Comparison of Electrocardiographic Criteria for the Detection of Cardiac Abnormalities in Elite Black and White Athletes

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Background—Recent efforts have focused on improving the specificity of the European Society of Cardiology (ESC) criteria for ECG interpretation in athletes. These criteria are derived predominantly from white athletes (WAs) and do not account for the effect of Afro-Caribbean ethnicity or novel research questioning the relevance of several isolated ECG patterns. We assessed the impact of the ESC criteria, the newly published Seattle criteria, and a group of proposed refined criteria in a large cohort of black athletes (BAs) and WAs.

Methods and Results—Between 2000 and 2012, 1208 BAs were evaluated with history, examination, 12-lead ECG, and further investigations as appropriate. ECGs were retrospectively analyzed according to the ESC recommendations, Seattle criteria, and proposed refined criteria which exclude several specific ECG patterns when present in isolation. All 3 criteria were also applied to 4297 WAs and 103 young athletes with hypertrophic cardiomyopathy. The ESC recommendations raised suspicion of a cardiac abnormality in 40.4% of BAs and 16.2% of WAs. The Seattle criteria reduced abnormal ECGs to 18.4% in BAs and 7.1% in WAs. The refined criteria further reduced abnormal ECGs to 11.5% in BAs and 5.3% in WAs. All 3 criteria identified 98.1% of athletes with hypertrophic cardiomyopathy. Compared with ESC recommendations, the refined criteria improved specificity from 40.3% to 84.2% in BAs and from 73.8% to 94.1% in WAs without compromising the sensitivity of the ECG in detecting pathology.

Conclusion—Refinement of current ECG screening criteria has the potential to significantly reduce the burden of false-positive ECGs in athletes, particularly BAs. (Circulation. 2014;129:1637-1649.)

Key Words: cardiomyopathies ■ echocardiography ■ electrocardiography ■ ethnic groups ■ exercise ■ hypertrophy ■ mass screening

Preparticipation screening for the early identification of young athletes at risk of exercise-related sudden cardiac death (SCD) is recommended by a growing number of sporting bodies and scientific organizations worldwide.1–3 Whereas evidence from Italy suggests that ECG-based screening is effective at detecting athletes with potentially serious cardiac disorders,4,5 justifiable concerns remain related to high false-positive rates arising from the overlap between physiological ECG patterns and those reflecting cardiac pathology.6–8

The 2010 European Society of Cardiology (ESC) recommendations for ECG interpretation in athletes have attempted to facilitate the differentiation between physiological ECG patterns (group 1) and those indicative of cardiac disease (group 2).9 Although such categorization has improved specificity,8,10 false-positive rates between 10% and 20% have invariably prompted calls for further refinement.11 A recent collaboration between international experts culminated in the Seattle criteria,12 which have improved specificity in some populations.13

New data based on large athlete cohorts from our group have revealed several isolated ECG patterns to have a low diagnostic yield for cardiac disease, questioning their relevance as markers of pathology in elite athletes.14,15 Current guidelines in practice are consensus based and do not fully incorporate such scientific observations in their recommendations. Furthermore, they are derived almost exclusively from unselected white athletes (WAs)16 and have not been evaluated in large cohorts of elite athletes of African/Afro-Caribbean origin (black athletes; BAs). The paucity of ECG interpretation criteria in BAs is of concern, given that they most...
frequently exhibit profound ECG alterations\textsuperscript{7,17–21} that overlap with primary cardiomyopathies, which magnifies their risk of an erroneous diagnosis.

This study assessed the performance of the ESC and Seattle criteria in large cohorts of highly trained BAs and WAs compared with proposed refined criteria (Figure 1A) that incorporate new research findings and the effect of black ethnicity.\textsuperscript{7,14,15,17,19,20} To determine their sensitivity for the detection of hypertrophic cardiomyopathy (HCM), all 3 criteria were applied to a well-characterized cohort of young, asymptomatic athletes with HCM.

**Methods**

The United Kingdom does not support a state-sponsored cardiac screening program in athletes. However, the charitable organization Cardiac Risk in the Young has an established cardiac screening program for young individuals that also serves many professional sporting organizations, including the English Institute of Sport, Lawn Tennis Association, Aviva Premiership Rugby, and Football Association.\textsuperscript{22} Up to 1000 athletes from numerous regional or national sporting squads are assessed annually. Most preliminary evaluations, including ECG and echocardiography, are performed at training centers through a mobile investigations unit and supervised

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**Figure 1.** The definition of an abnormal ECG using the (A) refined criteria, (B) European Society of Cardiology (ESC) recommendations,\textsuperscript{9} and (C) Seattle criteria.\textsuperscript{12}
by the principal investigator (S.S.). Most athletes with abnormal findings are investigated further in a dedicated Inherited Cardiac Diseases and Sports Cardiology Unit at St. George’s Hospital.1

Elite Athletes
Between 2000 and 2012, 1208 elite BAs and 4297 elite WAs 14 to 35 years of age were evaluated with a health questionnaire, cardiovascular examination, and 12-lead ECG. An athlete was considered elite if competing regularly at the regional, national, or international level and exercising for ≥26 h/wk. Ethnicity was self-assigned. Individuals with concerning symptoms, family history of cardiomyopathy or premature (<40 years) SCD, a cardiac murmur, or an abnormal ECG were assessed with 2-dimensional echocardiography and further investigations as necessary. A large proportion of elite athletes competing at the national or international level underwent 2-dimensional echocardiography as standard in accordance with the screening protocol required by their sporting organizations.

