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# Strategies for the prevention of sudden cardiac death during sports

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## Abstract

Sudden cardiac death of a young athlete is the most tragic event in sports and devastates the family, the sports medicine team, and the local community. Such a fatality represents the first manifestation of cardiac disease in up to 80% of young athletes who remain asymptomatic before sudden cardiac arrest occurs; this explains the limited power of screening modalities based solely on history and physical examination. The long-running Italian experience showed that electrocardiogram (ECG) screening definitively improves the sensitivity of preparticipation evaluation for heart diseases and substantially reduces the risk of death in the athletic field (primary prevention). However, some cardiac conditions such as coronary artery diseases, present no abnormalities on 12-lead ECG. Moreover, cardiac arrest due to non-penetrating chest injury (commotio cordis) cannot be prevented by screening. This justifies the efforts for implementing programmes of early external defibrillation of unpredictable arrhythmic cardiac arrest. This article reviews the epidemiology of sudden cardiac arrest in the athlete in terms of incidence, sport-related risk, underlying causes, and the currently available prevention programmes such as preparticipation screening and early external defibrillation by using automated external defibrillators. The best strategy is to combine synergistically primary prevention of sudden cardiac death by preparticipation identification of athletes affected by at-risk cardiomyopathies and secondary prevention with back-up defibrillation of unpredictable sudden cardiac arrest on the athletic field.

## Keywords

Athlete, cardiomyopathy, defibrillation, electrocardiogram, exercise, screening, sudden death

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## Introduction

The sudden and unexpected death of a young athlete is the most tragic event in sports. Such a fatality devastates the family, other competitors, institutions (high school, college, or professional organization), the sports medicine team and the community.<sup>1–3</sup> Sudden demise of an athlete has a tremendous impact on the media because it affects apparently healthy individuals who are regarded as the healthiest group in society and, often, as heroes. The catastrophic nature of the event mandates the medical community to develop and implement effective preventive strategies.

The most common mechanism of cardiac arrest in young competitive athletes is abrupt ventricular fibrillation as a consequence of an underlying cardiovascular disease.<sup>3,4</sup> The culprit diseases are often clinically silent and unlikely to be suspected or diagnosed on the basis of spontaneous symptoms. Preparticipation medical

evaluation including 12-lead electrocardiogram (ECG) offers the potential to identify asymptomatic athletes who have potentially lethal cardiovascular abnormalities and to protect them from the risk of sudden cardiovascular death (SCD) through disqualification from competitive sports (primary prevention).<sup>4,5</sup> However, some cardiac conditions such as coronary artery

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diseases, that predispose athletes to SCD present no abnormalities on 12-lead ECG.<sup>5</sup> Moreover, sudden cardiac arrest (SCA) due to non-penetrating chest injury (commotio cordis) cannot be prevented by screening.<sup>3</sup> In recent years, emergency response planning for SCA and the availability of automated external defibrillators (AEDs) has provided an additional strategy for the prevention of SCD in the athletic setting.<sup>6–10</sup> Recent data provides evidence that secondary prevention of SCD in athletes is possible through early defibrillation programmes and prompt access to on-site AED for electrical therapy of unpredictable SCA in the athletic field.

This article addresses the epidemiology of SCD in the athlete and reviews the most significant studies on the efficacy, feasibility, cost-effectiveness, and impact on mortality of currently available prevention strategies such as preparticipation screening and early defibrillation by AEDs.

