

Based on our data, the latest 2017 International Criteria performed the best among the four criteria as it had the highest specificity (97%) and PPV (11%), the joint highest NPV (93%) and the lowest false positive rate (3%). In clinical practice, the relevance of

this emerges when the ECG is negative, as clinicians can be reassured that these patients have a very high probability (93%) of truly not having any cardiac condition at that time. However, when the pre-participation ECG is abnormal based on the criteria, only a low probability exists of a truly underlying cardiac condition. This finding is relevant to current clinical practice, which recommends that ECG in pre-participation screening is interpreted according to the 2017 International Recommendations.¹⁴

The sensitivity by all four criteria is extremely poor, with at best 20% by ESC and Refined Criteria for our Singapore athletes. The issue of improving specificity at the price of sensitivity has been raised by Zorzi et al.,¹⁵ and this is especially disconcerting for our group of athletes. In our previous study on Singapore athletes,¹⁶ we have shown that an elite athlete's heart demonstrated similar morphologic exercise-induced cardiac remodelling as Caucasian athletes, but possibly to a lesser extent than the latter, as we did not observe any absolute left ventricular wall thickness beyond 1.2cm or left ventricular dilatation beyond 5.5cm. A recent study also showed that the upper limits of left ventricular wall thickness was 13mm and left ventricular diameter was 63mm in Southeast Asian athletes.¹⁷ In a separate study, we were not able to find any sports-related sudden cardiac deaths from hypertrophic cardiomyopathy in the Singapore population over 11 years.¹⁸ The low Singapore prevalence of cardiomyopathies might account for the low PPV, while the lower degree of electrical remodelling could explain the poor sensitivity.

There are several limitations to our study with the first being our study population. It was derived from a single centre registry and although our study population

included athletes of all the major ethnic groups in Singapore, we cannot rule out the possibility that other centres in our region may have differences in baseline demographics and ECG characteristics. It was also composed predominantly of males of Malay ethnicity, hence females and other ethnicities are under-represented. In addition, most of our athletes participated in soccer, which is classified as a mixed sporting discipline.¹⁹ Therefore, our study could not assess the utility of these four ECG criteria in other sporting disciplines such as power (e.g. weightlifting, short-distance running and gymnastics) and endurance (e.g. cycling, rowing and swimming). We also acknowledge that our study population only focused on the subset of athletes within our entire registry who had further cardiac investigations performed. Hence, we may not have picked up athletes with normal pre-participation screening who could have underlying cardiac abnormalities, which would then affect the sensitivity, specificity, PPV and NPV.

Secondly, despite ECG screening and further cardiac investigations such as echocardiography, we did not detect any case of HCM. This condition was reported to be the most common cause of sudden cardiac death in athletes, accounting for 36% (and perhaps up to 44%) of sudden cardiac death cases.³ However, HCM does produce classical deep T wave inversions in the praecordial leads, with less than 10% of HCM patients having a normal ECG.²⁰ Therefore, we believe that the ECG criteria in the latest 2017 International Recommendations would be able to detect HCM among athletes reliably.

Next, a significant proportion of our athletes only had one echocardiogram performed. Because individuals may

only develop HCM at a later stage, we cannot rule out the possibility that the false-negative rate may have been underestimated.

In addition, we recognise that echocardiography would only detect structural heart abnormalities and may miss out arrhythmic conditions. However, our ECG analysis did not pick up any case of Wolff-Parkinson-White syndrome or Brugada type 1 ECG patterns. There was one Brugada type 3 pattern, but this is no longer clinically relevant and does not satisfy the diagnosis of Brugada syndrome. There were 6 cases of long QT detected by ESC Criteria that had a cut-off of 440ms and 460ms for males and females, respectively. However, all 6 cases were less than 470ms and 480ms for males and females, respectively, and were hence not considered abnormal by the other three criteria.

Furthermore, as some of the echocardiograms were performed based on clinical grounds or as part of the screening protocols of the relevant sports organisation, some of the abnormalities detected on echocardiography may be incidental and not related to any ECG abnormality. For example, there were several patients that satisfied other criteria besides the 2017 International Criteria who were subsequently found to have echocardiographic abnormalities. With reference to Table 3, patients 2 (Q wave in lead III) and 3 (T wave inversion) were found to have ischaemic heart disease, patient 4 (Q wave in lead aVF) was found to have a dilated aortic root, patient 13 (Q wave in lead aVL) was found to have left ventricular non-compaction, and patients 19 (left atrial enlargement) and 20 (T wave inversion) were found to have mitral valve prolapse. While it is possible that some of these were incidental

Table 5. Sensitivity and specificity using different electrocardiographic criteria to detect cardiac abnormalities in the study population after excluding master athletes (95% confidence interval).

	European Society of Cardiology group 2 Criteria	Seattle Criteria	Refined Criteria	2017 International Criteria
Sensitivity, %	20.0 (4.3–48.1)	0 (0.0–21.8)	13.3 (1.7–40.5)	6.7 (0.2–31.9)
Specificity, %	60.3 (53.3–67.0)	92.8 (88.4–95.9)	81.8 (75.9–86.8)	96.7 (93.2–98.6)
Positive predictive value, %	3.5 (0.7–9.9)	0 (0–21.8)	5.0 (0.6–16.9)	12.5 (0.3–52.7)
Negative predictive value, %	91.3 (85.3–95.4)	92.8 (88.4–95.9)	92.9 (88.2–96.2)	93.5 (89.4–96.4)
False positive rate, %	39.7 (33.0–46.7)	7.2 (4.1–11.6)	18.2 (13.2–24.1)	3.3 (1.4–6.8)
False negative rate, %	80.0 (51.9–95.7)	100 (78.2–100)	86.7 (59.5–98.3)	93.3 (68.1–99.8)

findings, it is difficult to draw definitive conclusions regarding the positive predictive findings of each criterion in a small sample size.

In contrast to previous studies,^{5,8,10,12} our study included both young athletes as well as master athletes—athletes above 35 years old. Traditional pre-participation screening is focused on young athletes below the age of 35 and the four criteria are developed for such a population. We reanalysed our data after excluding the master athletes and had similar results (Table 5)—the 2017 International Criteria had the highest specificity (97%), PPV (13%) and NPV (94%), and the lowest false positive rate (3%). This is not surprising as master athletes only made up 19% of our study population. We also believe that including master athletes reflects real world practice of applying the ECG criteria to all age groups of athletes.

Lastly, even though our study population was recruited between 2007 and 2014, the ECGs were interpreted and analysed according to the four criteria, so would not have been different in an updated group of patients. Nevertheless, further contemporary research enrolling a larger group of patients from multiple centres around our region would help to ensure our athletes are not under-represented when future international pre-participation screening guidelines are being developed.

CONCLUSION

We have compared the latest 2017 International Criteria for ECG interpretation against the ESC group 2 changes, and the Seattle and Refined Criteria in our population of Southeast Asian athletes. The 2017 International Criteria had the highest specificity and PPV, joint highest NPV and lowest false positive rate among the 4 major ECG criteria. However, the sensitivity of all four criteria is very poor in our Singapore population. Further large-scale studies in the Singapore population would add more information into our ever-growing knowledge base of pre-participation ECG interpretation in athletes worldwide.

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