Investigations in Elite Athletes

ECG Interpretation

The first comprehensive recommendations for interpretation of a young athlete’s ECG were published by the ESC in 2005 and modified in 2010 to improve specificity. In 2012, an international panel adjourned in Seattle to provide yet another revision to facilitate the development of universally accepted guidelines for ECG interpretation in young athletes that may also be applicable to BAs. Between 2000 and 2010, our own practice for ECG interpretation in athletes was similar to the 2010 ESC recommendations and was associated with an unacceptably high false-positive rate.

Refined ECG Criteria
Between 2010 and 2012, we reassessed our practice of ECG interpretation in athletes more critically. On the basis of our long-standing experience of evaluating several thousand athletes and in line with recent consensus documents and research findings,7,12,14,15,17,19,20,26 we identified certain ECG anomalies (borderline variants; Figure 1A) currently included in the group 2 category of the ESC recommendations and some deemed abnormal by the Seattle criteria that we would now consider normal variants in asymptomatic athletes without a relevant family history or abnormal cardiac examination. Specifically, we would not recommend further investigation of athletes with any one of the following ECG patterns when present either in isolation or in association with recognized training-related ECG changes: (1) left atrial enlargement, (2) right atrial enlargement, (3) left axis deviation, (4) right axis deviation, and (5) Sokolow-Lyon voltage criteria for right ventricular hypertrophy. On the basis of our experience7 and in conjunction with the Bethesda guidelines25 and more recent Seattle criteria,12 we have increased the cutoff for an abnormal corrected QT interval (QTc) to 470 milliseconds in male and 480 milliseconds in female athletes. Finally, consistent with previous publications from our group,7,13,17,19,20 we no longer investigate asymptomatic BAs with T-wave inversion preceded by convex ST-segment elevation confined to V1 through V3, a practice also adopted by the recent Seattle criteria.12 Conversely, the presence of ≥2 of these 6 patterns in combination or in association with other group 2 ESC changes would be a requirement for further investigation. The refined criteria are illustrated in Figure 1A. Definitions of specific ECG patterns used in all 3 criteria are provided in Table 1.

Retrospective ECG Analysis
The ECGs of all 5505 elite athletes were analyzed retrospectively using the ESC recommendations and Seattle criteria, with specific attention given to the presence of abnormalities necessitating further investigation (ESC group 2 changes9 [Figure 1B]) or Seattle criteria abnormal ECG findings in athletes13 [Figure 1C]). We also applied the refined criteria retrospectively to our entire cohort of athletes. During ECG analysis, readers were blinded to pathological findings in all athletes.

Athletes With HCM
We applied the ESC recommendations, Seattle criteria, and refined criteria to a well-characterized cohort of 103 consecutive young athletes with HCM assessed in 4 dedicated cardiomyopathy clinics in London (United Kingdom) and the French Institute of Health and Medical Research in Rennes (France). All individuals were between 14 and 35 years of age, were asymptomatic, and exercised for a minimum of 4 h/wk at the time of presentation, enabling the performance of ECG criteria in identifying HCM to be assessed in a group comparable to that encountered during preparticipation evaluation. The initial 12-lead ECG obtained at the time of the first evaluation was used for analysis. Athletes were diagnosed with HCM after investigation for abnormalities identified through preparticipation evaluation, after cascade screening of family members of an individual affected with HCM, or after referral for a specialist opinion from another center.

HCM was diagnosed on the basis of left ventricular hypertrophy (LVH) ≥15 mm in any myocardial segment, as assessed on echocardiography or cardiac magnetic resonance imaging, in the presence of a nondilated left ventricle and the absence of another cardiac disorder or systemic condition capable of producing the same magnitude of LVH.29 In cases of mild LVH (<15 mm), HCM was diagnosed in the context of a combination of features,8 including ECG repolarization anomalies, specifically ST-segment depression or marked T-wave inversion; unusual patterns of LVH; the presence of a small left ventricular cavity; identification of HCM in a first-degree relative; or a positive gene test.

Ethics Approval
Ethics approval was granted by the National Research Ethics Service, Essex 2 Research Ethics Committee in the United Kingdom, the French Ministry of Health and Youth in France, and Shafallah Medical Genetic Center in Qatar. Written consent was obtained from athletes ≥16 years of age and from a parent or guardian for those <16 years of age.

