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Diagnostic yield of borderline ECG changes and ectopic beats in football players

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ABSTRACT

Objective To evaluate the diagnostic yield and clinical implications of so-called 'borderline' ECG findings and ectopic beats in elite football players, in accordance with the 2017 International Criteria (IC17) for ECG interpretation in athletes.

Methods A total of 17 685 professional footballers (84.7% males) underwent cardiac screening including a 12-lead ECG and echocardiography between 2017 and 2024. Borderline ECG changes were classified according to the IC17. Supraventricular and ventricular ectopic beats were also analysed. Prevalence of cardiac pathology (major and minor) among athletes with borderline changes was compared with those athletes with normal ECGs.

Results Borderline ECG findings were present in 1389 (7.9%) athletes (8.8% males, 2.6% females; $p < 0.001$), with right atrial enlargement being the most frequently observed pattern (5.5%). Major cardiac pathology was incidentally identified in 2 (1.43%) athletes with isolated left atrial enlargement, compared with 9 (0.06%) athletes with normal ECGs ($p = 0.004$), including 1 case of an anomalous coronary origin and another case with significant aortic root dilatation—both unrelated to the ECG findings. All other borderline patterns as well as ectopy did not reveal any major pathology. No major conditions were identified in 42 athletes with isolated ≥ 2 borderline ECG findings. Minor cardiac pathology was identified in 18 (1.41%) athletes with isolated borderline findings and in 3 (2.07%) athletes with isolated ectopy. When ≥ 2 borderline findings were present, 2.38% athletes revealed minor pathology ($p = 0.463$). Minor cardiac pathology was found in 212 (1.34%) of athletes with normal ECGs ($p = 0.836$).

Conclusion Borderline ECG criteria in the IC17 and ventricular ectopy are poor discriminators for major and minor cardiac pathology in athletes. Borderline changes including ≥ 2 findings do not warrant further evaluation and could be considered normal findings in future iterations of ECG interpretation criteria in athletes.

INTRODUCTION

Preparticipation cardiac screening is increasingly implemented for competitive athletes. The 12-lead ECG has been shown to be the most effective cardiac screening method to diagnose major cardiac conditions associated with sudden cardiac death (SCD).¹ ECG interpretation in athletes has historically recommended using various criteria

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ The 2017 International Criteria classify left and right atrial enlargement, axis deviation and complete right bundle branch block as borderline ECG findings, with further evaluation recommended when two or more are present. However, the diagnostic yield of these borderline findings, and of isolated ectopic beats, for detecting clinically relevant cardiac disease in athletes has remained uncertain.

WHAT THIS STUDY ADDS

⇒ In 17 685 elite football players, isolated borderline ECG findings and ectopy showed very poor diagnostic performance for major cardiac pathology, and athletes with two or more borderline findings did not have a higher prevalence of cardiac disease than athletes with normal ECGs. Minor pathology was also uncommon and occurred at a similar frequency in athletes with isolated borderline findings and those with normal ECGs.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ These data support reconsideration of borderline ECG findings as triggers for further investigation in asymptomatic athletes. Future ECG interpretation criteria may be able to classify these patterns as normal variants, reducing unnecessary investigations without materially compromising disease detection.

including European Society of Cardiology (ESC) recommendations, the Seattle criteria and the 'refined' criteria.^{2–5} Despite these advancements in ECG interpretation reducing false positive results,⁶ ambiguity still persists when interpreting so-called 'borderline' ECG changes such as voltage criteria for left atrial enlargement (LAE) and right atrial enlargement (RAE), left axis deviation (LAD), right axis deviation (RAD) and right bundle branch block (RBBB). The 2017 International Criteria (IC17) for ECG interpretation in athletes recommended further investigations in athletes manifesting two or more borderline ECG changes.⁷

Ventricular ectopic beats (VEs) and supraventricular ectopic beats (SVEs) have also garnered attention, particularly in conditions such as



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cardiomyopathy and myocarditis. While 'abnormal' ECG findings have clear pathways for further evaluation, the diagnostic yield of borderline findings and their significance remains under-explored. Given the current limitations, a deeper understanding of the diagnostic value of these borderline ECG findings is necessary. Addressing this knowledge gap is crucial for guiding further management of an athlete, be it by reducing unnecessary investigations and anxiety, or conversely, triggering further evaluation appropriately.

The aim of this study was to analyse the association of borderline ECG criteria and ectopy in athletes, with cardiovascular pathology that may predispose to SCD.

METHODS

Participants

This study was an observational cohort study of 17 685 consecutive elite football players who underwent mandatory preparticipation screening (PPS) as part of the England Football Association (FA) programme between 1 January 2017 and 30 August 2024. This encompassed all football players across professional football clubs and their academies in England. All players trained competitively (minimum of 12 hours/week). Written consent for screening was obtained for all players by the team doctor, with consent being sought from a parent or guardian for athletes younger than 16 years of age, in accordance with principles of the FA data governance.

All athletes underwent a screening health questionnaire, 12-lead ECG and echocardiography. ECGs were interpreted at the time of screening by expert sports cardiologists within the FA screening programme. Echocardiograms were performed by accredited cardiac physiologists and subsequently reviewed by an expert cardiologist. For the purposes of this study, all ECGs and cardiac investigations were re-evaluated independently by the first author (KY) in 2024 with retrospective application of the IC17. The first author was blinded to screening outcomes and any diagnoses subsequently established after PPS. Any discrepant or equivocal ECG findings were discussed with the principal investigator (AM), who made the final adjudication. Borderline ECG changes according to the IC17 included LAE, RAE, LAD, RAD and RBBB.⁷ LAE was defined as an increased P-wave duration (>120 ms) in lead I or II with negative portion of P-wave ≥ 1 mm in depth and ≥ 40 ms in duration in lead V₁.⁷ RAE was defined as peaked P-wave with ≥ 2.5 mm in leads II, III or aVF. LAD and RAD were defined as QRS axis of $\leq -30^\circ$ and $>120^\circ$, respectively. RBBB was defined as rSR' pattern in lead V₁ with QRS duration of ≥ 120 ms.