## Epidemiology of sudden death during sports

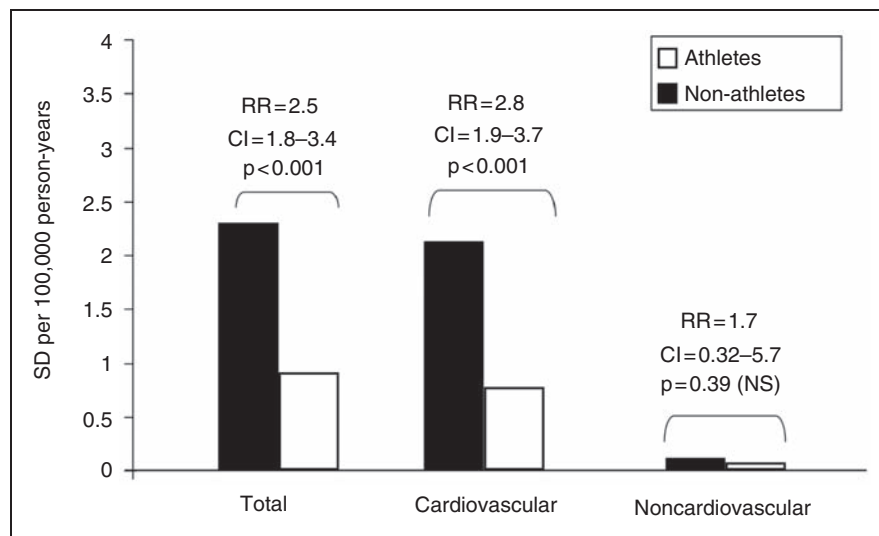
### Incidence of sudden death

The incidence of SCD during sports is fortunately low and varies in the different athlete series reported in the literature. In apparently healthy adults (>35 years of age), joggers, or marathon racers, the estimated rate of sports-related fatalities ranges from 1:15,000 to 1:50,000.<sup>4,11,12</sup> In comparison a significantly lower incidence of fatal events has been reported in young competitive athletes ( $\leq 35$  years of age). A prospective

population-based study in the Veneto region of Italy reported an incidence of sudden death of 2.3 (2.62 in males and 1.07 in females) per 100,000 athletes per year from all causes and of 2.1 per 100 000 athletes per year from cardiovascular diseases.<sup>12</sup> The same study demonstrated that adolescent and young adults involved in sports activity have 2.8 greater risk of SCD than their non-athletic counterparts<sup>12</sup> (Figure 1). In the USA, retrospective reviews reported that the prevalence of SCD in high school and college athletes ranges 0.4–0.6 per 100,000 athletes per year.<sup>13,14</sup> These estimates mostly relied on retrospective studies and search of public media reports, other electronic database, and catastrophic insurance claims, with unavoidable underestimation of the true incidence of events due to incomplete detection of sudden death victims.

The striking male predominance (male to female ratio up to 10:1) of SCD in athletes has been related to the higher participation rate of male compared with female in competitive sports, as well as the more intensive training load and level of athletic achievement of males. Furthermore, male gender was reported to be an independent predictor of sports-related SCD, most likely as a consequence of the greater prevalence and/or phenotypic expression in young males of cardiac diseases at risk of arrhythmic cardiac arrest, such as cardiomyopathies and premature coronary artery disease.<sup>12,15,16</sup>

Recently, Maron et al.<sup>17</sup> reported an annual incidence of SCD among US high-school and college athletes roughly similar to that observed in Italy after 24 years of preparticipation screening.<sup>18</sup> The study compared the incidence of SCD in: (1) high school and



**Figure 1.** Incidence and relative risk (RR) of sudden death among young athletes and non-athletes from total, cardiovascular, and non-cardiovascular causes. Adapted from Corrado et al.<sup>12</sup>

college athletes from Minnesota (USA), where no pre-participation ECG screening is practiced; and (2) young competitive athletes from the Veneto region (Italy), who have been exposed to systematic ECG screening since 1982. During 1993–2004, there were 12 deaths in the Veneto region and 11 in Minnesota (0.87 vs 0.93 per 100,000 athletes annually, respectively;  $p=0.88$ ). They concluded that because SCD rates in these demographically similar regions did not differ significantly in recent years, SCD in the athlete is a low event-rate phenomenon which is unlikely to be influenced by preparticipation cardiovascular evaluation. Because the risk of SCD in athletes is substantially greater in male athletes and increases significantly with age, the study findings simply reflect the differences in the athletic populations which were non-comparable for gender and age. The incidence of SCD has been estimated to be five- to ten-fold higher for male than for female athletes.<sup>12,13</sup> Male college athletes (age 18–22 years) had twice the estimated death rate of their high-school (age 12–18 years) counterparts (1.45/100,000 athletes/year vs. 0.66/100,000 athletes/year).<sup>13</sup> The US mortality rates mostly refer to high school and college participants (age 12–22 years), including approximately 65% males. The Italian athletic population significantly differs because of the inclusion of more males (approximately 80%) and, most importantly, because of a broader age range (12–35 years), including a significant group of older competitors. Noteworthy is that the mean age of Italian athletes who died suddenly was  $23 \pm 2$  years, with 60% of the victims aged  $>22$  years,<sup>7</sup> whereas the mean age of sudden death victims in the Maron's study was  $17 \pm 4$  years ( $p < 0.01$ ).<sup>17</sup> This age-group discrepancy accounts for the different prevalence between the two series of atherosclerotic coronary artery disease, a recognized increasing cause of SCD in young adults aged  $>20$  years, which was absent in the Minnesota series and was reported only from the Veneto region (eight of 55 sudden death victims, i.e. 15%). While the Italian data were systematically gathered according to a prospective study design, the US SCD rates reported by Maron et al.<sup>17</sup> were mostly based on a retrospective analysis of data provided by different sources, such as the Minnesota State High School League, news media information services, web-based search engines, and LexisNexis archival information database. Thus, reasonable concerns exist regarding the reliability of these sources of information in order to estimate the athlete's SCD rate, because of their inherent limitations in the data collection, unavoidably resulting in underestimation of mortality.

