Chapter 2
Using an Electrocardiogram as a Component of Athlete Screening

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Should Every Athlete Have an ECG Added to Their Pre-participation Screening Exam? Findings from Epidemiological Studies

The optimal pre-participation screening strategy to detect cardiac abnormalities that place athletes at risk for exercise-triggered sudden cardiac death (SCD) is unresolved. It has been customary in the USA and recommended by all major medical societies involved in the care of athletes that pre-participation screening of athletes should be performed and that this evaluation should include a history and physical exam (H&P) [1–4]. To assist with standardization and optimization of the H&P, the American Heart Association (AHA) has provided consensus recommendations for a 14-Element H&P to serve as a guideline for the performance of these exams [5]. While a careful H&P will uncover many previously undiagnosed cardiac disorders that can predispose to exercise-triggered SCD, the sensitivity and specificity of this exam are imperfect. To enhance screening, it has been advocated to incorporate a 12-lead electrocardiogram (ECG) universally into the pre-participation evaluation of athletes in order to improve the effectiveness of cardiac screening [2, 6, 7]. There remains significant discussion and debate, however, on this issue.

Controversies surrounding mass screening of asymptomatic athletes with ECGs relate to concerns regarding cost and resource allocation, the accuracy of the ECG to identify occult cardiovascular disease, and the consequences of false-positive ECGs. At the same time, there is a recognition that ECGs can increase the yield of screening to detect cardiac abnormalities that are associated with SCD in athletes [8, 9].

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A significant impetus for the promotion of universal ECG inclusion into athlete screening stems from data generated from the long-standing Italian national athlete screening program. In 1971 the Italian government instituted legislation requiring medical supervision of all competitive athletes, but in 1982, the law was significantly enhanced and formalized to require annual pre-participation medical screening that included an H&P plus ECG [10, 11]. In a study of SCD rates in the Veneto region of Italy between 1979 and 2004, the introduction of ECG-inclusive athlete screening resulted in an 89% reduction (3.6 deaths per 100,000 person-years to 0.4 deaths per 100,000 person-years) in the SCD rate of athletes, most of which was attributable to the detection of cardiomyopathies uncovered by screening, while no such trend during this time period was observed in unscreened age-matched nonathletes [12] (Fig. 2.1).

Other large-scale initiatives to universally incorporate ECGs into pre-participation evaluations, however, have not replicated the Italian findings. In 1997, Israel enacted the Israeli Sport Law which mandated pre-participation medical screening of competitive athletes including an annual H&P and ECG, plus a treadmill ECG stress test every 4 years (yearly stress tests for athletes ≥ 35 years of age) [13, 14]. In a study of athlete SCD rates in Israel between 1985 and 2009 (12 years before and 12 years after the initiation of this legislation), no measurable differences in athlete SCD rates were observed (2.66 events per 100,000 person-years prior to legislation vs 2.54 events per 100,000 person-years after legislation, $P = 0.88$) [14]. Additionally, in a study comparing athlete SCD rates over an 11-year period (1993–2004) in Veneto, where athlete screening included an ECG, and Minnesota, a
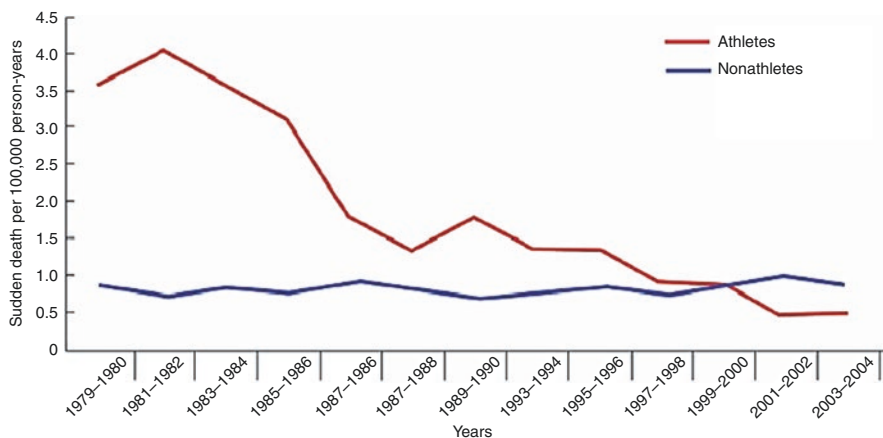

Fig. 2.1 Annual sudden cardiac death rates among screened competitive athletes and unscreened nonathletes in the Veneto region of Italy from 1979 to 2004. (Reprinted with permission from Corrodo et al. [10], Elsevier)

demographically similar area to Veneto and where athlete pre-participation screening was limited to H&P only, no differences in SCD rates were observed [15]. These studies that formed different conclusions from the Italian study regarding the utility of the ECG for SCD prevention have raised questions regarding the appropriateness of the universal incorporation of ECGs into screening.

Strengths and Pitfalls of the ECG in Athlete Screening

The determination of policies and practice regarding the optimal use of the ECG in athlete screening cannot be based solely on data generated from large-scale epidemiological studies. Analyses of the strengths and pitfalls of the ECG itself are also essential to assist with the formulation of a strategy. Assessments of the intrinsic characteristics of the ECG are integral components of the guideline recommendations and position statements regarding athlete screening currently put forth by leading medical organizations. Important strengths and pitfalls of the ECG as related to athlete screening are summarized in Table 2.1.