An abnormal ECG was defined by the IC17.⁶ T-wave inversion (TWI) accounted for age and ethnicity: anterior TWI confined to V1–V3 in non-Afro-Caribbean athletes <16 years and V1–V4 in Afro-Caribbean athletes was considered physiological; inferior and lateral TWI were considered abnormal. Ventricular pre-excitation was diagnosed in the presence of delta wave and PR interval <120 ms. Corrected QT (QTc) interval abnormalities were defined as ≥ 470 ms for males and ≥ 480 ms for females. Pathological Q-wave was defined as Q/R ratio of ≥ 0.25 , or Q-wave duration of ≥ 40 ms in two or more contiguous leads. ST depression was defined as 0.5 mm or more depression in two or more contiguous leads.

A normal ECG was defined as the absence of borderline or abnormal ECG findings according to the IC17 and the absence of SVEs or VEs on the resting 12-lead ECG.

Isolated borderline ECG changes were defined as borderline findings occurring in the absence of additional borderline or

abnormal ECG changes, in accordance with the IC17. Similarly, VEs and SVEs were considered isolated when no concomitant abnormal ECG changes were present. The QRS duration of an ectopic beat was analysed using the DFR Callipers.⁸ The ECG characteristics of VEs were described according to morphology and frontal plane axis on the resting 12-lead ECG where assessable; cases without sufficient information for full classification were recorded as indeterminate.

Two-dimensional transthoracic echocardiography was performed by cardiac physiologists accredited by the British Society of Echocardiography using a standard protocol for athletes.^{9–10} Standard views were obtained, and wall thickness, cavity dimension measurements and identification of the origins of the left and right coronary arteries were made in accordance with established guidelines.^{10–12}

The result of the cardiac evaluation for each football player was categorised into: (1) 'normal'—no findings requiring action; (2) 'indeterminate'—findings that require further evaluation to distinguish physiological changes from potential pathology; and (3) 'abnormal'—findings consistent with cardiac pathology. Indeterminate findings could then be reclassified as normal or abnormal following further evaluation. With abnormal findings, the decision to deem a football player fit to train and play was made on a case-by-case basis with a shared decision-making approach and in line with contemporary recommendations.^{13–15} Further investigations were performed at regional specialist centres, once an abnormality was detected; this included athletes with potential cardiovascular symptoms reported on their health questionnaires, an abnormal ECG or with structural abnormalities detected on echocardiogram including abnormally enlarged cardiac dimensions and/or low ejection fraction or other uncommon echocardiographic features.^{16–17}

Further investigations included: prolonged ECG monitoring, exercise stress testing, cardiovascular magnetic resonance (CMR) imaging and cardiac CT (CCT), depending on the clinical indication in line with national and ESC guidelines.^{18–19} Athletes with a prolonged QTc interval were subjected to an exercise test and carefully investigated for the presence of symptoms and family history. Athletes with an accessory pathway and short PR interval were evaluated for features of Wolff-Parkinson-White (WPW) pattern and referred for an exercise test and/or electrophysiological studies if clinically indicated. Athletes with isolated borderline ECG findings, a single VE or SVEs were not routinely referred for further investigation on the basis of these findings alone. In contrast, athletes with ≥ 2 VEs were routinely referred for additional evaluation, in keeping with the screening pathway. Beyond this, further investigations were also undertaken when clinically indicated by the overall assessment, including concerning cardiovascular symptoms, relevant family history, associated abnormal ECG findings, ectopic morphology judged to be concerning or structural abnormalities detected on echocardiography. Once a cardiac disorder was detected, it was further classified as either a major condition associated with SCD or a minor condition. Major cardiac conditions included any form of cardiomyopathy, myocarditis, intramyocardial mass, an anomalous origin of a coronary artery, WPW pattern, long QT syndrome, Brugada syndrome, any ventricular arrhythmia, channelopathy, severe degree of valvular pathology, or significant aortopathy.

Minor conditions included congenital heart disease such as atrial septal defect (ASD), small ventricular septal defect, patent ductus arteriosus (PDA), valvular heart disease such as bicuspid aortic valve (BAV), valvular pathology or an aortopathy with mild or moderate severity and supraventricular arrhythmia.

Diagnosis of major pathology

Major cardiac pathology was classified according to recognised causes of sudden cardiac arrest/SCD (SCA/D) in young athletes, including structural, congenital and primary electrical disorders, as previously described.^{20,21} For the purposes of this study, specific diagnostic definitions were prespecified for selected major conditions most relevant to the present screening pathway and cohort, while other diagnoses were adjudicated according to established imaging, clinical and guideline-based criteria.²² Hypertrophic cardiomyopathy was defined by a left ventricular (LV) wall thickness of ≥ 15 mm in one or more myocardial segments, which is not solely explained by loading conditions (z-score >2 in adolescents).²³ A diagnosis of dilated cardiomyopathy (DCM) was considered if the athlete had a dilated LV (LV end-diastolic dimension of >56 mm in males and >51 mm in females) and a reduced EF ($<54\%$); further evaluation was considered for those with a positive family history.²⁴ Arrhythmogenic cardiomyopathy was based on published criteria.²⁵ Long-QT syndrome was based on a QTc interval ≥ 480 ms in association with low amplitude, notched or biphasic T-waves in at least three leads, paradoxical prolongation of the QTc interval with exercise and/or a positive genetic test.²⁶ A diagnosis of WPW was made if there was a short PR interval (≤ 120 ms) and a prolonged QRS duration (>120 ms), in the presence of a delta wave (slurred QRS upstroke/downstroke).¹⁶ A diagnosis of Brugada syndrome was made if there was characteristic ST elevation in leads V_1 – V_3 .²⁷

Comparison of athletes with borderline changes and athletes with a normal ECG

Athletes with a normal ECG served as the reference group for comparative analyses. The diagnostic performance analyses were restricted to athletes without abnormal ECG findings according to the IC17, namely those with a normal ECG, isolated borderline ECG findings, isolated ectopy and isolated ≥ 2 borderline ECG findings. Echocardiography measurements in athletes with borderline ECG changes were compared with measurements in athletes manifesting a normal ECG. The prevalence of major and minor cardiac conditions in athletes with isolated borderline ECG changes and isolated ectopy was also compared with that in the normal ECG group.

Statistical analysis

Statistical analysis was performed using Microsoft Excel V.2048 and IBM SPSS Statistics V.31.0.1.0 (IBM, Armonk, New York, USA). Normal distribution of all continuous variables was examined using the Shapiro-Wilk test. Values are expressed as either mean $\pm$ SD or percentages, as appropriate. Differences in prevalence between two independent populations were analysed using the χ^2 test of independence or Fisher's exact test as appropriate, and continuous variables were analysed using the two-sample t-test. Echocardiographic parameters were compared between independent groups using a two-sample comparison of means, with results presented as mean differences and 95% CIs. Diagnostic performance of isolated borderline ECG findings and ectopy for identifying major and minor cardiac pathology was assessed by calculating sensitivity, specificity and positive predictive value. Statistical significance was defined as a two-tailed p value of <0.05 throughout.