Other studies with more rigorous data collection and reliable denominator estimates reported an incidence of either SCD or SCA of young individuals and athletes in the USA more similar to that found in the Veneto

region of Italy. During 1960–1989, a significant higher incidence of SCD (about 4.5/100,000 person/years), was found in the young adult population (20–40 years old) of residents from Olmsted County, Minnesota.<sup>19</sup> Although this study did not report the relative proportion of athletes and non-athletes among sudden death victims, it clearly demonstrates that in the same geographic area of Maron's study, the incidence of SCD among young adults over the age of 20 increases exponentially to an extent comparable to that observed in the Veneto region in the pre-screening period. Most importantly, these data on mortality rates were very accurate because of the reliability of both the numerator – autopsy examination is compulsory for every case of sudden death occurring in Olmsted County and all autopsy examination were actually performed in the pathology department of the Mayo Clinic – and the denominator, which is based on census data of the Olmsted County population. The design of this study was very similar to the Italian which, since 1979 has relied upon systematic investigation and collection of juvenile sudden deaths occurring in the Veneto region, with morphological examination of all hearts performed by the same team of experienced cardiovascular pathologists according to a standard protocol.<sup>12,18,20</sup>

Atkins et al.<sup>21</sup> carried out a prospective, population-based investigation on the incidence of out-hospital SCA with involvement of more than 260 emergency medical service agencies at 11 US and Canadian sites. Based on all cases of SCA with an emergency medical response and the census reports, they reported a rate of cardiovascular events of 3.75/100,000 young individuals (age 14–24) per year. Moreover, a survey of US high school with AED found an annual incidence of SCA of 4.4/100,000 high school student athletes.<sup>10</sup> Finally, over a 25-year period, a systematic autopsy study on nontraumatic sudden death in US military recruits (age 18–35 years), reported an annual incidence of SCD of 11.1/100,000.<sup>22</sup>

### Causes of sudden death

As reported in Table 1, the causes of SCD during sports activity reflect the age of participants. Atherosclerotic coronary artery disease accounts for the vast majority of fatalities in adults (age  $>35$  years), while cardiomyopathies have been consistently implicated as the leading cause of cardiac arrest in younger athletes.<sup>1–5,12–16,23–25</sup> Hypertrophic cardiomyopathy (HCM) (Figure 2A) has been reported to account for more than one-third of fatal cases in the USA, and arrhythmogenic right ventricular cardiomyopathy/dysplasia (Figure 2B) accounted for approximately one-quarter of fatal cases in the Veneto region of Italy.<sup>1,2,4,12</sup>

**Table 1.** Cardiovascular causes of sudden death associated with sports

Age (years)	Cause of death	
<35	Hypertrophic cardiomyopathy	
	Arrhythmogenic right ventricular cardiomyopathy/dysplasia	
	Congenital anomalies of coronary arteries	
	Premature atherosclerotic coronary artery disease	
	Myocarditis	
	Aortic rupture	
	Valvular disease	
	Pre-excitation syndromes	
	Cardiac conduction diseases	
	Ion channel diseases	
	Congenital heart disease, operated or unoperated	
	≥35	Atherosclerotic coronary artery disease