Table 2.1 Strengths and pitfalls of the ECG for athlete screening

Strengths of the ECG	Pitfalls of the ECG
The ECG is abnormal in a high proportion of athletes with cardiomyopathies	False-positive ECGs occur despite the use of athlete-specific ECG interpretation criteria
The ECG is the best initial screening tool to detect intrinsic conduction abnormalities that are associated with SCD in athletes including ventricular pre-excitation, ion channelopathies, and long QT syndrome	Several cardiovascular disorders associated with SCD in athletes will not be detected by an ECG including atherosclerotic coronary artery disease, anomalous coronary arteries, bicuspid aortic valves, and Marfan Syndrome
The ECG increases the sensitivity above H&P alone to detect cardiovascular disorders that can predispose to exercise-triggered SCD	Downstream testing required to evaluate a large number of athletes with ECGs classified as abnormal can adversely affect an athlete's participation status and place a significant strain on healthcare systems to provide streamlined and affordable testing
The ECG is non-expensive and fast	Technical factors including lead placement variability, inaccuracies in interval (esp. QT interval) measurements, and interobserver variability in ECG interpretation adversely affect the reliability of the test
There are low false-positive rates with the newest sets of athlete-specific ECG interpretation criteria	The incidence of SCD in athletes is low, and false-positive ECGs vastly outnumber true positives. Risk/benefit of an ECG for an asymptomatic athlete not entirely clear

Strengths of the ECG

The ECG is an effective diagnostic tool for the detection of underlying structural heart disease as an ECG will be abnormal in a high proportion of individuals with cardiomyopathies. Additionally, the cost of an ECG is low and the test requires only a few minutes to perform. Numerous studies have shown that ECG abnormalities are present in approximately 75–95% of individuals with hypertrophic cardiomyopathy (HCM), a prominent cause of exercise-triggered SCD [16–19]. ECG abnormalities are similarly seen in a high proportion of patients with arrhythmogenic right ventricular cardiomyopathy (ARVC) [20–22]. The value of an ECG for diagnosing arrhythmic disorders is even greater than that for detecting underlying structural heart disease. The ECG is the initial diagnostic modality of choice for identifying conduction abnormalities that are associated with SCD in athletes including ventricular pre-excitation and ion channelopathies such as long QT syndrome.

Owing to these intrinsic capabilities to detect important cardiac disorders associated with SCD in athletes, the ECG has been shown to increase the power and sensitivity of athlete screening when added to the H&P. The use of the ECG as part of the Italian national athlete screening program in the Veneto region over a 17-year period (1979–1996) was shown to significantly increase the yield for the detection of HCM over the H&P alone [8]. Similarly, within the USA, prospective studies of ECG-inclusive screening programs in high school [23, 24] and collegiate [9, 25, 26] athletes demonstrated that the ECG increased the detection and had increased sensitivity and specificity for identifying potentially lethal cardiac conditions than the H&P alone. A National Collegiate Athletic Association (NCAA) sponsored prospective study across 35 universities that included over 5000 athletes reported that the sensitivity for the ECG in detecting serious underlying cardiac disorders was 100% in comparison with 15.4% for the H&P [27]. These analyses and review of the strengths of the ECG to enhance screening are fundamental components of the arguments favoring the universal inclusion of an ECG in the pre-participation examination of athletes.

Pitfalls of the ECG

Notwithstanding these arguments favoring the standard inclusion of an ECG in athlete screening, several properties of the ECG, plus realities that healthcare providers and athletes encounter when ECGs are utilized in this capacity, need also be considered. False-positive ECGs continue to exist despite the formulation and use of expert consensus athlete-specific ECG interpretation criteria [28]. Even with the most current and specific athlete ECG criteria published to date (International Recommendations [29]), false-positive rates can reach as high as 6.8–15.6% when these ECG criteria are applied and studied prospectively in athlete groups [30–32]. In addition to false-positives, an ECG may not always demonstrate typical patterns

or alert to the presence of underlying structural heart disease. False-negative ECGs can be present in up to 10% of cases of HCM and up to 1/3 of cases of ARVC [33, 34]. With respect to HCM in particular, it is known that the phenotype and ECG expression of this disorder can develop during adolescence or early adulthood, a time period that coincides with the majority of competitive athlete careers, thus requiring repetitive screening to optimally employ ECGs in this setting [35, 36]. In addition to issues surrounding false-positives and false-negatives, ECGs will not detect several important cardiovascular disorders that are known to be associated with SCD in athletes including atherosclerotic coronary artery disease, anomalous coronary artery origins, bicuspid aortic valves, and Marfan syndrome.

Technical factors inherent in ECG acquisition also provide a basis to advise caution with respect to mass screening of athletes with ECGs. The appearance of the waveforms on the ECG tracing is highly dependent on limb and precordial lead placement, and variability in lead placements that inevitably occur in the widespread performance of ECGs leads to significant inconsistencies in the accuracy and interpretation of the test [37–39]. Similarly, variabilities and difficulties in obtaining accurate interval measurements, especially as they relate to precise QT interval measurement, are another important source of inconsistency that affect the reliability and interpretation of the ECG [40, 41]. These technical factors contribute to significant interobserver variability in the interpretation of ECG tracings and are principal elements impacting quality control that have important implications for athlete screening both on an individual and population bases [42, 43].