Patient and public involvement

Patients or the public were not involved in the design, conduct, reporting, or dissemination plans of our research.

Equity, diversity and inclusion

The author group consists of 4 women and 16 men, and consists of junior, mid-career and senior researchers. Authors represent diverse ethnic backgrounds. Our study population included all elite football players who underwent mandatory cardiovascular screening during the study period and comprised both male and female athletes from a range of socioeconomic backgrounds. However, socioeconomic backgrounds in terms of cardiovascular impact were not assessed.

RESULTS

Demographics

The total cohort included 17 685 athletes including 14 982 (84.7%) males and 2703 (15.3%) females. The mean age of the total cohort was 17.5 ± 4.4 years; 17.1 ± 3.9 versus 20.1 ± 5.5 years ($p < 0.001$) for males and females, respectively. The majority were of white ethnicity ($n = 12\,288$, 69.5%), followed by Afro-Caribbean origin ($n = 3058$, 17.3%), mixed-race ($n = 1963$, 11.1%) and Asian ethnicity ($n = 193$, 1.1%). The mean body surface area (BSA) was 1.87 ± 0.18 m² for male athletes and 1.72 ± 0.12 m² for female athletes ($p < 0.001$). According to the IC17, 15 768 (89.2%) athletes had a normal ECG, 1389 (7.9%) had borderline ECG findings and 528 (3.0%) had abnormal ECG findings.

Prevalence of borderline ECG changes

The prevalence of borderline ECG changes according to the IC17, SVEs and VEs are displayed in table 1 according to sex. Overall, borderline ECG changes were observed in 1319 (8.8%) male athletes and 70 (2.6%) female athletes ($p < 0.001$). Of these, 1273 athletes (7.2% of the total cohort; 91.6% of all borderline findings) had isolated single borderline ECG changes without additional borderline or abnormal ECG findings including 1204 males and 69 females. RAE was the most frequently observed borderline change overall ($n = 975$, 5.5%) and in isolation ($n = 882$, 5.0%). Isolated LAE was present in 140 (0.8%) athletes, isolated RAD in 96 (0.5%), isolated LAD in 136 (0.8%) and isolated RBBB in 19 (0.1%). Male athletes demonstrated higher prevalence of RAE than female athletes (928 (6.19%) vs 47 (1.74%); $p < 0.001$); LAE (158 (1.05%) vs 8 (0.30%); $p < 0.001$), RAD (100 (0.67%) vs 7 (0.26%); $p = 0.017$) and LAD (152 (1.01%) vs 8 (0.30%); $p < 0.001$). Among athletes with isolated borderline ECG findings, 67 (5.3%) athletes underwent additional investigations.

Table 1 Prevalence of borderline ECG changes, single ventricular ectopic, ≥ 2 ventricular ectopic and supraventricular ectopic

ECG finding	Total cohort (n=17 685)	Male (n=14 982)	Female (n=2703)	P value
Right bundle branch block*	27 (0.15%)	26 (0.17%)	1 (0.04%)	0.18
Right atrial enlargement *	975 (5.51%)	928 (6.19%)	47 (1.74%)	<0.001
Left atrial enlargement *	166 (0.94%)	158 (1.05%)	8 (0.30%)	<0.001
Right axis deviation*	107 (0.61%)	100 (0.67%)	7 (0.26%)	0.017
Left axis deviation*	160 (0.90%)	152 (1.01%)	8 (0.30%)	<0.001
Single ventricular ectopic	24 (0.14%)	22 (0.15%)	2 (0.07%)	0.39
Supraventricular ectopic(s)	79 (0.45%)	70 (0.47%)	9 (0.33%)	0.42
≥ 2 ventricular ectopic	45 (0.25%)	41 (0.27%)	4 (0.15%)	0.301
*Two or more borderline ECG findings were noted in 45 athletes (44 males and 1 female).				

Two or more borderline ECG changes were seen in 45 (0.25%) athletes comprising 44 (0.29%) male athletes and 1 (0.04%) female athlete, of whom 42 (0.24%) had isolated ≥ 2 borderline findings after exclusion of those with concomitant abnormal ECG findings. Among athletes demonstrating ≥ 2 borderline ECG changes, 3 (6.7%) male athletes manifested concomitant abnormal TWI. Excluding those with abnormal TWI, 4 (9.5%) male athletes manifesting ≥ 2 borderline ECG changes were referred for further investigations due to concerning cardiac symptoms, reduced right ventricular (RV) function and concerning RV morphology on echocardiography.

Association of borderline ECG changes with additional ECG changes

Figure 1 summarises the proportions of borderline ECG changes associated with additional borderline and abnormal ECG findings. RBBB was most frequently associated with other borderline or abnormal ECG findings, followed by LAD, RAE and RAD.

RBBB showed the highest degree of overlap with RAE in 3 (11.1%) athletes and abnormal TWI in 3 (11.1%) athletes. LAE overlapped with RAE in 19 (11.4%) athletes and LAD in 3 (1.8%) athletes, while LAD was infrequently associated with RAE in 12 (7.5%) and abnormal TWI in 8 (5.0%) athletes. Associations involving delta waves, Q-waves or ST-depression were less common across all findings. Furthermore, among athletes with RBBB, 6 (22.2%) had a QRS duration ≥ 140 ms. Of these, 1 (16.7%) showed concomitant abnormal anterior TWI, while 2

(33.3%) had additional borderline ECG changes (one with LAE and RAD, the other with RAE).