Other substrates for sports-related SCD in the young include premature atherosclerotic coronary artery disease (Figure 2C), congenital coronary anomalies (Figure 2D), myocarditis, dilated cardiomyopathy, mitral valve prolapse, conduction system diseases, and Wolff–Parkinson–White syndrome.<sup>1,2,25</sup> Two to five per cent of young people and athletes who die suddenly have no evidence of structural heart diseases and the cause of their cardiac arrest is in all likelihood related to a primary electrical heart disease such as inherited cardiac ion channel defects (channelopathies), including long and short QT syndromes, Brugada syndrome, and polymorphic ventricular tachycardia.<sup>26</sup> Sudden death may be also caused by either a non-arrhythmic mechanism – e.g. spontaneous aortic rupture complicating Marfan’s syndrome or bicuspid aortic valve – or by diseases not related to the heart – e.g. bronchial asthma or rupture of a cerebral aneurysm. Blunt, non-penetrating, and often innocent-appearing blows to the precordium may trigger ventricular fibrillation without structural injury to ribs, sternum, or heart itself (commotio cordis).<sup>27</sup>

### Primary prevention of sudden death

The primary purpose of preparticipation screening is to identify the cohort of athletes affected by unsuspected cardiovascular diseases and to prevent SCD during sports by appropriate interventions. Both the American Heart Association and the European Society of Cardiology consensus panel recommendations agree that cardiovascular screening for young competitive athletes is justifiable and compelling on ethical, legal, and medical grounds.<sup>28,29</sup> However, intense debate exists on the screening protocol used.

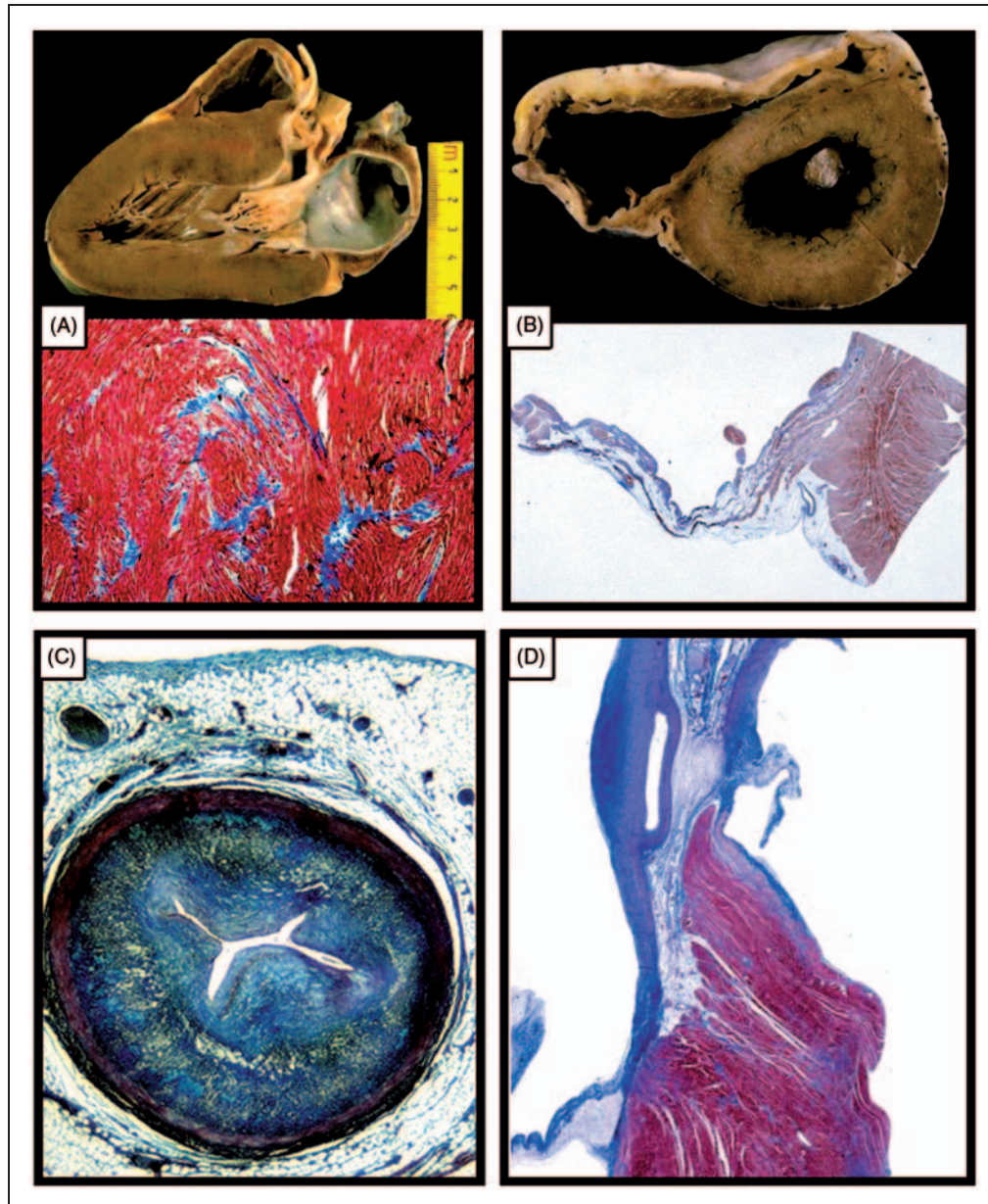
Preparticipation cardiovascular screening has traditionally been performed in the USA by means of history (personal and family) and physical examination, without 12-lead ECG or other testing. However, such a screening strategy has a limited power to detect potentially lethal cardiovascular abnormalities in young athletes, because most cardiovascular conditions responsible for SCD in young competitive athletes are clinically silent and unlikely to be suspected or diagnosed on the basis of spontaneous symptoms.<sup>1–3</sup>