The classification of an athlete's screening ECG as abnormal will necessitate further evaluation and downstream testing to ensure athlete health and safety. These evaluations often have immediate and potentially long-term adverse effects on an individual athlete's participation status as well as significant impacts on health resource utilization. Typical next steps to evaluate athletes with abnormal ECGs include subspecialist consultations, echocardiograms, stress tests, extended rhythm monitoring, cardiac MRI (CMR), or potentially invasive cardiac testing. With many millions of athletes worldwide competing at high school, collegiate, adult amateur, and professional levels, even an exceptionally small percentage of asymptomatic athletes required to undergo further evaluation because of abnormal ECG classification would place a tremendous strain on healthcare systems to provide streamlined and affordable downstream testing. The debate and discussion remain, given low published estimated incidences of SCD in athletes ranging from 0.6 to 1.2 per 100K athlete-years [15, 44, 45] without universal ECG screening, on the ultimate risks and benefits of ECG use in screening.

Medical Society Guidelines and Position Statements

At the present time, there is no universal agreement among leading medical organizations on recommendations for the use of ECGs in athlete pre-participation screening examinations. Table 2.2 summarizes the current position statements of these medical organizations regarding the standard inclusion of ECGs into pre-participation

Table 2.2 Position statements of leading medical organizations regarding the standard inclusion of ECGs into pre-participation screening programs

Medical organization/society	Routine use of ECG in athlete pre-participation screening	Position statement source
American Heart Association/ American College of Cardiology (AHA/ACC)	Not recommended	Eligibility and disqualification recommendations for competitive athletes with cardiovascular abnormalities: task force 2: pre-participation screening for cardiovascular disease in competitive athletes – a scientific statement from the American Heart Association and American College of Cardiology Circulation 2015; 132: e267–e272
National Collegiate Athletic Association (NCAA)	No formal recommendation for or against universal incorporation of ECGs – guidelines for optimal processes provided for member institutions who choose to implement	Interassociation consensus statement on cardiovascular care of college student-athletes J Am Coll Cardiol 2016; 67: 2981–95
European Society of Cardiology (ESC)	Recommended	Pre-participation cardiovascular evaluation for athletic participants to prevent sudden death: position paper from the EHRA and the EACPR, branches of the ESC. Endorsed by APHRS, HRS, and SOLAECE Eur J Prev Cardiol 2017; 24: 41–69
International Olympic Committee (IOC)	Recommended	The International Olympic Committee (IOC) consensus statement on periodic health evaluation of elite athletes, March 2009 Clin J Sport Med 2009; 19: 347–60
Canadian Cardiovascular Society/Canadian Heart Rhythm Society (CCS)	Not recommended	Canadian Cardiovascular Society/ Canadian Heart Rhythm Society Joint Position Statement on the cardiovascular screening of competitive athletes Can J Cardiol. 2019; 35: 1–11
American Medical Society of Sports Medicine (AMSSM)	No formal recommendation for or against universal incorporation of ECGs	AMSSM position statement on cardiovascular pre-participation screening in athletes: current evidence, knowledge gaps, recommendations, and future directions Clin J Sport Med 2016; 26: 347–361

screening programs. While recommendations differ, a key concept emphasized by all guidelines and position statements is that any institution or organization that chooses to include ECGs into the pre-participation screening process must have a thorough understanding of both the strengths and pitfalls of the ECG, as well as the potential benefits and risk to the athlete. Safeguards and essential elements for this process include that ECG interpretation must be performed by healthcare

professionals familiar with the spectrum of ECG findings in athletes and that experts in the cardiovascular care of athletes are closely aligned to provide oversight and to efficiently and expeditiously manage downstream testing [2–4, 46–48].

How Do We Interpret Athlete ECGs?

Development of Athlete-Specific ECG Interpretation Criteria

When the decision has been made to perform an ECG on an athlete, whether it is for the purpose of screening or to evaluate a clinical concern, healthcare providers must next try and determine whether the observed ECG findings are normal or abnormal requiring further evaluation. It is appreciated that long-term and intensive athletic training results in physiologic, adaptive cardiac remodeling [49–51]. As such, surface ECGs that reflect underlying cardiac structure can frequently be different in well-trained athletes than in age-matched nonathletes [52, 53]. The challenge for healthcare providers in this setting is to distinguish physiologic, training-related ECG changes from findings that may suggest an underlying cardiac disorder. To assist in this process, with the goal to increase specificity and minimize false-positive rates in ECG interpretation, expert consensus athlete-specific ECG interpretation criteria have been developed. The first formalized set of athlete-specific ECG interpretation criteria was compiled by the European Society of Cardiology (ESC) in 2005 [54]. These criteria provided a table of abnormal ECG findings that, if present, suggested a need for further evaluation. When these criteria were applied prospectively in athlete groups, however, false-positive ECG rates were found to be unacceptably high, with a comprehensive study of 1005 elite mixed-sports athletes showing a false-positive rate of 40% using these criteria [52]. The ESC subsequently developed and published a modernized set of criteria in 2010 that separated ECG findings into common and physiologic "training-related ECG findings" and findings that were not to be expected as a result of athletic training and classified as "abnormal" [55]. These newer criteria did improve specificity and lower false-positive rates in comparison with the 2005 criteria, but abnormal ECG classification rates of approximately 10% were still observed in cohorts of athletes engaged in a cross section of sports [56]. An important additional limitation of the 2010 ESC criteria stemmed from the fact that these criteria were derived from analyses of ECGs in primarily white athletes and they did not incorporate emerging data highlighting different repolarization and T wave patterns between white and black athletes [57–59].