Prevalence of ectopy

Single VE, ≥ 2 VEs and SVEs were identified in 24 (0.14%), 45 (0.25%) and 79 (0.45%) athletes, respectively. Overall, ectopy was present in 148 (0.84%) athletes, of whom 145 (0.82%) had isolated ectopy without concomitant abnormal ECG findings. Isolated single VE was present in 23 (0.13%) athletes, isolated ≥ 2 VEs in 44 (0.25%) and isolated SVEs in 78 (0.44%). In contrast with the borderline ECG changes, there were no differences in the prevalence of single VE, SVEs or ≥ 2 VEs between the sexes (22 (0.15%) vs 2 (0.07%); $p=0.39$, 70 (0.47%) vs 9 (0.33%); $p=0.42$, and 41 (0.27%) vs 4 (0.15%), $p=0.301$, respectively). Characteristics of the VEs are based on the overall ectopy cohort and are shown in figure 2. The majority of single VEs demonstrated inferior axis. There was no difference in the prevalence of RBBB and left bundle branch block (LBBB) morphologies among athletes demonstrating a single VE (9 (37.5%) vs 7 (29.2%); $p=0.804$). Among athletes with a single VE, 16 (66.7%) athletes revealed a QRS duration ≥ 140 ms. Among athletes with ≥ 2 VEs, 44 (97.8%) demonstrated a monomorphic pattern and 1 (2.2%) demonstrated polymorphic VEs. The majority of athletes with ≥ 2 VEs (32 (71.1%)) had an inferior axis, while 10 (22.2%) showed a superior axis and 2 (4.4%) were indeterminate. LBBB morphology was more common than RBBB morphology in athletes with ≥ 2 VEs (24 (53.3%) vs 17

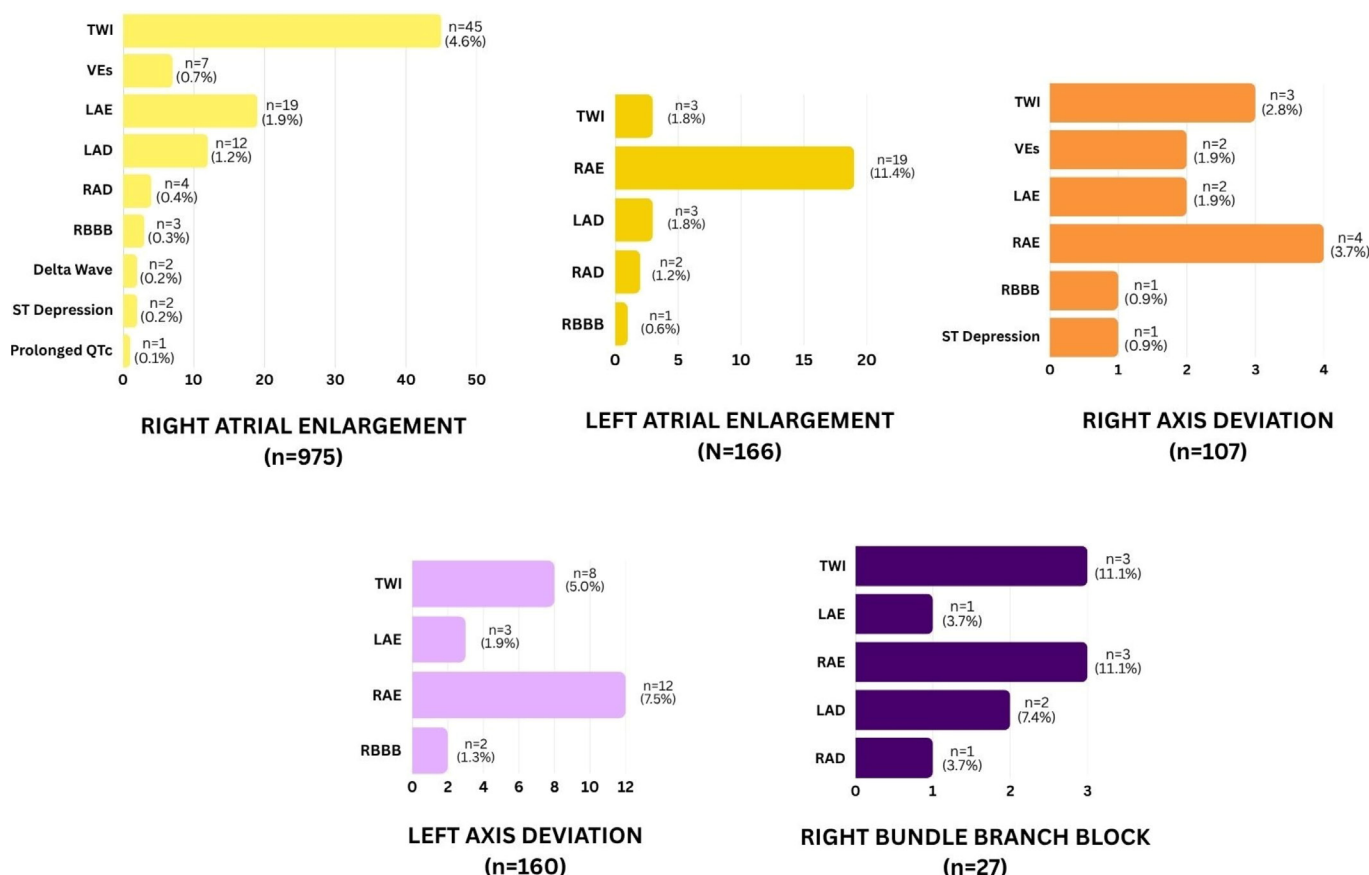


Figure 1 Proportions of borderline ECG changes associated with additional borderline and abnormal ECG changes. Footnote: Athletes with a given borderline ECG pattern could have more than one additional borderline or abnormal ECG finding and therefore contribute to more than one bar within the same panel. Percentages are expressed relative to the total number of athletes with each index borderline ECG finding. LAE, left atrial enlargement; LAD, left axis deviation; QTc, corrected QT interval; RAD, right axis deviation; RAE, right atrial enlargement; RBBB, right bundle branch block; TWI, T-wave inversion; VEs, ventricular ectopic beats.

