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Towards safer sport: modern perspectives on cardiovascular screening for the prevention of sudden cardiac death in athletes

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Abstract
Background: Sudden cardiac death (SCD), defined as an unexpected fatal event within 1 hour of symptom onset (witnessed) or 24 hours (unwitnessed), is a leading cause of sport-related mortality, even in apparently healthy athletes. True incidence remains unclear due to variable definitions, reporting heterogeneity, and diagnostic limitations. Understanding mechanisms and risk factors is essential for effective screening and prevention.
Aim: This review examines cardiac anomaly screening in athletes, focusing on optimal modalities, target groups, and economic considerations. It also synthesizes evidence on epidemiology, structural and physiological risk factors, prevention strategies, and knowledge gaps.
Methods: A narrative review of PubMed and Google Scholar included original research, reviews, meta-analyses, and guidelines. Studies were analyzed for epidemiology, risk factors, pathomechanisms, and prevention strategies to provide an integrated overview.
Results: SCD etiology and risk profiles are heterogeneous, limiting universal screening. ECG use remains debated due to cost and false results. Questionnaires and physical exams are widely recommended, but advanced diagnostics face financial and logistical constraints. Reporting inconsistencies, variable athlete definitions, and resource disparities complicate implementation.
Conclusions: SCD in athletes arises from diverse cardiovascular disorders, making universal screening difficult. Evidence supports context-dependent, targeted strategies that balance feasibility, equity, and risk reduction.

Key words: sudden cardiac death, athletes, cardiomyopathy, screening, exercise-related mortality

1. Introduction

Sudden cardiac death (SCD) is defined as an unexpected fatal event resulting from cardiac disease that occurs within one hour of the onset of symptoms in witnessed cases (Kumar A et al., 2021) or within 24 hours in unwitnessed cased (Ghani U et al., 2023). SCD remains a major public health issue worldwide. In Europe, approximately 350,000 individuals die suddenly each year, whereas in the United States the figure reaches nearly 400 000, with most cases attributable to underlying cardiac pathology such as coronary artery disease (CAD), cardiomyopathies and arrhythmogenic conditions (Markwerth P et al., 2021). Moreover, SCD is recognized as a leading cause of health-related mortality among athletes (Harmon KG et al., 2014). Its occurrence in physically fit individuals presumed to be in optimal health attracts exceptional attention – both medically and publicly – due to the striking contrast between apparent good health and sudden fatal event.

Although the true incidence of the SCD in athletic population is still not fully settled (DeFroda SF et al., 2019), its social and medical impact is unquestionably significant. The challenges in recognising incidence of SCD stem from several factors, including inconsistent, ambiguous definitions, heterogeneity across reporting systems, and frequent difficulties in establishing a definitive cause of death even on autopsy. A deeper understanding of the risk factors, epidemiology, and underlying mechanisms of SCD in athletes is essential for developing an effective screening programme, as such knowledge would enable the establishment of targeted criteria tailored to specific sports and individual risk profiles. Consequently, a well-designed screening strategy has the potential to facilitate early detection and support timely preventive interventions, thereby reducing the likelihood of SCD in physically active population.

2. Research materials and methods

This literature review was conducted using a narrative synthesis methodology to integrate heterogeneous evidence from diverse study types. A comprehensive and structured search of two major scientific databases (PubMed, Google Scholar) was performed. Search terms included “sudden cardiac death”, “athletes”, “screening”, “exercise-related mortality”. The review incorporated peer-reviewed original research articles, systematic reviews, meta-analyses and international guidelines relevant to SCD, especially in athletic population, with particular emphasis on the studies examining current perspectives on cardiovascular screening in athletes presumed to be in a good health. All studies underwent an initial screening followed by full-text evaluation. Exclusion criteria included reports of exercise-related deaths not caused by heart condition. Included studies were later analyzed in four main domains: the epidemiology

and incidence of SCD in athletes, pathophysiology and underlying mechanisms, major risk factors and modern perspectives on potential screening methods. Data from the selected studies were systematically categorized, compared, and critically evaluated. The information was synthesized into an integrated narrative overview, with particular attention to areas of consensus, ongoing controversies, and gaps in existing evidence.

The primary objective of this review is to critically examine current state of knowledge regarding both the value and feasibility of implementing routine screening for cardiac abnormalities in athletic populations. Specifically, it aims to evaluate the evidence supporting various diagnostic approaches, identify the specific subgroups of athletes and risk profiles most likely to benefit from structured screening programs, and asses the broader financial and organizational considerations involved in adopting such measures.