Statistical Analysis
Data were expressed as mean±SD or percentages as appropriate and analyzed with SPSS software, version 20 (Chicago, IL). Continuous variables were tested for normality using the Kolmogorov-Smirnov test. Group differences were tested with the Student t test or Mann-Whitney U test for normally and
Table 1. ECG Parameters Used to Define Various ECG Abnormalities in the European Society of Cardiology Recommendations, Seattle Criteria, and Refined Criteria

<table>
<thead>
<tr>
<th>ECG Abnormality</th>
<th>European Society of Cardiology Recommendations$^*$</th>
<th>Seattle Criteria$^2$</th>
<th>Refined Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left atrial enlargement</td>
<td>Negative portion of the P wave in lead V$_1$ $\geq$0.1 mV in depth and $\geq$40 ms in duration</td>
<td>Prolonged P wave duration of $\geq$120 ms in lead I or II with negative portion of the P wave $\geq$1 mm in depth and $\geq$40 ms in duration in lead V$_i$</td>
<td>As ESC</td>
</tr>
<tr>
<td>Right atrial enlargement</td>
<td>P-wave amplitude $\geq$2.5 mm in lead II, III, or aVF</td>
<td>As ESC</td>
<td>As ESC</td>
</tr>
<tr>
<td>Left QRS axis deviation</td>
<td>$-30^\circ$ to $-90^\circ$</td>
<td>As ESC</td>
<td>As ESC</td>
</tr>
<tr>
<td>Right QRS axis deviation</td>
<td>$&gt;115^\circ$</td>
<td>$&gt;120^\circ$</td>
<td>As ESC</td>
</tr>
<tr>
<td>Right ventricular hypertrophy</td>
<td>Sum of R wave in V$_i$ and S wave in V$_i$ or V$_6$ $\geq$10.5 mm</td>
<td>Sum of R wave in V$_i$ and S wave in V$_i$ $\geq$10.5 mm and right axis deviation $&gt;120^\circ$</td>
<td>As ESC</td>
</tr>
<tr>
<td>Complete LBBB</td>
<td>QRS $\geq$120 ms, predominantly negative QRS complex in lead V$_i$ (QS or rS), and upright monophasic R wave in leads I and V$_6$</td>
<td>As ESC</td>
<td>As ESC</td>
</tr>
<tr>
<td>Complete RBBB</td>
<td>RSP$^*$ pattern in anterior precordial leads with QRS duration $\geq$120 ms</td>
<td>Not relevant</td>
<td>As ESC</td>
</tr>
<tr>
<td>Intraventricular conduction delay</td>
<td>Any QRS duration $\geq$120 ms including RBBB and LBBB</td>
<td>Any QRS duration $\geq$140 ms or complete LBBB</td>
<td>As ESC</td>
</tr>
<tr>
<td>Pathological Q-wave</td>
<td>$&gt;4$ mm deep in any lead except III, aVR</td>
<td>$&gt;3$ mm deep or $&gt;40$ ms duration in $\geq$2 leads except III and aVR</td>
<td>$\geq$40 ms in duration or $\geq$25% of the height of the ensuing R wave</td>
</tr>
<tr>
<td>Significant T-wave inversion</td>
<td>$\geq$2 mm in $\geq$2 adjacent leads (deep) or “minor” in $\geq$2 leads</td>
<td>$&gt;1$ mm in depth in $\geq$2 leads V$_i$–V$_i$, II and aVF, or I and aVL (excludes III, aVR, and V$_6$)</td>
<td>As Seattle</td>
</tr>
<tr>
<td>ST-segment depression</td>
<td>$\geq$0.5 mm deep in $\geq$2 leads</td>
<td>As ESC</td>
<td>As ESC</td>
</tr>
<tr>
<td>Ventricular preexcitation</td>
<td>PR interval $&lt;120$ ms with or without delta wave</td>
<td>PR interval $&lt;120$ ms with delta wave</td>
<td>As Seattle criteria</td>
</tr>
</tbody>
</table>

LBBB indicates left bundle-branch block; and RBBB, right bundle-branch block.

non-normally distributed variables, respectively. The $\chi^2$ test was used to compare the proportion of positive ECGs in BA$s versus WA$s within each criterion, with significance defined as $P<0.05$ throughout. Positive agreement between the 3 criteria was determined using $k$ and $c$ statistics.

The sensitivity and specificity for the screening process and 95% confidence intervals were calculated from the athletic population who underwent history, examination, ECG, and echocardiography as standard, using 2×2 contingency tables in GraphPad Prism software, version 6.01 (La Jolla, CA). Sensitivity was defined as the ability to detect any cardiac disorder in this cohort (serious or minor) through the screening procedures performed (history, examination, ECG, and echocardiography). A serious cardiac disorder was defined as one that has been implicated as a recognized cause of exercise-related SCD (heart failure, myocardial infarction, valvular heart disease, arrhythmias, congenital heart disease, etc.). Specificity was defined as the ability to correctly identify athletes without a cardiac disorder in this cohort with the screening procedures performed. Echocardiography was used as the gold-standard test for the detection or exclusion of structural disease. Negative and positive predictive values were calculated on the basis of the definitions above.