Based on these observed ethnic differences in repolarization, and in the effort to further improve ECG specificity, an international summit of sports cardiologists and sports medicine physicians convened in Seattle in 2012 to derive an improved set of criteria, and these "Seattle Criteria" were published in 2013 [60]. The Seattle criteria classified a pattern of convex ST elevation combined with T wave inversion

(TWI) in leads V1–V4 as a normal ECG variant in black athletes based on data demonstrating that this T wave pattern was not associated with underlying cardiac pathology in black athletes [59, 60]. In addition, the Seattle criteria shortened cutoffs to define QT prolongation and lengthened cutoffs to define abnormal QRS widening [60].

Subsequent to the publication of the Seattle criteria, a large-scale analysis that included over 2500 mixed-sports athletes and nearly 10,000 controls demonstrated that the ECG findings of atrial enlargement and axis deviation in isolation, findings classified as abnormal by Seattle criteria, were not associated with cardiac pathology when matched ECG and echocardiographic data were compared. Removal of these ECG findings from abnormal ECG classification reduced false-positive ECG rates from 13% to 7.5% [61]. The incorporation of this data led to the creation of the "Revised Criteria" published in 2014 which added a category of borderline ECG findings in addition to training-related and abnormal ECG findings [62]. Borderline variants, when present in isolation, were no longer classified as abnormal ECG findings, but if two or more borderline variants were present, then the ECG would be classified as abnormal.

A summary of the evolution of these athlete-specific ECG interpretation criteria, as well as the designation of ECG findings within each set of these criteria, is shown in Fig. 2.2. While specificity has improved with each updated set of criteria, it is important to recognize inherent limitations of these criteria. The designation of individual ECG findings as normal or abnormal was based primarily on expert consensus opinion. In addition, the criteria were not sport-specific, and they did not
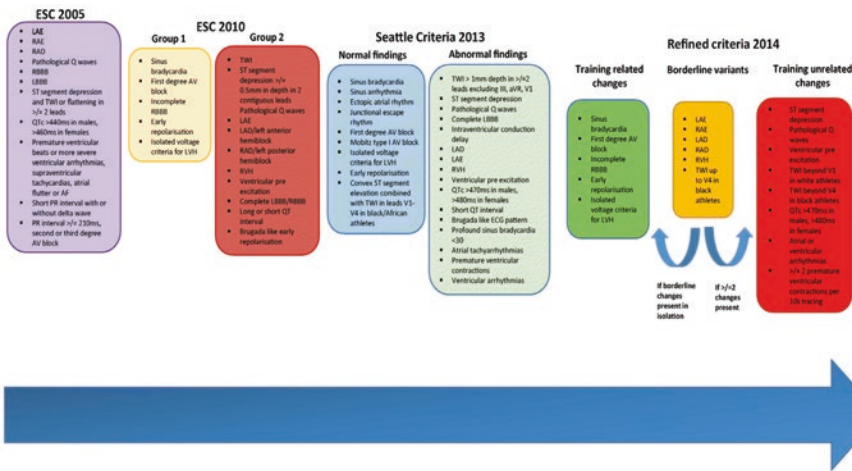

Fig. 2.2 Evolution of athlete-specific ECG interpretation criteria. (Reprinted without modification from Basu and Malhotra [70]. Springer Nature (http://creativecommons.org/licenses/by/4.0/)). *LAE* left atrial enlargement, *RAE* right atrial enlargement, *LVH* left ventricular hypertrophy, *RVH* right ventricular hypertrophy, *LAD* left axis deviation, *RAD* right axis deviation, *RBBB* right bundle branch block, *LBBB* left bundle branch block, *TWI* T wave inversion, *QTc* corrected QT interval, *AF* atrial fibrillation, *AV* atrioventricular

incorporate how varied hemodynamic demands of different sports, or the level or years of intensive training, may alter adaptive cardiac remodeling and ECG manifestations of these cardiac structural and electrical changes. Rather, the criteria were designed to be used in a "one size fits all" approach. A further limitation was the fact that the criteria sets were not studied prospectively to test or assess their accuracy in athlete groups prior to publication. Nonetheless, these expert consensus criteria have provided a vitally important frame of reference for healthcare providers to evaluate athlete ECGs. All practitioners who perform and interpret ECGs in athletes should be intimately familiar with the newest and most up-to-date versions of these criteria.