2.3.2. AI.

Artificial intelligence-based language tools were employed during manuscript preparation to enhance grammatical accuracy, improve linguistic clarity, and ensure overall coherence of the text. These tools were used exclusively for stylistic refinement and did not influence data interpretation or conclusions drawn. Their use aimed to improve readability and communicative precision, thereby enhancing the overall quality and professionalism of the final manuscript.

3. Research results

3.1. Epidemiology

The true incidence of SCD remains unknown, as no mandatory reporting system exists for sport-related death, particularly in school-level athletics (DeFroda SF et al., 2019). Additional uncertainty arises from the absence of a standardized definition of the term “athlete”. Many studies fail to distinguish between professional athletes and individuals participating in sport activities at recreational, academic, or high school level. Finocchiaro G et al. (2024) highlighted a global decline in autopsy rate, adding further unclarity to incidence of SCD. Recent data from the Fédération Internationale de Football Association (FIFA) indicate that among 617 documented SCD cases in young football players across 67 countries, post-mortem examinations were performed in only 20,5% of cases (Egger F et al., 2022). Similarly, a European review by Banner J et al. (2021) showed that only 60% of SCD cases in individuals

under 50 years of age underwent autopsy. Despite being performed, in many cases the cause of death cannot be determined even after an autopsy.

Large-scale studies offer further insight into these complexities. A 20-year investigation of National Collegiate Athletic Association reported an overall SCD incidence of 1 per 63,628 athlete years (Petek BJ et al., 2024). Ealier data from Corrado D et al. (2006) showed an incidence of 1.9 per 100000 person-years. Steinvil A et al. (2011) studied SCD in Israel population and reported a comparable rate of 2.6 per 100000 athlete-years.

3.2. Risk factors

Sex

Li et. al (2025) published a systematic review and meta-analysis demonstrating a marked sex disparity: the incidence of SCD in female competitive athletes was approximately six times lower than in the male athletes (incidence rate ratio of 5.5). Several hypotheses have been proposed to explain the higher incidence of SCD in male athletes compared with their female counterparts. Sex-specific differences include cardiac adaptation to prolonged training, different patterns of heart chamber remodeling, and a higher prevalence of CAD and myocardial fibrosis in men, which may serve as an arrhythmogenic substrate (Finocchiaro G et al., 2021; Finocchiaro G et al., 2019; Haukilahti MAE et al., 2019). Hormonal factors may also contribute, especially the absence of protective effects of estrogen in men. In addition, behavioral and psychological risk factors, such as a greater tendency for males to engage in risk-associated or addictive behaviors or to push the exertion to an extreme level may be of importance (Haukilahti MAE et al., 2019; Drici MD et al., 1996; Cavasin MA et al., 2003).

Ethnicity

Petek BJ et al. (2024) further indicated that the incidence of SCD was higher among Black population compared with other ethnic groups.

Sport discipline

The study of Corrado D et al. published in 1998 indicated that in European population, SCD in athletes was most frequently reported in football players, with similar conclusion of the study on Israel population (Yanai O et al., 2000). In contrast, multiple studies involving American athletes (Corrado D et al., 2003; Drezner JA et al., 2009; Harmon KG et al., 2011) identified

the highest incidence of SCD in basketball players. It must be taken into consideration that this disparity may be influenced by regional variation in the cultural prominence and participation rates of specific sports, which subsequently influences overall risk distribution.

3.3 Underlying mechanisms of SCD

SCD is a fatal event that can arise from a wide range of congenital and acquired cardiac abnormalities. The following paragraph summarize the key conditions identified in the literature as major causes of SCD in athletes.

Hypertrophic cardiomyopathy (HCM)

HCM is considered the most common cause of SCD in athletes under the age of 35 (Pelliccia A et al., 1991). In a cohort study by Maron BJ et al. (2006) involving 1866 young athletes, HCM accounted for nearly 40% of SCD cases. Diagnostic challenges arise because athletes develop cardiovascular adaptations to the frequent and intensive training, including left ventricle hypertrophy (LVH). This structural change is a part of the morphological concept of the “athlete’s heart” (Maron BJ et al., 1986). Importantly, increased left ventricular wall thickness is also a diagnostic criterion for HCM. Consequently, distinguishing between physiological LVH and genetically determined HCM is particularly challenging and requires comprehensive multimodal diagnostic evaluation (Sheikh N et al., 2015; Malhotra A et al., 2017).