Results

Athlete Demographics

The majority of BA$s and WA$s were male (85.8% and 76.8%, respectively). Overall, WA$s were younger than BA$s (19.3±5.4 versus 22.2±5.7 years; $P<0.001$). WA$s and BA$s had similar body surface areas (1.92±0.26 versus 1.92±0.21 m²; $P=0.7$), and all had a blood pressure of $\leq$140/90 mmHg. Athletes competed in a total of 31 different sporting disciplines; the top 5 sports represented were soccer (26.2%), rugby (11.6%), athletics (11.1%), tennis (9.5%), and swimming (6.5%). WA$s exercised for slightly more hours per week than BA$s (16.3±7.5 versus 15.5±6.1 hours; $P<0.001$). Of the BA$s, 56.4% were of West African origin, 26.5% Caribbean, 14.9% North African, and 4.8% East African; 4.6% were of mixed ethnicity, and 2.7% were from the Americas.

Characteristics of Athletes With HCM

The average age of athletes with HCM was 24.3±6.9 years (range, 14–35 years), and the majority (94.2%) were male. Athletes with HCM exercised for an average of 9.7±5.1 h/wk. A significant percentage of the total HCM cohort (n=34, 33.0%) were African/Afro-Caribbean. Further characteristics of athletes with HCM are provided in Table 2.

Nine athletes (8.7%) with HCM showed concentric LVH and wall thicknesses $<15$ mm, placing them in a diagnostic grey zone between athlete’s heart and HCM. Of these, 7 were Afro-Caribbean. All 9 exhibited deep T-wave inversion extending into the inferolateral leads, 2 showed pathological Q waves, and 4 revealed resting ST-segment depression. The mean relative wall thickness in this group was 0.5±0.08. Four athletes exhibited late gadolinium enhancement on cardiac magnetic resonance imaging, and 3 had a family history of HCM or SCD.
Table 2. Characteristics of 103 Athletes With Hypertrophic Cardiomyopathy

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age at diagnosis, y</td>
<td>24.3±6.9</td>
</tr>
<tr>
<td>Male sex, %</td>
<td>94.2</td>
</tr>
<tr>
<td>African/Afro-Caribbean ethnicity, %</td>
<td>33.0</td>
</tr>
<tr>
<td>Blood pressure, mm Hg</td>
<td>123±12/73±11</td>
</tr>
<tr>
<td>Family history of hypertrophic cardiomyopathy/sudden cardiac death, %</td>
<td>29.2</td>
</tr>
<tr>
<td>Mode of diagnosis, %</td>
<td>81.3</td>
</tr>
<tr>
<td>Preparticipation screening abnormal ECG</td>
<td>16.7</td>
</tr>
<tr>
<td>Other</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Echocardiographic characteristics

- Left atrial dimension, mm: 38.1±6.6
- Left ventricular cavity dimension in diastole, mm: 47.3±5.9
- Maximal left ventricular wall thickness, mm: 15.5±2.9
- Relative wall thickness: 0.61±0.23
- Left ventricular mass, g: 255.1±76.9
- Mitral inflow E wave, m/s: 0.77±0.17
- Mitral inflow A wave, m/s: 0.47±0.11
- E/A: 1.78±0.55
- E' lateral, m/s: 0.12±0.03
- E' septal, m/s: 0.08±0.02
- E/E' average: 8.2±2.8
- Resting systolic anterior motion of mitral valve leaflets, %: 8.6
- Resting left ventricular outflow tract gradient ≥30 mm Hg, %: 3.4
- Left ventricular ejection fraction, %: 68.2±7.2
- LVH pattern, %
  - Apical: 35.7
  - Septal: 44.0
  - Concentric: 15.5
  - Other: 4.8
- ECG characteristics, %
  - Sinus bradycardia (heart rate <60 bpm): 52.4
  - LVH (Sokolow-Lyon criteria): 60.2
  - Romhilt-Estes score ≥4/≥5: 88.3/68.9
- Right ventricular hypertrophy (Sokolow-Lyon criteria): 10.7
- Left atrial enlargement: 37.9
- Right atrial enlargement: 18.4
- Left axis deviation: 7.8
- Right axis deviation: 1.9
- Pathological Q waves: 25.2
- Inverted T waves: 97.1
  - Deep: 87.4
  - V1–V4: 2.0
  - Inferior leads: 11.0
  - Laternal leads: 87.0
- ST-segment elevation: 63.1
- ST-segment depression: 54.4

Analysis of ECGs

Application of the ESC Recommendations and Seattle Criteria

The number of ECGs deemed abnormal with the use of the ESC recommendations and Seattle criteria is illustrated in Figure 2. Application of the ESC recommendations to our total athlete cohort resulted in 1183 athletes (21.5%) being designated as abnormal. BAs were 2.5 times more likely to exhibit an abnormal ECG compared with WAs (40.4% versus 16.2%; P<0.0001). The most prevalent ECG abnormalities in BAs were T-wave inversion (19.3%), right ventricular hypertrophy (10.7%), and left or right atrial enlargement (13.8%; Figure 3).

The Seattle criteria reduced the number of abnormal ECGs to 9.6% for the total athlete cohort. With the use of the Seattle criteria, BAs were 2.6 times more likely to exhibit an abnormal ECG compared with WAs (18.4% versus 7.1%; P<0.0001; Figure 2).