2017 International Recommendations

The most recent set of athlete-specific ECG interpretation criteria was published in 2017 by an international group of experts in sports cardiology, inherited cardiac disease, and sports medicine [29]. The International Recommendations put forth by this group represent the most current and specific guideline recommendations for the interpretation of ECGs in athletes. The International Recommendations further increase specificity from prior ECG criteria sets by re-classifying right bundle branch block (RBBB) from an abnormal ECG finding to a borderline variant, based on data demonstrating that RBBB was more prevalent in athletes than nonathletes but that this ECG pattern was not inherently reflective of underlying structural heart disease in athletes [63]. In addition, the definition of an abnormal Q wave was made more stringent. Since their publication, while false-positive rates are still shown to exist, the International Recommendations have outperformed the previous ESC, Seattle, and refined criteria and reduce false-positive ECG rates in studies of pediatric athletes, professional cyclists, and professional basketball players in the National Basketball Association (NBA) [30–32].

The flowchart to evaluate an athlete's ECG using the International Recommendations is shown in Fig. 2.3. ECG findings in green are classified as physiologic, training-related findings that do not warrant further evaluation without other clinical indications. Sample ECG tracings of common training-related ECG patterns are shown in Fig. 2.4. ECG findings in yellow are classified as borderline ECG changes – included in this category are axis deviation, atrial enlargement, and complete RBBB. These findings in isolation do not warrant further evaluation, but two or more borderline findings would change the ECG classification to abnormal. ECG findings in red are classified as abnormal and are findings not known to be connected to athletic remodeling. Further evaluation is recommended for ECG findings in this category. The precise definitions used for each abnormal ECG finding are shown in Table 2.3. Sample tracings representing ECG patterns in this category are shown in Fig. 2.5.

An additional component of the International Recommendations that helped to further distinguish it from prior athlete ECG criteria sets was the placement of
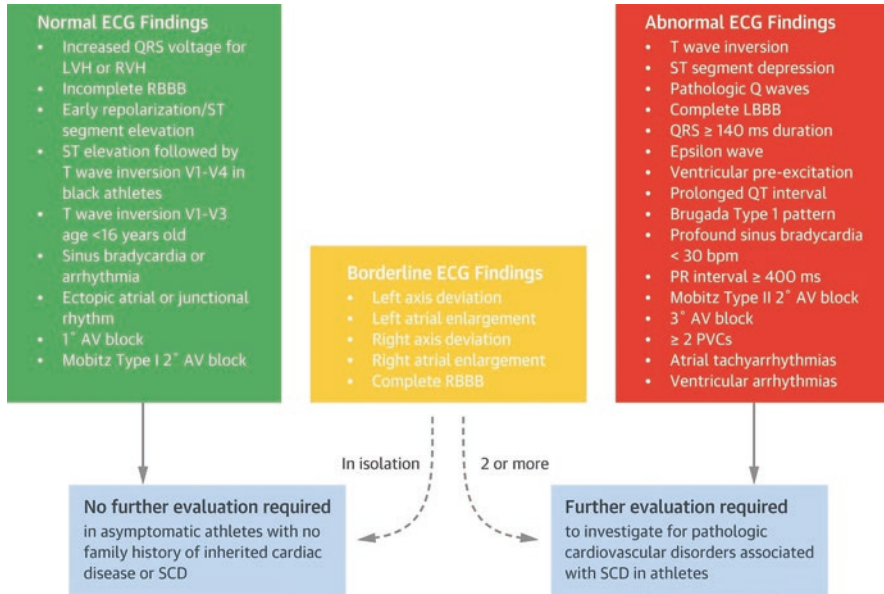
Normal ECG Findings	Borderline ECG Findings	Abnormal ECG Findings
• Increased QRS voltage for LVH or RVH • Incomplete RBBB • Early repolarization/ST segment elevation • ST elevation followed by T wave inversion V1-V4 in black athletes • T wave inversion V1-V3 age <16 years old • Sinus bradycardia or arrhythmia • Ectopic atrial or junctional rhythm • 1° AV block • Mobitz Type I 2° AV block	• Left axis deviation • Left atrial enlargement • Right axis deviation • Right atrial enlargement • Complete RBBB	• T wave inversion • ST segment depression • Pathologic Q waves • Complete LBBB • QRS ≥ 140 ms duration • Epsilon wave • Ventricular pre-excitation • Prolonged QT interval • Brugada Type 1 pattern • Profound sinus bradycardia < 30 bpm • PR interval ≥ 400 ms • Mobitz Type II 2° AV block • 3° AV block • ≥ 2 PVCs • Atrial tachyarrhythmias • Ventricular arrhythmias

In isolation / 2 or more

No further evaluation required in asymptomatic athletes with no family history of inherited cardiac disease or SCD

Further evaluation required to investigate for pathologic cardiovascular disorders associated with SCD in athletes

Fig. 2.3 Flowchart for ECG interpretation using the International Recommendations. (Reprinted with permission from Sharma et al. [27], Elsevier)

greater emphasis on the recognition of abnormal TWI. While there are patterns of TWI that have been demonstrated to be relatively common in athletes and not associated with underlying cardiac pathology, including TWI confined to V1 and V2 in white athletes [64], TWI in leads V1–V3 in pediatric athletes <16 years old (juvenile TWI) [65], and TWI in V1–V4 preceded by convex ST elevation in black athletes (Fig. 2.4d) [59, 60], other patterns of TWI are not prevalent findings in athletes. TWI that involves the inferolateral leads are highly uncommon in athletes regardless of ethnicity [35, 59, 66]. Given also the fact that TWI involving the inferior and lateral leads is frequently present in HCM [33, 67, 68], the presence of inferolateral TWI in an athlete warrants further investigation. Sample tracings demonstrating abnormal inferolateral TWI are shown in Fig. 2.6.