Arrythmogenic right ventricular cardiomyopathy (ARVC)

ARVC is a hereditary cardiac disorder characterized by progressive myocyte loss, with replacement by fibrofatty tissue, most prominently affecting the right ventricle (RV) (Kochi et al., 2021). This structural remodeling of the RV substantially increases the risk of arrhythmias, such as ventricular tachycardia or ventricular fibrillation. In an autopsy study conducted in 2015, De Noronha et al. reported ARVC as the cause in 14% of athlete SCD cases in athletes, ranking it third only to HCM and idiopathic LVH. Conversely, the studies in the Italian population have identified ARVC as the most frequent cause of SCD in athletes (Corrado et al., 2003).

Long QT syndrome (LQTS)

LQTS comprises a group of congenital channelopathies caused by mutations in more than 600 different genes, leading to a prolongation of the QT interval, reflecting a delay between the

onset of depolarization and the completion of repolarization, which clinically manifests as an increased susceptibility to life-threatening arrhythmias (Gomez et al., 2016). Schwartz et al. (2001) reported that in patients with LQT1 (the most common subtype of LQTS associated with mutations in *KCNQ1* gene [Kapplinger et al., 2009]), physical exertion was a trigger for 62% of SCD cases.

Congenital anomalies of coronary arteries

Li et al. (2025) reported sex-specific differences in SCD etiologies: HCM predominates among male athletes, whereas congenital coronary anomalies appear relatively more frequent among female athletes. Kastellanos S et al. (2018) noted that the anomalous origin of a coronary artery from the contralateral sinus is the cardiac anomaly most commonly linked to SCD, especially when the aberrant artery passes between the aorta and the pulmonary trunk. The suggested underlying mechanism involves ventricular arrhythmias triggered by ischemia, which can occur during exercise as the aortic root and pulmonary trunk expand, potentially compressing the anomalous coronary artery (Kochi AN et al., 2021).

Coronary artery disease

While cardiomyopathies and channelopathies are the leading causes of SCD in younger athletes (<35 years), CAD becomes the predominant etiology in older athletes (>35 years) (Ghani U et al., 2023; Han J et al., 2023). Ischemia resulting from an imbalance between myocardial oxygen supply and demand serves as a major trigger for fatal arrhythmias. In a prospective analysis of 144 SCD cases, Böhm et al. (2016) found that CAD and acute myocardial infarction were responsible for 34 deaths, with a markedly higher prevalence among athletes older than 35 years.

Myocarditis

Myocarditis is an inflammatory disease of the myocardium caused by viral, bacterial, parasitic, or autoimmune mechanisms. Clinical presentation is highly variable, ranging from an asymptomatic course to symptoms mimicking acute coronary syndrome, ventricular arrhythmias, or SCD (Schulz-Menger J et al., 2025). Harmon KG et al. (2015) identified myocarditis as one of the most important causes of SCD in young athletes. Autopsy studies have detected myocarditis in approximately 8% of SCD cases (Vassalini M et al., 2016). Interestingly, the extent of inflammatory infiltrates does not appear to correlate with the risk of SCD (Eichhorn C et al., 2020).

Pre-excitation syndromes

Wolff-Parkinson-White syndrome is a disorder characterized by the presence of an accessory conduction pathway between the atria and ventricles, bypassing the normal atrioventricular conduction system (Bharia A et al., 2015). The electrocardiographic diagnostic criteria include a short PR interval (less than 120 ms), widened QRS complex, and a characteristic delta wave (Molinari M et al., 2024). Obeyesekere MN et al. (2012) reported SCD incidence of 0.1% in asymptomatic patients and 0.3% in patients with symptomatic arrhythmias. Determining the true prevalence of pre-excitation syndromes is challenging due to the lack of routine electrocardiography (ECG) screening among athletes, as well as the fact that the accessory pathway is not detectable in post-mortem examination. Consequently, pre-excitation syndromes may account for some of autopsy negative SCDs, which represent the most common form of SCD in many studies (Petek BJ et al., 2024; Tester DJ et al., 2006).

3.4 Screening

3.4.1 Pre-participation evaluation (PPE) programmes

Pre-participation cardiovascular screening before athletic competition is endorsed by major international organizations, including the American Heart Association (AHA), the European Society of Cardiology (ESC), the International Olympic Committee (IOC), and numerous medical organizations and sport federations around the world (Mont L et al., 2017; Ljungqvist A et al., 2009; Maron BJ et al., 2015; Drezner et al., 2017). One of most widely recognized models is the Italian national pre-participation screening programme, initiated in 1982, which mandates annual evaluation for competitive athletes consisting of a personal and family history questionnaire, psychical examination (PE), resting 12-lead ECG and stress testing when indicated (Sarto P et al., 2023). In a landmark review published in 2009, Corrado D et al. reported that this programme significantly reduced the incidence of SCD among young athletes, largely by identifying at-risk individuals and restricting them from professional sport when needed.