Refined Criteria

The refined criteria reduced the number of abnormal ECGs to 6.6% for the total athlete cohort. Compared with the ESC and Seattle criteria, the refined criteria were associated with a significant reduction in the number of abnormal ECGs in both BAs and WAs, to 11.5% and 5.3%, respectively (P<0.0001; Figure 2). Relative to the ESC recommendations, the refined criteria offered a 71.5% reduction in abnormal ECGs in BAs and a 67.3% reduction in WAs. In absolute terms, the refined criteria offered a further 37.5% reduction in abnormal ECGs in both BAs and WAs (28.9% versus 10.9%, respectively). Relative to the Seattle criteria, the refined criteria offered a 25.4% reduction in abnormal ECGs in BAs and a 30.4% reduction in WAs. On the basis of the refined criteria, the leading cause for an abnormal ECG in BAs remained T-wave inversion (Figure 3) in the inferior and lateral leads.

Comparison of Criteria for Agreement

Comparison of the 3 criteria for positive results in BAs and WAs revealed the strongest agreement between the Seattle and refined criteria, particularly in WAs (Table 3 and Figure 4). There was only fair to moderate agreement between the ESC recommendations and the refined and Seattle criteria for BAs and WAs.

Application of the ESC, Seattle, and Refined Criteria to Athletes With HCM

All 3 ECG criteria detected all but 2 athletes with HCM (1.9%) on the basis of ECG alone. Both athletes exhibited a normal ECG. The first individual was diagnosed after routine echocardiography as part of his preparticipation evaluation; the second was diagnosed after family screening for HCM (Table 4).

None of the athletes with HCM exhibited isolated atrial enlargement, axis deviation, or right ventricular hypertrophy on their ECGs. Similarly, none of the BAs with HCM showed isolated T-wave inversion in V1 through V4.

Identification of Pathology

Of the 3210 athletes (58.3%) who underwent echocardiography (2392 WAs [55.7%] and 818 BAs [67.7%]), 1183 (36.9%) had an ECG deemed abnormal (695 WAs and 488 BAs), 28 (0.9%) had symptoms, 24 (0.7%) had a cardiac murmur,
20 (0.6%) had a significant family history. The remaining 1955 athletes (60.9%) underwent echocardiography despite normal preliminary investigations as a result of their club policy.

Of the 3210 athletes who underwent both ECG and echocardiography, 40 (1.25%) were diagnosed with a cardiac disorder. Specifically, 15 (0.47%) had a serious disorder: HCM
Wolff-Parkinson-White syndrome (n=5), long-QT syndrome (n=3), Brugada syndrome (n=1), and anomalous coronary artery origin (n=1). Twenty-five (0.78%) had a minor congenital/valvular abnormality: bicuspid aortic valve (n=10), mitral valve prolapse (n=7), atrial septal defect (n=3), ventricular septal defect (n=2), mild aortic regurgitation (n=1), mild pulmonary stenosis (n=1), and cor triatriatum (n=1; Figure 5).

Fourteen of the 15 athletes (93.3%) with a potentially serious cardiac disorder (including all 5 cases of HCM) were identified with ECG, and only 1 (6.7%) was detected on the basis of symptoms. Of the athletes with minor congenital abnormalities, 10 (40.0%) were identified on the basis of abnormal examination findings, and 15 (60.0%) were detected on routine echocardiography in the setting of a normal history, examination, and ECG.

In contrast to the ability to detect sinister disorders, the ECG alone failed to identify all 25 individuals with minor congenital or valvular abnormalities, regardless of the ECG criteria used. The ECGs in these athletes revealed either normal or isolated group 1 changes.

### Sensitivity and Specificity of the ESC Recommendations, Seattle Criteria, and Refined Criteria

Of the 3210 athletes who underwent echocardiography, 3087 (96.2%) were required to do so as part of their club’s

### Table 3. Agreement Between the 3 Criteria: Seattle, Refined, and European Society of Cardiology

<table>
<thead>
<tr>
<th></th>
<th>Positive ECGs, n</th>
<th>(\kappa)</th>
<th>95% Confidence Interval</th>
<th>(c) Statistic</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Black athletes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESC positive, Seattle positive</td>
<td>222</td>
<td>0.50</td>
<td>0.45–0.55</td>
<td>0.78</td>
<td>0.76–0.80</td>
</tr>
<tr>
<td>Seattle positive, refined positive</td>
<td>139</td>
<td>0.73</td>
<td>0.68–0.79</td>
<td>0.93</td>
<td>0.92–0.95</td>
</tr>
<tr>
<td>ESC positive, refined positive</td>
<td>139</td>
<td>0.32</td>
<td>0.26–0.38</td>
<td>0.71</td>
<td>0.69–0.74</td>
</tr>
<tr>
<td><strong>White athletes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESC positive, Seattle positive</td>
<td>305</td>
<td>0.57</td>
<td>0.53–0.61</td>
<td>0.91</td>
<td>0.90–0.92</td>
</tr>
<tr>
<td>Seattle positive, refined positive</td>
<td>228</td>
<td>0.85</td>
<td>0.81–0.88</td>
<td>0.98</td>
<td>0.98–0.99</td>
</tr>
<tr>
<td>ESC positive, refined positive</td>
<td>228</td>
<td>0.45</td>
<td>0.40–0.50</td>
<td>0.89</td>
<td>0.88–0.90</td>
</tr>
</tbody>
</table>

ESC indicates European Society of Cardiology.