Twelve-lead ECG enhances the sensitivity of the screening process by allowing early detection of cardiovascular conditions distinctively manifesting with ECG abnormalities, such as HCM, arrhythmogenic right ventricular cardiomyopathy/dysplasia, dilated cardiomyopathy, Wolff–Parkinson–White syndrome, Lènegre conduction disease, long and short QT syndromes, and Brugada syndrome.<sup>28</sup> Overall, these conditions account for two-thirds of SCD in young competitive athletes. Italy is the only country in the world where law mandates that every subject engaged in competitive sports activity must undergo a clinical evaluation to obtain eligibility before entering in competitive sports.<sup>30</sup> A nationwide mass preparticipation screening programme, essentially based on 12-lead ECG, has been the practice for more than 25 years.<sup>5,18,20,31</sup> The preparticipation evaluation involves nearly 6 million athletes of all ages annually, representing about 10% of the overall Italian population. A flow chart illustrating the Italian screening protocol is reported in Figure 3.

### Efficacy of ECG screening

The long running Italian experience has shown that ECG screening actually identifies asymptomatic athletes with previously undiagnosed cardiovascular abnormalities.<sup>1,2,18,20</sup>

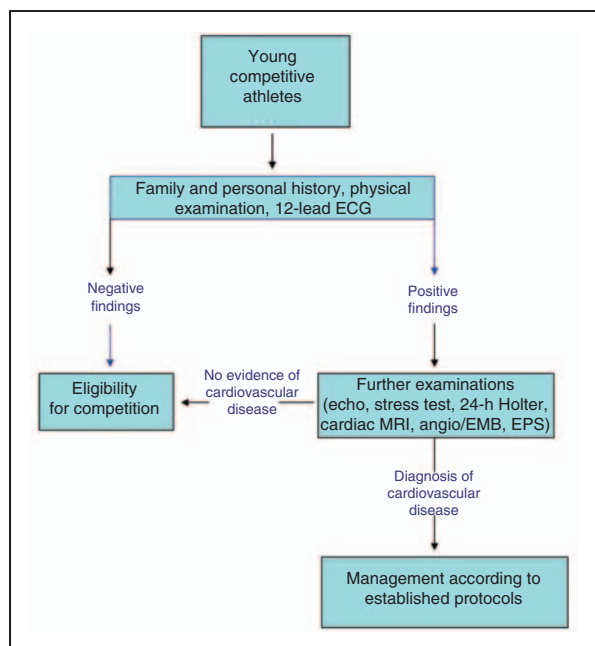
Although echocardiography is the main diagnostic tool for recognition of HCM, it is expensive and impractical for screening large athletic population.<sup>29–31</sup> The Italian screening protocol utilizing ECG in addition to history and physical examination has proven to successfully identify HCM in the general population of young competitive athletes. Among 33,735 athletes undergoing preparticipation screening at the Center for Sport Medicine in Padua, 22 (0.07%) showed definitive evidence, both clinical and echocardiographic, of HCM.<sup>20</sup> An absolute value of screening sensitivity for HCM cannot be derived from these data because systematic echocardiographic findings were not available. However, the 0.07% prevalence of HCM found in the white athletic population of the Veneto region of Italy, evaluated by history, physical examination, and ECG, is similar to the 0.10% prevalence reported