Despite clear evidence that unified and consistently implemented PPE protocols can meaningfully decrease SCD incidence among athletes, no internationally harmonized guidelines exist regarding the optimal components of such assessments. The AHA and

American College of Cardiology (ACC) recommend that initial, first-line screening rely primarily on a detailed personal and family medical history (Maron BJ et al., 2007). In contrast, the IOC, and the ESC advocate for the incorporation of resting ECG as a routine part of the screening protocols, even for asymptomatic athletes (Bille K et al., 2006). The following sections review individual screening tools and summarize the emphasis placed on each by leading organizations in their respective recommendations.

3.4.2 Methods of screening

Personal and family medical history followed by physical examination:

A fundamental component of PPE in competitive athletes is a comprehensive assessment of personal and family medical history. In the Eligibility and Disqualification Recommendations for Competitive Athletes, issued by the ACC, the AHA assigned a Class I recommendation to the use of their standardized 14-point questionnaire as a part of PPE (Maron BJ et al., 2015). Additionally, six international organizations collaboratively developed a unified screening tool - the Pre-Participation Evaluation Monograph (currently in its 5th edition, PPE-5) (MacDonald J et al., 2021; Maron BJ et al., 2014) to further standardize the process. Both tools collect detailed information on symptoms experienced throughout the athlete's lifetime (episodes of syncope, chest pain, seizures, dyspnea, reduced exercise tolerance), previously diagnosed conditions (hypertension, dyslipidemia, heart murmurs and several vascular diseases), and a family history of unexpected deaths and cardiovascular disorders.

Despite the long-standing availability of the guidelines, adherence remains suboptimal. In a confidential survey performed in 2013, Madsen LN et al. reported persistently low compliance with AHA screening recommendations, attributing this largely to insufficient awareness among clinicians. A meta-analysis by Harmon et. al published in 2015, involving 47,137 athletes, reported that the sensitivity and specificity of medical history questionnaires were 20% and 94%, whereas physical examination alone demonstrated a sensitivity of 9% and specificity of 97%. It must be taken into consideration that without improving the adherence to the guidelines in terms of PPE, their real efficacy cannot be fully realized (Lawless CE et al., 2014).

3.4.3 ECG

The use of ECG in the athlete screening represents an essential component of preventive testing both in Italy (Corrado D et al., 2006) and Israel (Steinvil A et al., 2011). Moreover, since 2005 ESC officially recommends the implementation of standard 12-lead ECG for detection of pathological conditions amongst athletes (Maron BJ et al., 2014). ECG enables the identification of channelopathies such as LQTS, pre-excitation syndromes as well as cardiomyopathies (Finocchiaro G et al., 2024). Emery MS et al. (2018) state that the sensitivity of ECG in detecting cardiovascular abnormalities in athletes is substantially higher than in patient medical history and PE. Nevertheless, ECG screening carries also important limitations, primarily related to interpretative challenges in athletes, whose cardiac structural and physiological remodeling associated with intensive training may lead to false positive findings. These challenges are particularly pronounced when the ECG is assessed by clinicians lacking specific expertise in sports cardiology (Dhutia H et al., 2018). Furthermore, the assessement is complicated by wide spectrum of ECG alternations that vary according to the specific type and intensity of athletic activity. Another challenge involves the substantial cost associated with providing preventive ECG to all athletes. If any first-line screening test yields abnormal findings, the athlete should undergo further evaluation using additional diagnostic modalities. In addition to standard 12-lead ECG, long-term ambulatory ECG monitoring with Holter device is frequently employed, especially in athletes with recurrent symptoms such as palpitations or syncope. Optimal evaluation of athletes with intermittent heart rhythm disturbances may be achieved through the use of continuous loop recorders, which store short ECG segments, typically 1-3 minutes, and can be activated by the patient, allowing the capture of several minutes of rhythm preceding the symptomatic event (Kochi AN et al., 2021).

3.4.4 Cardiopulmonary resuscitation (CPR)

Another essential strategy for preventing SCD in athletes is ensuring the presence of qualified medical personnel at all sporting events, enabling the prompt initiation of high-quality CPR in the event of cardiac arrest. The most critical determinant of survival is the interval between the onset of SCD and defibrillation; therefore, rapid access to CPR and automated external defibrillators is pivotal in improving outcomes. Furthermore, widespread training in basic life support and increased public awareness of SCD can significantly enhance survival rates and overall prognosis among athletes experiencing SCD (Finocchiaro et al., 2024).