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**Figure 4.** Correlation of \(\kappa\) and \(c\) statistic for each pair of criteria in white and black athletes (line represents trend of how these correlations are located). ESC indicates European Society of Cardiology.
policy, regardless of clinical or ECG findings (805 BAs and 2282 WAs). This group contained all athletes diagnosed with pathology and was used to assess the effect of the refined criteria on the sensitivity and specificity of the overall screening process (Table 5). Compared with the ESC recommendations, the Seattle criteria were associated with a marked improvement in specificity for both BAs (40.3% to 79.3%) and WAs (73.8% to 92.1%). The refined criteria offered a further improvement in specificity, to 84.2% in BAs and 94.1% in WAs.

Sensitivity for all cardiac diseases remained 70.0% in BAs and 60.0% in WAs for all 3 criteria. After exclusion of minor congenital and valvular abnormalities, the sensitivity for all 3 criteria improved to 100% in both BAs and WAs without compromising specificity (ESC: 40.1% BAs and 73.5% WAs; Seattle: 79.3% BAs and 92.1% WAs; refined criteria: 84.2% BAs and 93.9% WAs; Table 6).

**Interobserver Variability Between ECG Findings**

There was excellent agreement with respect to ECG findings during reanalysis of a random selection of 1000 ECGs by the first and senior authors, translating to a $\kappa$ (measurement of agreement) of 0.97 ($P<0.0001$).

**Further Investigations and ECG Predictors of Cardiac Disease**

A substantial number of athletes (3210, 58.3%) underwent additional investigations after the ECG (Figure 6). This group included 1955 asymptomatic athletes with normal/training-related ECG patterns who would have normally been cleared without additional tests but were required to have echocardiography as part of their club’s policy. None of the 1955 athletes were diagnosed with a serious structural disorder.

Five hundred nineteen athletes (9.4%) were recommended for further investigations after ECG and echocardiography.

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Table 4. Characteristics of Athletes With Hypertrophic Cardiomyopathy and a Normal ECG

<table>
<thead>
<tr>
<th>Age of Presentation, y</th>
<th>Sex</th>
<th>Ethnicity</th>
<th>Mode of Identification</th>
<th>Symptoms</th>
<th>Family History of Hypertrophic Cardiomyopathy</th>
<th>Examination Findings</th>
<th>ECG Findings</th>
<th>Maximum LVWT (Pattern), mm</th>
<th>Relative Wall Thickness</th>
<th>LGE on CMRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>Male</td>
<td>White</td>
<td>Preparticipation screening*</td>
<td>None</td>
<td>No</td>
<td>Nil</td>
<td>Nil</td>
<td>14† (Asymmetrical septal)</td>
<td>0.53</td>
<td>No</td>
</tr>
<tr>
<td>23</td>
<td>Male</td>
<td>White</td>
<td>Familial screening</td>
<td>None</td>
<td>Yes</td>
<td>Nil</td>
<td>Nil</td>
<td>14† (Asymmetrical septal)</td>
<td>0.42</td>
<td>No</td>
</tr>
</tbody>
</table>

CMRI indicates cardiac magnetic resonance imaging; LGE, late gadolinium enhancement; and LVWT, left ventricular wall thickness.

*On routine echocardiography.
†No regression of left ventricular hypertrophy after detraining.

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Figure 5. Number of athletes with pathology, characterized by ethnicity and screening modality triggering diagnosis. Green indicates minor congenital/valvular defects; and red, serious pathology.
Of these, 466 were advised to obtain a cardiac magnetic resonance imaging scan, exercise test, and Holter monitor to exclude a cardiomyopathy on the basis of marked ECG repolarization changes \( (n=389) \) or structural changes that placed them in the grey zone for cardiomyopathy \( (n=77) \), and 53 were advised an exercise test and Holter monitor on the basis of symptoms or family history \( (n=38) \) or a prolonged QT interval \( (n=15) \). Complete data were available in 454 athletes \( (87.5\%) \), including all those with a prolonged QT interval, inferolateral T-wave inversion, and a wall thickness \( \geq 13 \text{ mm} \) (Figure 7).

Exercise testing facilitated the diagnosis of long-QT syndrome in 3 of 15 athletes \( (20\%) \) with a prolonged QT interval. All 3 athletes revealed a QTc >500 milliseconds. Cardiac magnetic resonance imaging after echocardiography aided the diagnosis of a cardiomyopathy in only 2 of 401 athletes \( (0.5\%) \) with marked repolarization changes or echocardiographic features of possible cardiomyopathy. Both athletes had HCM and exhibited lateral T-wave inversion, and a wall thickness \( \geq 13 \text{ mm} \) (Figure 6).

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Discussion

This study compared the performance of current ESC and Seattle criteria for ECG interpretation in athletes compared with proposed refined criteria in a large cohort of elite BAs and WAs. All 3 criteria were also applied to a young group of asymptomatic athletes with HCM to assess their ability to detect a condition that accounts for a significant proportion of SCD in young athletes and often forms part of the differential diagnosis in athletic individuals with ECG anomalies or mild LVH on echocardiography.