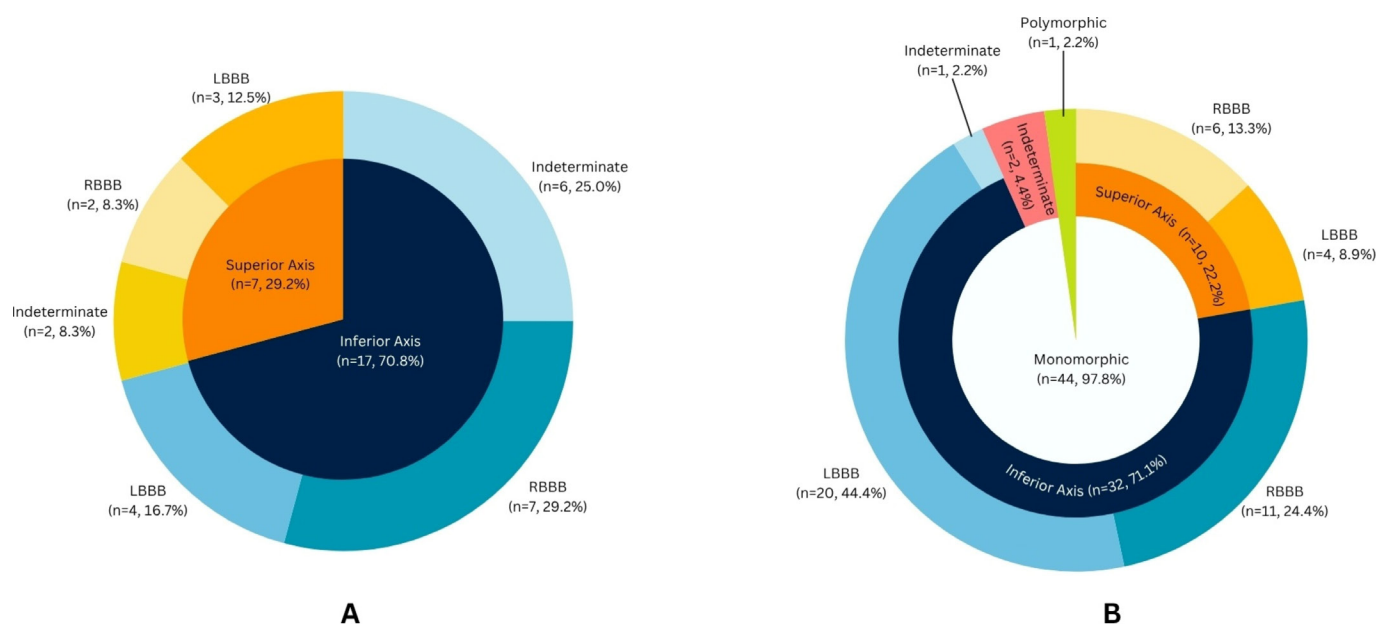


Figure 2 Characteristics (axis and morphology) of single ventricular ectopic beat (A) and ≥ 2 ventricular ectopic beats (B). LBBB, left bundle branch block; RBBB, right bundle branch block.

(37.8%); $p=0.35$), while morphology was indeterminate in one athlete (2.2%). Furthermore, 35 (77.8%) athletes with ≥ 2 VEs had a QRS duration ≥ 140 ms.

Among athletes with isolated single VEs, 6 (26.1%) underwent additional investigations beyond screening echocardiography. Among athletes with isolated SVEs, 6 (7.7%) underwent further evaluation. By contrast, athletes with isolated ≥ 2 VEs were routinely referred, and 44 (100%) athletes underwent additional investigations beyond baseline screening.

Echocardiographic characteristics of athletes with isolated borderline ECG changes

Figure 3 presents a comparison of echocardiographic parameters in male and female athletes with isolated borderline ECG changes versus those with the control group who demonstrated normal ECG findings. Athletes with LAE revealed a greater left atrial volume (47 ± 14 vs 43 ± 14 mL (95% CI 0.54 to 7.46)), increased maximal LV wall thickness (9.58 ± 1.50 vs 9.10 ± 1.36 mm (95% CI 0.18 to 0.78)), and higher LV mass (174 ± 42 vs 161 ± 41 g (95% CI 4.68 to 21.32)). In those with LAD, the absolute LV diameter was larger (51.3 ± 4.4 vs 50.2 ± 4.5 mm (95% CI 0.19 to 2.01)); however, this difference was not significant after indexing for BSA (27.4 ± 2.1 vs 27.0 ± 2.3 mm/m² (95% CI -0.05 to 0.85)).

RBBB was associated with a larger absolute RV size (39.9 ± 5.3 vs 37.5 ± 4.8 mm (95% CI 0.001 to 4.80)), but after indexing for body size, no significant difference in basal RV diameter was found compared with controls (20.7 ± 1.8 vs 20.2 ± 2.5 mm/m² (95% CI -0.33 to 1.33)). RAE on ECG did not correspond to increased right atrial size on echocardiography (16.2 ± 3.5 vs 16.4 ± 3.4 cm² (95% CI -0.59 to 0.19)).

Prevalence of major cardiac pathology in athletes with borderline ECG changes

The prevalence of major cardiac pathology among athletes with each of the isolated borderline ECG changes is shown in table 2. Two (0.16%) cases of cardiac conditions associated with SCD were identified among athletes with isolated borderline ECG

changes, including one case of an anomalous origin of the coronary artery and one case of severe dilatation of the aortic root requiring a personalised external aortic root support operation, both identified incidentally in athletes with isolated LAE. The prevalence of major cardiac disease was higher in athletes with isolated LAE than in those with normal ECGs (2 (1.43%) vs 9 (0.06%); $p=0.004$). No other isolated borderline ECG change was associated with major cardiac disease. No athlete with an isolated borderline ECG change showed features suggestive of cardiomyopathy in the absence of additional abnormal ECG findings, such as TWI.

Although females were less likely to manifest any of borderline ECG changes (2.6% females vs 8.8% males; $p<0.001$), the prevalence of major cardiac conditions among male and female athletes with isolated borderline changes was similar (2 (0.2%) vs 0 (0%); $p=1.0$).

Prevalence of minor cardiac pathology in athletes with borderline ECG changes

Minor cardiac pathology was identified in a total of 18 (1.41%) athletes among athletes with isolated borderline ECG changes, including 17 (1.41%) males and 1 (1.45%) female ($p=1.0$). The prevalence of minor cardiac pathology among athletes with each of the isolated borderline ECG changes ranged from 0% to 5% (table 3), including congenital abnormalities such as BAV, pulmonary valve stenosis, ASD and PDA, and other abnormalities which need surveillance such as dilated aortic root/ascending aorta and valvular abnormalities (more than mild valvular regurgitation). Athletes with any of the isolated borderline ECG changes manifested similar prevalence of minor cardiac conditions when compared against athletes with isolated ≥ 2 borderline ECG changes (18 (1.41%) vs 1 (2.38%); $p=0.463$) and athletes with normal ECGs (18 (1.41%) vs 212 (1.34%); $p=0.836$). No cardiac conditions were identified in athletes with RAD. None of the 3 (15.8%) athletes with an isolated RBBB and a QRS duration of ≥ 140 ms was diagnosed with a cardiac condition.