4. Discussion

SCD is a catastrophic event with a multifactorial etiology, encompassing both congenital and acquired pathologies. The most common underlying causes of SCD cary substantially across factors such as age, sex, ethnicity, and athletic discipline. This heterogeneity poses a major challenge to the implementation of a uniform screening programme, as it cannot target a single disease but must instead account for a broad spectrum of distinct cardiovascular abnormalities. Effective screening strategies therefore need to be comprehensive, individualized, and adaptable to the diverse risk profiles within the athlete population.

A truly comprehensive evaluation for all potential causes of SCD would require a wide array of diagnostic tests, ranging from relatively inexpensive and accessible tools such as questionnaires and ECG to costly and technically complex investigations, including advanced imaging modalities. The practical and financial demands of such an extensive protocol would render its widespread implementation unfeasible. Moreover, even an idealized screening protocol would inevitably miss some underlying conditions, meaning that the risk of SCD could never be entirely eliminated. These limitations underscore the need for a balanced, evidence-based approach to athlete cardiac screening, optimizing risk reduction while remaining feasible in real-world settings.

No international consensus has yet been established regarding which age groups, ethnicities, or specific type of should undergo routine cardiac screening. Furthermore, the definition of “athlete” remains inconsistent, leaving uncertainty as to whether screening should be limited to professional athletes or also include amateurs and school-aged participants engaged in organized sports. Guidelines from the AHA, ACC, and ESC consistently recommend that screening include a standardized personal and family medical history questionnaire (such as the 14-item AHA questionnaire or PPE-5) and PE. However, consensus is lacking regarding the role of ECG: the ESC recommends its use as a first-line screening tool, whereas the AHA does not (Sharma S et al., 2021; Corrado D et al., 2005; Maron BJ et al., 2015). Controversy regarding ECG utility centers on cost-effectiveness and the risk of false positive results (Sarto P et al., 2023).

Furthermore, the psychological and logistic implications of screening must also be considered. False positive results, especially in younger athletes with physiological ECG adaptations to training, may lead to unnecessary diagnostic workup, temporary or permanent sports disqualification, and significant emotional distress. Conversely, false negatives pose their own risks by providing a misleading sense of security. Striking an appropriate balance between

sensitivity and specificity is therefore essential, yet challenging, due to the overlap between normal athletic remodeling and pathological conditions such as HCM or ARVC (Sheikh N et al., 2015; Malhotra A et al., 2017).

Kochi AN et al. (2021) emphasized that because the usefulness of a screening approach depends heavily on the traits of the population being assessed, one uniform screening protocol is unlikely to provide optimal effectiveness for every subgroup.

Any anomalies detected during screening require further diagnostic evaluation, including 24-hour Holter monitoring, echocardiography, and, in selected cases, cardiac magnetic resonance imaging (Mavrogeni SI et al., 2018).

Finally, equitable access to screening remains a global challenge, particularly in low- and middle-income countries where resources for advanced cardiovascular diagnostics are limited. Implementing even basic screening protocols may be difficult in regions lacking trained healthcare personnel, ECG equipment, or infrastructure for follow-up evaluation. These disparities raise ethical concerns regarding the universal applicability of screening recommendations and highlight the risk that overly resource-intensive protocols may exacerbate existing inequalities in athlete safety. A sustainable, tiered approach, adapting screening intensity to local resources, disease prevalence, and athletic demands, may offer the most pragmatic path forward.

5. Conclusions

SCD in athletes arises from a diverse array of both congenital and acquired cardiovascular disorders, complicating efforts to design a universal and effective screening strategy. The absence of international consensus reflects challenges related to population heterogeneity, inconsistent definitions of who qualifies as an athlete, and conflicting guideline recommendations – particularly regarding the use of ECG. Although screening programmes have been proven to reduce SCD risk, their effectiveness varies, and adherence remain low. Overly comprehensive protocols are limited by financial, logistical, and ethical constraints. False positives and false negatives results, as well as unequal access to advanced diagnostic further undermine universal applicability. Collectively, the evidence supports a balanced, context-dependent screening approach that maximizes risk reduction while remaining feasible and equitable across different athletic and healthcare environments.

Disclosure

Author's Contribution:

Conceptualization and Methodology: KW, WK, MM, MS, KK, AM, MSz, AH, MJ, MP

Investigation: KW, WK, MM, MS, KK, AM, MSz, AH, MJ, MP

Resources: Not applicable.

Writing - rough preparation: KW, WK, MM, MS, KK, AM, MSz, AH, MJ, MP

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