**Figure 2.** Leading causes of sudden cardiovascular death in young competitive athletes. (A) Hypertrophic cardiomyopathy: long axis cut of the heart specimen showing asymmetric septal hypertrophy with subaortic bulging and septal endocardial fibrous plaque (top); histology of the interventricular septum revealing typical myocardial disarray with interstitial fibrosis (bottom) (Heidenhain trichrome); (B) Arrhythmogenic right ventricular cardiomyopathy/dysplasia: cross section of the heart specimen with infundibular and inferior subtricuspidal aneurysms (top); panoramic histological view of an aneurysm of the inferior wall showing wall thinning with fibro-fatty replacement (bottom) (Heidenhain trichrome); (C) Premature coronary artery disease: histology of the proximal tract of the left anterior descending coronary artery showing a fibrous plaque causing severe lumen narrowing (Heidenhain trichrome); (D) Congenital coronary anomaly: panoramic histological view showing the intramural aortic course with a slit-like lumen of the anomalous right coronary artery arising from the left aortic sinus of Valsalva and running between the aorta and the pulmonary trunk (Heidenhain trichrome). Adapted from Corrado et al.<sup>2</sup>

for young white individuals in the USA, as assessed by echocardiography. This finding indicates that ECG screening may be as sensitive as echocardiographic screening in detecting HCM in the young athletic population.

Comparison between sensitivity of Italian and US screening protocols demonstrated that 12-lead ECG makes the difference. Among 22 athletes with HCM who were detected by ECG screening at the Center for Sport Medicine in Padua and disqualified from



**Figure 3.** Flow chart illustrating the Italian preparticipation screening protocol. The initial cardiovascular evaluation consists of complete personal and family history, physical examination including blood pressure measurement, and 12-lead electrocardiogram (ECG). Athletes who have positive findings at basal screening are referred for additional testing, initially non-invasive such as echocardiography, 24-hour ambulatory Holter monitoring, and exercise testing. Alternatively or in uncertain cases, invasive tests such as contrast ventriculography (both right and left), coronary angiography, endomyocardial biopsy, and electrophysiological study may be necessary in order to confirm or rule out the suspicion of heart disease. Athletes recognized to be affected by cardiovascular conditions potentially responsible for sudden death in association with exercise and sport participation are managed according to the available recommendations for sports eligibility. The athletic evaluation is performed by a physician with the specific training, medical skill, and cultural background to reliably identify clinical symptoms and signs associated with those cardiovascular diseases responsible for exercise-related sudden death. In Italy, physicians primarily responsible for preparticipation screening and eligibility for competitive sports attend postgraduate residency training programmes in sports medicine (and sports cardiology) full-time for 4 years. Such specialists work in sports medical centres specifically devoted to periodical evaluation of athletes. The screening starts at the beginning of competitive athletic activity that for the majority of sports disciplines corresponds to an athlete age of 12–14 years. Preparticipation evaluation is repeated on a regular basis (every 1 or 2 years) in order to timely identify progression over the time of some diseases. EMB, endomyocardial biopsy; EPS, electrophysiological study; MRI, magnetic resonance imaging. Adapted from Corrado et al.<sup>28</sup>

competition, only five (23%) would have been identified on the basis of a positive family history, symptoms, or abnormal physical findings in the absence of an ECG.<sup>20</sup> Hence, the estimated sensitivity of Italian screening