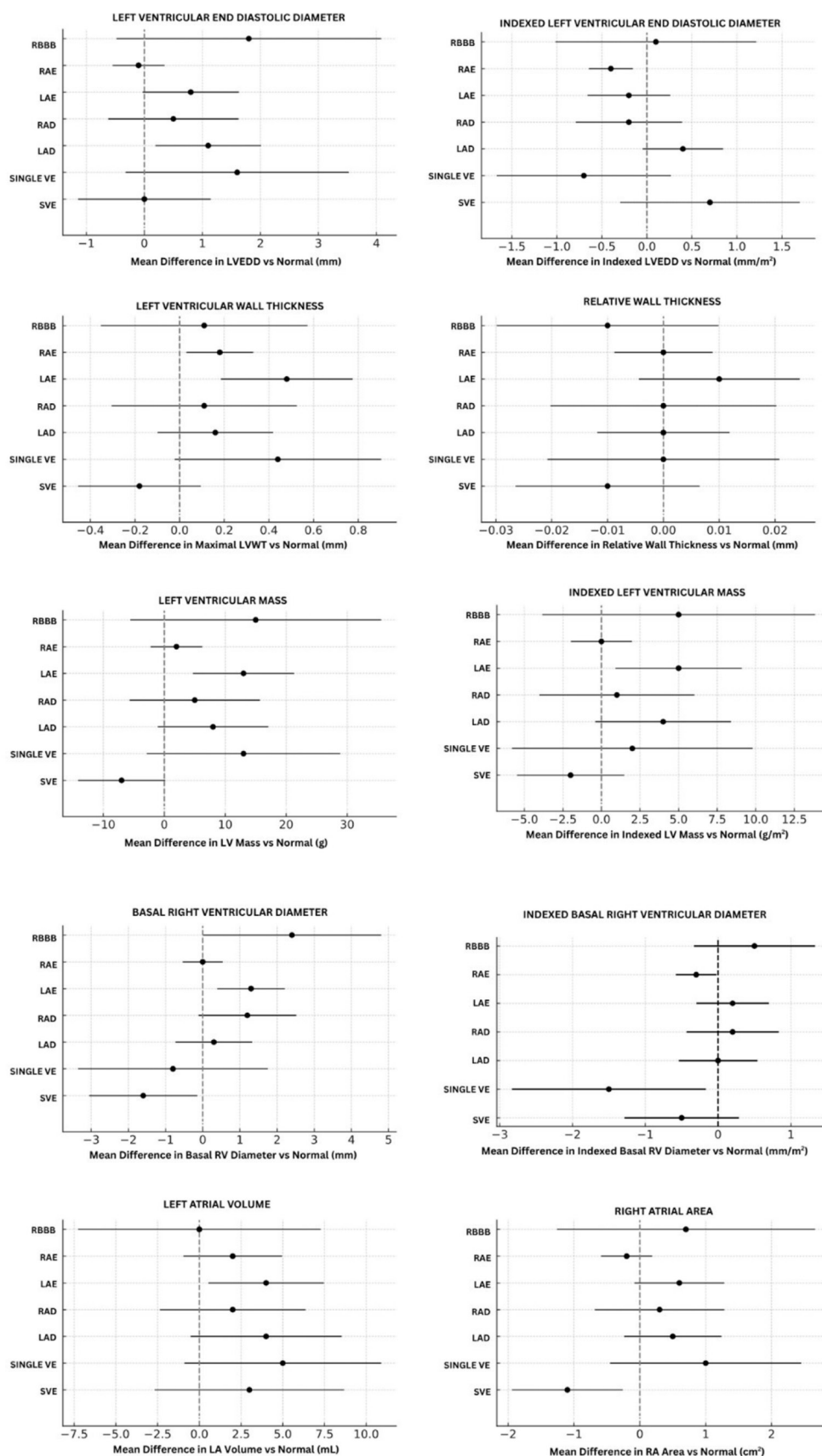


Figure 3 Echocardiographic characteristics of athletes with isolated borderline changes compared with athletes without borderline and/or abnormal ECG changes (male and female). LA, left atrial; LAE, LA enlargement; LAD, left axis deviation; LV, left ventricular; LVEDD, LV end diastolic diameter; LVWT, LV wall thickness; RA, right atrial; RAD, right axis deviation; RAE, RA enlargement; RBBB, right bundle branch block; RV, right ventricular; SVE, supraventricular ectopic beat; VE, ventricular ectopic beat.

Table 2 Prevalence of major cardiac conditions in athletes with isolated borderline ECG changes (+ single ventricular ectopic, ≥ 2 ventricular ectopic and supraventricular ectopic)

ECG finding	Proportion of ECG finding associated with major cardiac conditions (%)	P value vs ≥ 2 borderline changes	P value vs normal ECG with major cardiac pathology (0.06%, n=15 768)
Right bundle branch block (n=19)	0	1.0	1.0
Right atrial enlargement (n=882)	0	1.0	1.0
Left atrial enlargement (n=140)	1.43	1.0	0.004
Right axis deviation (n=96)	0	1.0	1.0
Left axis deviation (n=136)	0	1.0	1.0
Single ventricular ectopic (n=23)	0	1.0	1.0
Supraventricular ectopic(s) (n=78)	0	1.0	1.0
≥ 2 ventricular ectopic (n=44)	0	1.0	1.0
≥ 2 borderline changes (n=42)	0	Not applicable	1.0

Overall cardiac pathology in athletes with isolated and multiple borderline ECG findings

No individual borderline ECG finding, when present in isolation, was associated with a significantly different prevalence of major and minor cardiac pathology compared with athletes who had ≥ 2 borderline findings. Furthermore, comparing athletes with any isolated borderline ECG finding to those with

Table 3 Prevalence of minor cardiac conditions in athletes with isolated borderline ECG changes

ECG finding	Proportion of ECG finding associated with minor cardiac conditions (%)	P value vs ≥ 2 borderline changes	P value vs normal ECG with minor cardiac pathology (1.34%, n=15 768)
Right bundle branch block (n=19)	5.26	0.530	0.228
Right atrial enlargement (n=882)	1.13	0.402	0.704
Left atrial enlargement (n=140)	2.86	1.000	0.123
Right axis deviation (n=96)	0	0.304	0.642
Left axis deviation (n=136)	2.21	1.000	0.435
Single ventricular ectopic (n=23)	8.70	0.284	0.038
Supraventricular ectopic(s) (n=78)	0	0.350	0.629
≥ 2 ventricular ectopic (n=44)	2.27	1.000	0.452
≥ 2 borderline changes (n=42)	2.38	Not applicable	0.435

(+ single ventricular ectopic, ≥ 2 ventricular ectopic and supraventricular ectopic).