ESC Recommendations and Seattle Criteria Versus Refined Criteria

The results indicate that although current ESC recommendations perform well in detecting HCM and excluding potentially sinister structural disease, they are associated with unacceptably high false-positive rates, particularly in BAs. On the basis of current ESC recommendations, almost 1 in 2 BAs and almost 1 in 5 WAs exhibit ECG patterns warranting further evaluation (Figure 2). These findings are highly problematic,

Table 5. Sensitivity and Specificity of the Screening Process Using Different ECG Criteria to Detect Both Major and Minor Cardiac Abnormalities (95% Confidence Interval)

<table>
<thead>
<tr>
<th></th>
<th>Black Athletes ((n=805))</th>
<th>White Athletes ((n=2282))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>European Society of Cardiology</td>
<td>Seattle Criteria</td>
</tr>
<tr>
<td>Sensitivity, %</td>
<td>70.0 ( (34.8–93.3) )</td>
<td>70.0 ( (34.8–93.3) )</td>
</tr>
<tr>
<td>Specificity, %</td>
<td>40.3 ( (36.8–43.8) )</td>
<td>79.3 ( (76.3–82.0) )</td>
</tr>
<tr>
<td>Positive predictive value, %</td>
<td>1.5 ( (0.6–3.0) )</td>
<td>4.1 ( (1.7–8.2) )</td>
</tr>
<tr>
<td>Negative predictive value, %</td>
<td>99.1 ( (97.3–99.8) )</td>
<td>99.5 ( (98.7–99.9) )</td>
</tr>
<tr>
<td>False-positive rate, %</td>
<td>59.7</td>
<td>20.7</td>
</tr>
<tr>
<td>False-negative rate, %</td>
<td>30.0</td>
<td>30.0</td>
</tr>
</tbody>
</table>

Table 6. Sensitivity and Specificity of the Screening Process Using Different ECG Criteria to Detect Major Cardiac Abnormalities Only (95% Confidence Interval)

<table>
<thead>
<tr>
<th></th>
<th>Black Athletes ((n=805))</th>
<th>White Athletes ((n=2282))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>European Society of Cardiology</td>
<td>Seattle Criteria</td>
</tr>
<tr>
<td>Sensitivity, %</td>
<td>100 ( (39.8–100) )</td>
<td>100 ( (39.8–100) )</td>
</tr>
<tr>
<td>Specificity, %</td>
<td>40.1 ( (36.7–43.6) )</td>
<td>79.3 ( (76.3–82.0) )</td>
</tr>
<tr>
<td>Positive predictive value, %</td>
<td>0.8 ( (0.2–2.1) )</td>
<td>2.4 ( (0.6–5.9) )</td>
</tr>
<tr>
<td>Negative predictive value, %</td>
<td>99.2 ( (98.9–100) )</td>
<td>99.4 ( (99.0–100) )</td>
</tr>
<tr>
<td>False-positive rate, %</td>
<td>59.9</td>
<td>20.7</td>
</tr>
<tr>
<td>False-negative rate, %</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
particularly in countries accommodating large populations of BAIs, including the United Kingdom and the United States.

In agreement with a recent analysis, the Seattle criteria perform well in identifying sinister disease and are associated with a significant improvement in specificity in WAs. However, despite accounting for anterior T-wave inversion (V1–V4) as a normal ethnic variant, almost one fifth of BAs continue to exhibit abnormal ECG patterns (Figure 2) after application of the Seattle criteria, primarily as a result of the presence of isolated voltage criteria for atrial enlargement and left axis deviation. Such ECG patterns also appear highly relevant in WAs and account for a high proportion of abnormal ECGs (Figures 2 and 3). We have recently demonstrated that the presence of any one of these ECG patterns, either in isolation or in combination with recognized training-related ECG patterns, correlates poorly with underlying cardiac disorders in asymptomatic elite athletes. By excluding these ECG patterns from the abnormal category, the refined criteria result in a significant improvement in specificity in athletes of both ethnicities while maintaining sensitivity (Tables 5 and 6).

The refined criteria have the most impressive impact on the BA population, in whom the false-positive ECG rate is decreased by >70% compared with current ESC recommendations. Indeed, application of the refined criteria results in a lower positive ECG rate in BAs (11.5%) than is presently observed in WAs (16.2%) with the ESC recommendations (Figure 2). Importantly, the refined criteria also have a significant impact on WAs, reducing the false-positive ECG rate to a far more acceptable level of 5.9%. In the current financial climate, the impact on resources and cost savings inherent in such refinement is difficult to ignore.

**Clinical Implications**

**Identification of Pathology**

The refined criteria identified all elite athletes with potentially sinister pathology and the majority of athletes (98.1%) with HCM. These observations are particularly important for BAs, who reveal a higher relative risk of exercise-related SCD resulting from HCM. Regardless of the criteria used, the ECG was poor at identifying minor congenital abnormalities and valvular heart disease, some of which may theoretically degenerate more rapidly in individuals exercising at high intensities. Inclusion of clinical examination, which is usual practice in both the American Heart Association and ESC screening protocols, improved the detection rate to >40%, highlighting the importance of this aspect of preparticipation cardiovascular evaluation.