Data generated by large-scale and longitudinal studies of athletes with inferolateral TWI helped to further shape the guideline recommendations that are included in the International Recommendations for athletes with this ECG pattern. In a database of over 12,000 Italian mixed-sports asymptomatic athletes, 0.6% had baseline abnormal TWI (the majority in the inferolateral leads) but otherwise normal cardiovascular screening exams. When these athletes were followed over a mean period of 9 years, 6% of these athletes were subsequently observed to develop a cardiomyopathy, and 7% were observed to develop other cardiac disorders [35]. In a separate study of over 6000 mixed-sports athletes in which 2.4% were detected to have abnormal TWI (83.9% involving inferior or lateral leads), 44.5% of these athletes were ultimately found to have cardiac disease [66]. In these cases of established
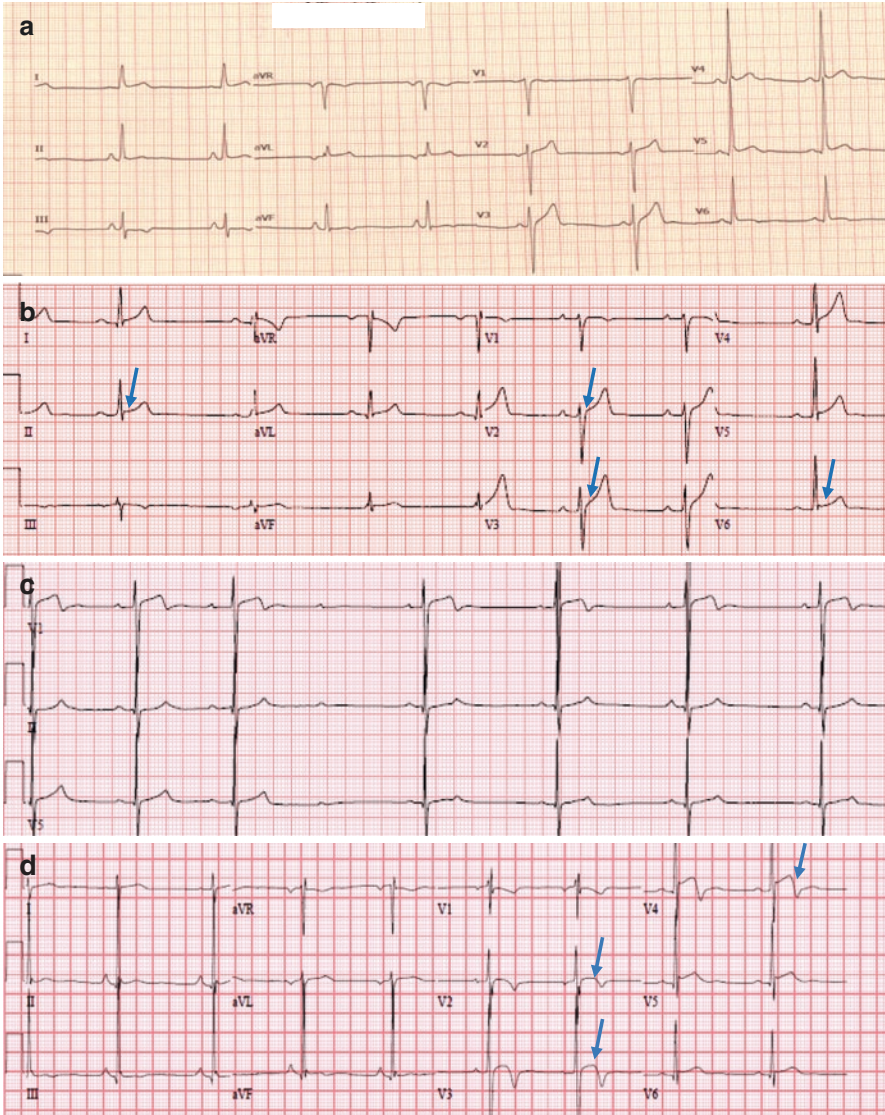
Fig. 2.4 Representative ECG tracings for common "training-related" ECG patterns. (**a**) Voltage criteria for left ventricular hypertrophy (Sokolow-Lyon criteria). (**b**) Early repolarization seen by diffuse elevation of the QRS-ST junction (J point) (blue arrows). (**c**) Sinus rhythm with type I atrioventricular block (Wenckebach). (**d**) Convex ST elevation with T wave inversion V1–V4 in a black athlete (blue arrows)