≥ 2 borderline findings showed no significant difference in the overall prevalence of major and minor cardiac pathology (20 (1.57%) vs 1 (2.38%); $p=0.50$). This remained the case even when comparing athletes with ≥ 2 borderline ECG changes to those without any borderline, abnormal findings and/or ectopy (1 (2.38%) vs 221 (1.40%); $p=0.448$).

Prevalence of cardiac pathology in athletes with ventricular ectopy and supraventricular ectopy

No major cardiac pathology was identified in athletes with ectopy. Athletes with an isolated single VE had a higher prevalence of minor cardiac pathology than those with any other individual isolated borderline ECG change, including athletes with ≥ 2 borderline findings. Two of 23 (8.70%) athletes with a single VE and an inferior axis, and 1 of 44 (2.27%) with ≥ 2 VEs revealed minor cardiac conditions (BAV and aortic root dilatation). All three had an ectopic QRS duration ≥ 140 ms. In the VE cohort (single or ≥ 2 beats), isolated VEs with QRS ≥ 140 ms were associated with cardiac conditions in 3 of 51 athletes (5.88%), all of which were minor, exceeding the prevalence among athletes with a normal ECG (5.88% vs 1.34%; $p=0.025$). In contrast, SVEs were not associated with an underlying cardiac condition.

Prevalence of cardiac pathology among athletes with a normal ECG

The total of 15 768 athletes including 13 162 males and 2606 females manifested a normal ECG without borderline or abnormal changes and resting ectopic beats at the time of cardiac screening. Major cardiac conditions were diagnosed in 9 (0.06%) athletes all of whom were males. These included: anomalous origin of coronary arteries (n=1), BAV with severe aortic regurgitation (n=1), BAV with aortopathy (n=1), BAV with both severe aortic regurgitation and aortopathy (n=1), DCM (n=1), intramyocardial mass (n=1) and epicardial myocardial scar detected on CMR (n=3). Among three athletes with myocardial scar on CMR, two underwent CMR due to symptoms and one due to a reduction of QRS complex voltage in inferolateral leads compared with the player's previous ECG without relevant family history of cardiac conditions or symptoms.

Minor cardiac conditions were diagnosed in 212 (1.34%) athletes. There was no difference between males and females with a normal ECG, in terms of prevalence of major and minor cardiac conditions (major: 9 males (0.07%) vs 0 females (0%); $p=0.289$; minor: 182 males (1.38%) vs 30 females (1.15%); $p=0.430$).

Diagnostic performance of isolated borderline ECG criteria and ectopy

Table 4 shows the diagnostic performance of the five isolated borderline ECG findings along with VEs and SVEs for identifying major cardiac pathology in the cohort without abnormal ECG findings. Across all isolated ECG findings and their combinations, sensitivity was 0%, except isolated LAE reaching 18.2% if one included the two incidental major structural pathologies. Specificity remained uniformly high in all cases ($>94\%$), but positive predictive values were low, not exceeding 1.4% for LAE. The presence of ≥ 2 borderline ECG changes demonstrated a sensitivity and positive predictive value of 0% for major cardiac pathology.

The diagnostic performance of isolated borderline ECG findings for diagnosing minor cardiac conditions was similarly very low (table 5). RAE demonstrated the highest sensitivity (4.3%)

Table 4 Diagnostic performance for cardiac conditions associated with SCD in isolated minor ECG changes in the cohort without abnormal (red box) ECG changes

ECG change (isolated)	Sensitivity (%)	Specificity (%)	Positive predictive value (%)
Right bundle branch block	0	99.9	0
Right atrial enlargement	0	94.9	0
Left atrial enlargement	18.2	99.2	1.4
Right axis deviation	0	99.4	0
Left axis deviation	0	99.2	0
Any of borderline ECG changes	18.2	92.6	0.2
≥2 borderline ECG changes	0	99.8	0
Single ventricular ectopic	0	99.9	0
Supraventricular ectopic	0	99.5	0

SCD, sudden cardiac death.

among the evaluated parameters, though its positive predictive value (1.1%) remained low. Single VE beats yielded the highest positive predictive value (8.7%) for minor cardiac conditions, although with a sensitivity of just 0.9%. Other findings such as RBBB and LAE showed high specificity (99.9% and 99.2%, respectively) but poor sensitivity (0.4% and 1.7%, respectively). The presence of ≥2 borderline ECG changes did not significantly enhance diagnostic performance for detecting minor cardiac pathology, with a sensitivity of 0.4% and a positive predictive value of 2.4% for minor cardiac pathology.

DISCUSSION

The present study evaluated the clinical significance of borderline ECG findings defined by the IC17, together with ectopic beats, in a large cohort of elite football players undergoing preparticipation cardiac screening. All the borderline criteria performed very poorly at identifying major cardiac pathology with only LAE having a sensitivity of 18.2%, while no other borderline ECG changes were associated with major cardiac conditions. In the two athletes with major cardiac pathology, LAE was most likely an incidental finding, as it is not typically associated with an anomalous coronary origin or significant aortic root dilatation. The presence of ≥2 borderline ECG changes did not correlate with a higher prevalence of cardiac disease compared with any isolated borderline ECG changes or in those with a

Table 5 Diagnostic performance for minor cardiac conditions in isolated minor ECG changes in the cohort without abnormal (red box) ECG changes

ECG change (isolated)	Sensitivity (%)	Specificity (%)	Positive predictive value (%)
Right bundle branch block	0.4	99.9	5.3
Right atrial enlargement	4.3	94.9	1.1
Left atrial enlargement	1.7	99.2	2.9
Right axis deviation	0	99.4	0
Left axis deviation	1.3	99.2	2.2
Any borderline ECG changes	7.7	92.6	1.4
≥2 borderline ECG changes	0.4	99.8	2.4
Single ventricular ectopic	0.9	99.9	8.7
Supraventricular ectopic	0	99.5	0

'Any of borderline ECG changes' represent those specified by the International criteria of ECG interpretation.

normal ECG. Similarly, SVEs and VEs were very poorly associated with cardiac pathology.