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**Figure 6.** Diagnostic algorithm for further investigations after initial screening that led to an ultimate cardiac diagnosis in our athlete cohort. The total numbers of athletes cleared are shown on the right (green box), and the total numbers of athletes diagnosed with a cardiac condition are shown at the bottom (purple box). Sixty-five athletes requiring second-tier investigations failed to attend (orange box).
Future Directions
Despite the ongoing debate between the American Heart Association and ESC concerning routine use of 12-lead ECGs, the vast majority of professional sporting organizations in the United States and Europe incorporate an ECG in their screening protocols. Therefore a significant number of athletes, including BAs who make up almost 70% of individuals participating in certain sports in the United States, continue to be evaluated with ECG before clearance to compete. The high false-positive rates observed in BAs with current ECG screening criteria support concerns raised by the American Heart Association. With this consideration in mind, the best alternative is to strive toward an improvement in screening specificity through a better understanding of benign versus abnormal ECG patterns, coupled with appropriate training and education of physicians in the correct interpretation of an athlete’s ECG.

The ESC recommendations are unfavorable to BAs. The recently published Seattle criteria perform better by incorporating a growing body of scientific evidence relating to electric remodeling in athletes of Afro-Caribbean ethnicity. Further refinement of current ECG criteria as demonstrated above improves the unfavorable situation in BAs without compromising the detection of HCM. We have previously reported that T-wave inversion confined to V1 through V4 in BAs is a normal variant. This study revealed that T-wave inversion confined to the inferior leads failed to predict cardiomyopathy in BAs (Figure 7). Therefore, it is possible that exclusion of this particular repolarization pattern in BAs in the future may reduce the false-positive rate to <10%.

Study Limitations
In this study, echocardiographic data were not available in all individuals; therefore, we may have underestimated the prevalence of some minor abnormalities. However, a large number of athletes (3210) underwent both ECG and echocardiography, which enabled robust conclusions on the role of ECG in identifying diseases implicated in exercise-related SCD. Given that many athletes with a normal ECG received only 1 echocardiogram, we cannot comment accurately on the false-negative results because some individuals may develop HCM at a later date. Although 98% of our athletes with HCM exhibited an abnormal ECG, we recognize the heterogeneity of HCM and that a small proportion may reveal normal ECGs or one of the aforementioned isolated ECG patterns that we would now consider as normal variants. Finally, the study was conducted in elite athletes; therefore, the applicability and comparisons of the refined criteria with the ESC recommendations and the Seattle criteria in nonelite athletes should be an area for further study.

Conclusions
Application of the proposed refined criteria significantly reduces the number of false-positive ECGs in both elite BAs
and WAs without compromising sensitivity. Coupled with appropriate training of physicians in ECG interpretation, such refinement of ECG screening criteria would minimize the risk of an erroneous diagnosis in BAs and lead to substantial savings from unnecessary investigations in both cohorts. The results from this preliminary study require further evaluation and confirmation by other centers. It is our aspiration that the data will provide an important evidence base for revising existing guidelines in the future.

Acknowledgments

We thank Cardiac Risk in the Young for providing the portable echocardiography equipment and ECG machines used for the study in the United Kingdom.

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Disclosures

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CLINICAL PERSPECTIVE

Despite efforts to improve the specificity of ECG screening criteria in athletes, the issue of high false-positive rates is concerning. Athletes of African/Afro-Caribbean origin (black athletes; BAs) exhibit more profound electric changes compared with white athletes (WAs) and may be more susceptible to false-positive results and erroneous disqualification. The established 2010 European Society of Cardiology recommendations for ECG interpretation in athletes are derived exclusively from WAs and have not been tested in BAs. This study reports the performance of current ECG interpretation criteria in elite BAs and WAs compared with proposed “refined criteria,” which incorporate new research findings on benign ECG patterns in athletes and the effect of black ethnicity. The European Society of Cardiology recommendations, the more recent Seattle criteria, and the refined criteria were tested in 1208 BAs and 4297 WAs. All 3 criteria were applied to 103 young, asymptomatic athletes with hypertrophic cardiomyopathy. The European Society of Cardiology recommendations resulted in 40.4% BAs and 16.2% WAs exhibiting a positive ECG that would require investigation. The Seattle criteria reduced the number of positive ECGs to 18.4% in BAs and 7.1% in WAs. The refined criteria produced the greatest reduction, to 11.5% in BAs and 5.3% in WAs. All 3 criteria maintained 98% sensitivity to detect hypertrophic cardiomyopathy. Incorporation of the refined criteria into future ECG interpretation guidelines in athletes will reduce the burden of false-positive results in both WAs and BAs. The 71% reduction in positive ECGs in BAs compared with European Society of Cardiology recommendations has huge implications in countries accommodating a large population of BAs.
Comparison of Electrocardiographic Criteria for the Detection of Cardiac Abnormalities in Elite Black and White Athletes
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