Table 2.3 Abnormal and borderline ECG findings with definitions as per international recommendations

| Abnormal ECG findings	Definition
Abnormal T wave inversion (TWI)	≥1 mm in depth in two or more contiguous leads; excludes aVR, III, and V1
Anterior	V2–V4 Excludes black athletes with J-point elevation and convex ST elevation followed by TWI in V2–V4; athletes age <16 with TWI in V1–V3; and biphasic T waves in only V3
Lateral	I and aVL, V5 *and/or* V6 (only one lead of TWI required in V5 or V6)
Inferolateral	II and aVF, V5–V6, I and aVL
Inferior	II and aVF
ST depression	≥0.5 mm in depth in two or more contiguous leads
Abnormal Q waves	Q/R ratio ≥0.25 or ≥40 ms in duration in two or more contiguous leads
Complete left bundle branch block (LBBB)	QRS ≥120 ms, predominately negative QRS complex in lead V1 (QS or rS), and upright notched or slurred R wave in leads I and V6
Nonspecific intraventricular conduction delay (IVCD)	Any QRS duration ≥140 ms
Epsilon wave	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–V3
Ventricular pre-excitation	PR interval <120 ms with a delta wave (slurred upstroke in the QRS complex and wide QRS (≥120 ms)
Prolonged QT interval	QTc ≥470 ms (female) QTc ≥480 ms (male) QTc ≥500 ms (marked QT prolongation)
Brugada type 1 pattern	Coved pattern: initial ST elevation ≥2 mm (high take-off) with downsloping ST elevation followed by a negative symmetric T wave in >1 leads in V1–V3
Profound sinus bradycardia	<30 beats/min or sinus pauses ≥3 s
Profound 1° AV block	≥400 ms
Mobitz type II 2° AV block	Intermittently non-conducted P waves with a fixed PR interval
3° AV block	Complete heart block
Atrial tachyarrhythmias	Supraventricular tachycardia, atrial fibrillation, atrial flutter
Premature ventricular contractions (PVC)	≥2 PVCs per 10 s tracing
Ventricular arrhythmias	Couplets, triplets, and non-sustained ventricular tachycardia
Borderline ECG findings	*These ECG findings in isolation do not represent pathologic cardiovascular disease in athletes, but the presence of two or more borderline findings may warrant further investigation*
Left axis deviation	−30° to −90°
Left atrial enlargement (LAE)	Prolonged P wave duration of >120 ms in leads I or II with negative portion of the P wave ≥1 mm in depth and ≥40 ms in duration in lead V1
Right axis deviation	> 120°
Right atrial enlargement	P wave ≥2.5 mm in II, III, or aVF
Complete right bundle branch block (RBBB)	rSR' pattern in lead V1 and an S wave wider than R wave in lead V6 with QRS duration >120 ms

Adapted from Sharma et al. [27]
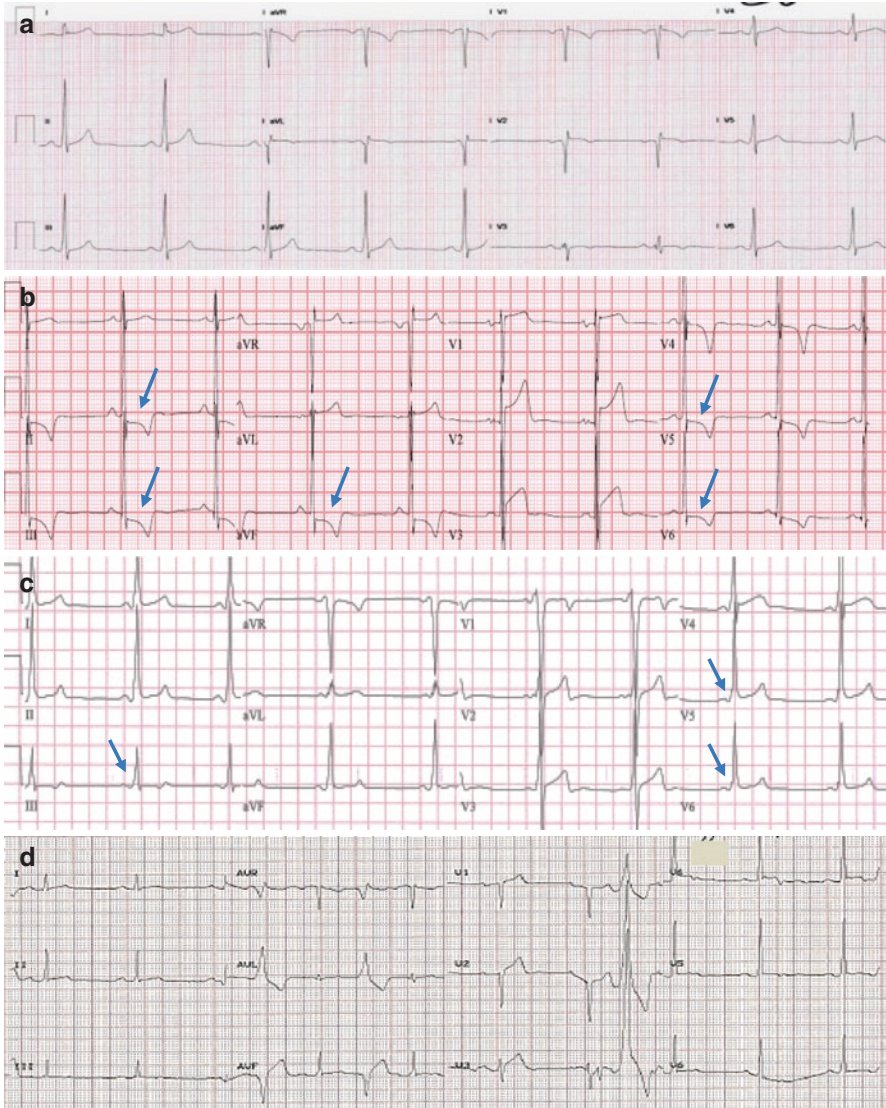
Fig. 2.5 Representative ECG tracings for abnormal ECG patterns in athletes. (**a**) Abnormal Q waves (V1–V2). (**b**) ST depressions with inferolateral T wave inversions (V5, V6, II, III, aVF) (blue arrows). (**c**) Ventricular pre-excitation (delta waves) (blue arrows). (**d**) Frequent PVCs