The overall prevalence of borderline ECG changes in our cohort is consistent with previously reported data.^{6,28} However, the rate of RAE was higher in the present study than in prior athletic cohorts. This difference may reflect the demographic profile which was more heterogeneous in terms of ethnicity and sex. The majority of VEs in our cohort demonstrated an inferior axis, suggesting that many were likely to be of outflow-tract origin, as previously described in athletes.²⁹ However, unlike another study of 10728 athletes of a similar age,³⁰ our study demonstrated that VEs with QRS duration of ≥140ms were more common.

Sex-specific differences were a prominent finding in our study. Male athletes exhibited a higher overall prevalence of borderline ECG changes for RAE, LAE, RAD and LAD. This contrasts with a previous study, which reported no sex-based differences in borderline ECG findings.⁶ The discrepancy may relate to the fourfold higher number of female athletes in our cohort. However, among athletes with any isolated borderline ECG changes, the prevalence of both major and minor cardiac conditions was similar between sexes. This finding argues against a sex-driven approach when borderline ECG changes are present.

Among the borderline ECG changes, only LAE was associated with a corresponding increase in left atrial size on echocardiography. In contrast, RAE, RAD and LAD were not associated with their respective structural abnormalities. In our study, RAD was not linked with increased RV size, which aligns with findings from Gati *et al.*²⁸ Conversely, LAD was previously reported to be associated with increased LV diameter.²⁸ However, the study did not consider indexed LV diameters with BSA. In our cohort, although absolute LV diameter was higher in the LAD group, indexed values were not increased, suggesting that increased absolute LV diameters in the LAD group reflect an increase in the body size of the group.

The current IC17 recommend further investigations only when ≥2 borderline ECG changes are present. Our findings challenge this approach. We observed no difference in the prevalence of cardiac pathology between athletes with 1 versus ≥2 borderline ECG findings. Although LAE was independently associated with a higher prevalence of cardiac pathology when compared with athletes with a normal ECG and cardiac pathology, the diagnostic performance of any borderline ECG criterion and ectopy to identify both major and minor cardiac pathology was extremely low. Particularly for major cardiac conditions, sensitivities of any isolated borderline ECG change were zero, except 18.2% for LAE which is likely falsely elevated from the identification of structural pathologies on echocardiography that are unrelated to the LAE finding on ECG. The diagnostic performance remained low even with ≥2 concomitant borderline ECG changes. Additionally, the prevalence of cardiac pathology in athletes with ≥2 borderline ECG changes did not differ from those without any borderline or abnormal ECG findings. These results suggest that borderline ECG changes can be regarded as normal findings when interpreting the ECG of athletes undergoing PPS.

RBBB has been reported not to be associated with cardiac pathology among athletes in multiple studies in the past.^{31–33} A recent study by MacLachlan *et al* demonstrated that 5% of young individuals with both isolated and non-isolated complete RBBB manifested cardiac pathology and one case of ASD was diagnosed among 43 young individuals with isolated RBBB and QRS duration ≥130ms.³⁴ Our study showed 0.15% prevalence of complete RBBB and 70.4% was isolated. Isolated RBBB with

a wide QRS duration was demonstrated only in three athletes and none of them was diagnosed with cardiac pathology.

Ventricular ectopy in athletes is usually benign in isolation,³⁰ but risk hinges on pattern rather than presence. Outflow tract or fascicular morphologies with exercise suppression and monomorphic beats generally indicate low risk, whereas uncommon morphologies such as a superior axis, a wider ectopic QRS complex or being exercise-induced warrant further investigations for concealed cardiomyopathy or myocardial scar. A previous study of 118 athletes reported structural cardiac abnormalities in four cases (3%) with uncommon VE morphologies during 6-year follow-up.³⁵ In our cohort, isolated VEs with an ectopic QRS duration ≥ 140 ms were associated with a higher prevalence of cardiac findings than a normal ECG, but all abnormalities identified were minor and consisted of bicuspid aortic valve or aortic root dilatation. Although these findings are not generally regarded as typical substrates for ventricular ectopy, bicuspid aortic valve has been associated with ventricular arrhythmias and outflow-tract premature ventricular beats in previous studies.^{36 37} Our data do not allow determination of whether the coexistence of bicuspid aortic valve and ventricular ectopy in this cohort reflects a causal association or an incidental finding. No athlete with VEs or SVEs demonstrated cardiomyopathy or other major arrhythmogenic structural disease, supporting the interpretation that ectopy detected in isolation on resting screening ECG is usually benign. SVEs, however, were not associated with any cardiac pathology, whether present in isolation or as more than one ectopic beat.

Limitations

There are limitations in this study. This was an observational cross-sectional study without longitudinal follow-up. This is, however, more reflective of the 'snapshot' nature of cardiac screening to detect pathology at the time of screening. Prospective controlled studies are warranted to further ratify the longer-term implications of harbouring a borderline ECG change. In addition, unequal representation of females and ethnicities in the sample may have introduced sex-related and ethnicity-related bias and limited the generalisability of findings. Nonetheless, the sample composition was more heterogeneous than ever, reflective of the real-world demographics within this popular sport and each subject underwent an ECG and an echocardiogram to ratify the significance of the ECG changes. Furthermore, although echocardiography was used as the universal first-line imaging modality in all athletes, it is not the definitive test for all conditions associated with SCA/D. In particular, anomalous coronary anatomy may require further characterisation with CCT or CMR, and myocardial scar is more reliably detected with CMR. Because these downstream investigations were performed only when clinically indicated rather than systematically across the entire cohort, some pathologies may have been underdetected, which may have influenced the reported diagnostic performance of borderline ECG findings and ectopy. Finally, as this was an elite football cohort undergoing mandatory screening within an established programme, the prevalence of major cardiac pathology may differ from that reported in less selected or previously unscreened populations, which may limit direct comparison of predictive values across screening studies.

CONCLUSION

This study supports that the borderline ECG findings from the IC17 are not predictive or related to cardiac pathology and therefore do not warrant further investigation in asymptomatic

athletes undergoing preparticipation evaluation in both males and females. Incorporating these findings into future iterations of ECG interpretation criteria in athletes will help reduce unnecessary further investigations and optimise resource utilisation.

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