disease, echocardiography detected underlying cardiac pathology in 53.6% of cases. CMR, however, led to a diagnosis of cardiomyopathy in an additional 16.5% of cases in athletes where the echocardiogram interpretation was normal and an additional 30% of cases in athletes where the echocardiogram findings were suspicious [66]. In a 1-year follow-up of the athletes with abnormal TWI but normal echo and CMR, 7.2% were subsequently found to develop signs of a cardiomyopathy [66].
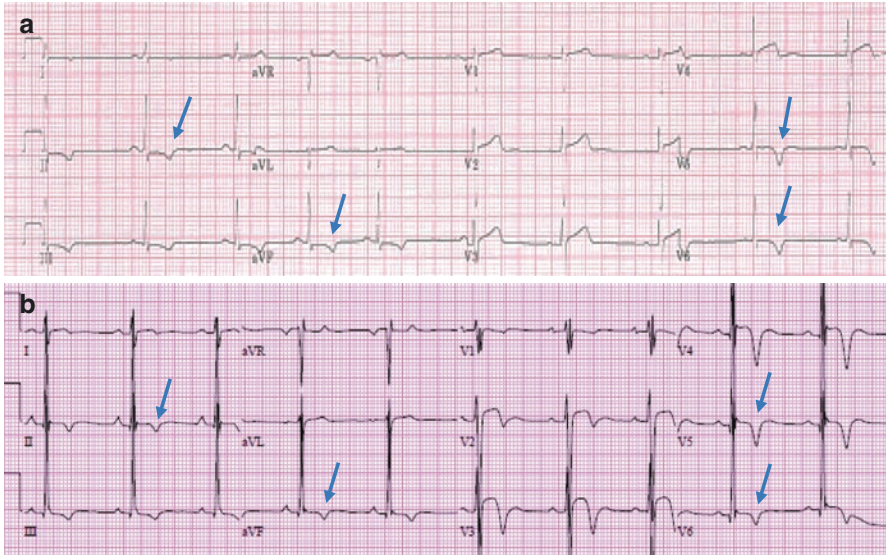
Fig. 2.6 Blue arrows demonstrate T wave inversions in the inferolateral leads. These T wave inversions are not considered training-related ECG findings and warrant additional investigation, including use of cardiac MRI with gadolineum, to exclude structural heart disease

The International Recommendations incorporated this data and highlight the importance of recognizing inferolateral TWI in athletes. The recommendations state that if echocardiography is not diagnostic, then CMR with gadolinium should be performed to further evaluate athletes with lateral or inferolateral TWI [29]. Cited advantages of CMR in this setting are that CMR can provide better delineation of myocardial hypertrophy of the LV apex if echocardiographic images are technically suboptimal and that late gadolinium enhancement, if present, could suggest myocardial fibrosis [29]. In addition, serial follow-up examinations are recommended for athletes with this ECG pattern [29].

Conclusions

Debate and discussion continue to surround the issue as to whether an ECG should universally be included in pre-participation screening examinations of asymptomatic athletes. Powerful arguments for and against the standard inclusion of an ECG are currently advanced by leading medical organizations throughout the world. At the present time, most organizations, including those in the USA, do not recommend adding an ECG to the screening process of asymptomatic athletes. While there is not universal agreement regarding policy, a consistent guideline recommendation is that if healthcare systems are to include an ECG as part of the standard pre-participation exam, then detailed protocols should be in place to efficiently

manage the downstream testing that will inevitably occur. Additionally, ECG interpretation should be performed by sports cardiologists or other healthcare providers with expertise in the cardiac evaluation and interpretation of ECGs in athletes.

It can be challenging and remains a clinical conundrum for healthcare providers to distinguish training-related ECG changes that occur as a consequence of athletic cardiac remodeling from ECG changes that could represent underlying cardiac pathology. Significant achievements have been made to develop athlete-specific ECG interpretation criteria that improve the accuracy of ECG interpretation and lower false-positive rates. The newest International Recommendations additionally highlight important ECG patterns that have a higher probability of portending cardiac disease. Further refinements of these ECG criteria, however, are needed. Given that varied hemodynamic demands of different sports variably affect training-related cardiac structural adaptation and ECG change, more sports-specific ECG standards are required. A "one size fits all" approach to ECG interpretation may not be the best approach. As highlighted by the American College of Cardiology Sports and Exercise Physiology Think Tank [69], the generation of more sport-specific normative cardiac data is needed to allow for more accurate interpretation of test results in athletes and to help further refine best practices to promote athlete health and safety. Similarly, the optimal strategy for the use of the ECG in athlete screening may not be to apply a uniform approach across all athlete groups, but to integrate athlete-specific and sport-specific data to serve the best interests of the athlete.

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