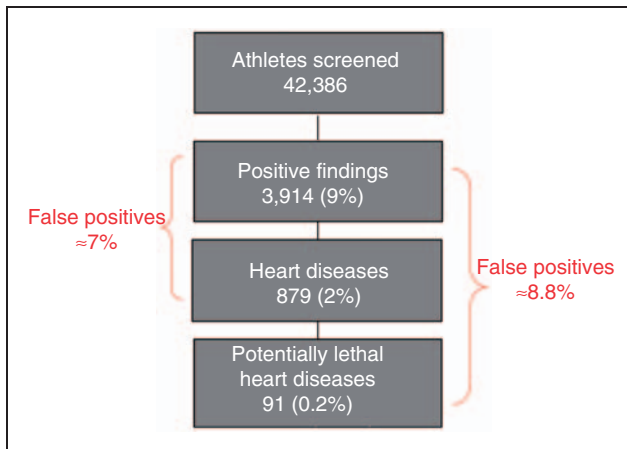
modality for identification of athletes with HCM is 77% greater than that of the screening protocol (not including ECG) recommended by the American Heart Association.<sup>29</sup> Echocardiographic study in addition to the basal protocol does not seem to significantly improve efficacy of the preparticipation screening in identifying HCM. Pelliccia et al. did not identify any HCM by routine echocardiographic examination in 4,450 elite athletes previously cleared by ECG at preparticipation evaluation.<sup>32</sup>

A recent US study on 510 student athletes showed that the addition of routine ECG to history and physical examination improved the detection of echocardiographically documented cardiac abnormalities from 5 to 10 out of 11, thereby improving the overall sensitivity to 90.9%.<sup>33</sup> However, using traditional ECG interpretation criteria, ECG screening was associated with an increased rate of false-positive results (16.9% vs. 5.5% for screening with history and examination only) and reduced the screening specificity to 82.7%. These findings raise the need of more modern criteria for interpretation of 12-lead ECG with the aim to decrease the number of false-positive results.

### Interpretation of athlete's ECG

ECG changes usually develop in trained athletes as a consequence of the heart adaptation to sustained physical exercise ('athlete's heart').<sup>34–36</sup> There is a misconception that such physiological ECG changes overlap significantly with ECG abnormalities seen in the cardiovascular diseases which cause sudden death in the young.<sup>37–40</sup> Therefore, the ECG has been considered to be a poor screening tool in the athlete, because of its presumed high level of false-positive results.<sup>29,37</sup> The Italian screening experience disproved that ECG is a non-specific and non-cost-effective test. Among 42,386 athletes initially screened by history, physical examination, and 12-lead ECG, 3,914 (9%) had positive findings as to require further examination, 879 (2%) were diagnosed with cardiovascular disorders, and 91 (0.2%) were ultimately disqualified for potentially lethal heart diseases.<sup>18</sup> The percentage of false-positive results, i.e. athletes with a normal heart but positive screening findings, was 7% for all cardiovascular disorders and 8.8% for heart diseases at high risk of sudden death during sports (Figure 4).

Recommendations for interpretation of 12-lead ECG in the athlete have been recently provided by a Consensus Statement of the Section of Sports Cardiology of the European Association of Cardiovascular Prevention and Rehabilitation.<sup>41</sup> The document provides cardiologists and sports medical physicians with a modern approach to distinguish between physiological and potentially pathological



**Figure 4.** Results of preparticipation screening from 1982 to 2004 at the Center for Sports Medicine of Padua, Italy. Adapted from Corrado et al.<sup>36</sup>

ECG patterns. Defining what ECG changes are physiological (common and training-related ECG abnormalities) and what are pathological (uncommon and training-unrelated ECG abnormalities) (Figure 5) has significant favourable effects on the athlete's cardiovascular management including clinical diagnosis, risk stratification, and cost savings. The effect of the use of the proposed modern criteria is to substantially increase the ECG specificity (by about 70%), primarily in the important group of athletes who exhibit pure voltage criteria for left ventricular hypertrophy and early repolarization abnormalities, but with the important requisite of maintaining sensitivity for detection (or suspicion) of cardiovascular diseases at risk of SCD during sports.<sup>41,42</sup>

### Mortality reduction

A time-trend analysis of the incidence of SCD in young competitive athletes age 12–35 years in the Veneto region of Italy during 1979–2004 has provided compelling evidence that ECG screening is a lifesaving strategy.<sup>18</sup> The long-term impact of the Italian screening programme on prevention of SCD in athletes was assessed by comparing temporal trends in SCD among screened athletes and unscreened non-athletes.

Assessed intervals were pre-screening (1979–1981), early-screening (1982–1992), and late screening (1993–2004). The analysis demonstrated a sharp decline of SCD in athletes after the introduction of the nationwide screening programme in 1982. Fifty-five SCDs occurred in screened athletes (1.9 deaths per 100,000 person-years) and 265 deaths in unscreened non-athletes (0.79 deaths per 100,000 person-years). The annual incidence of SCD in athletes decreased by

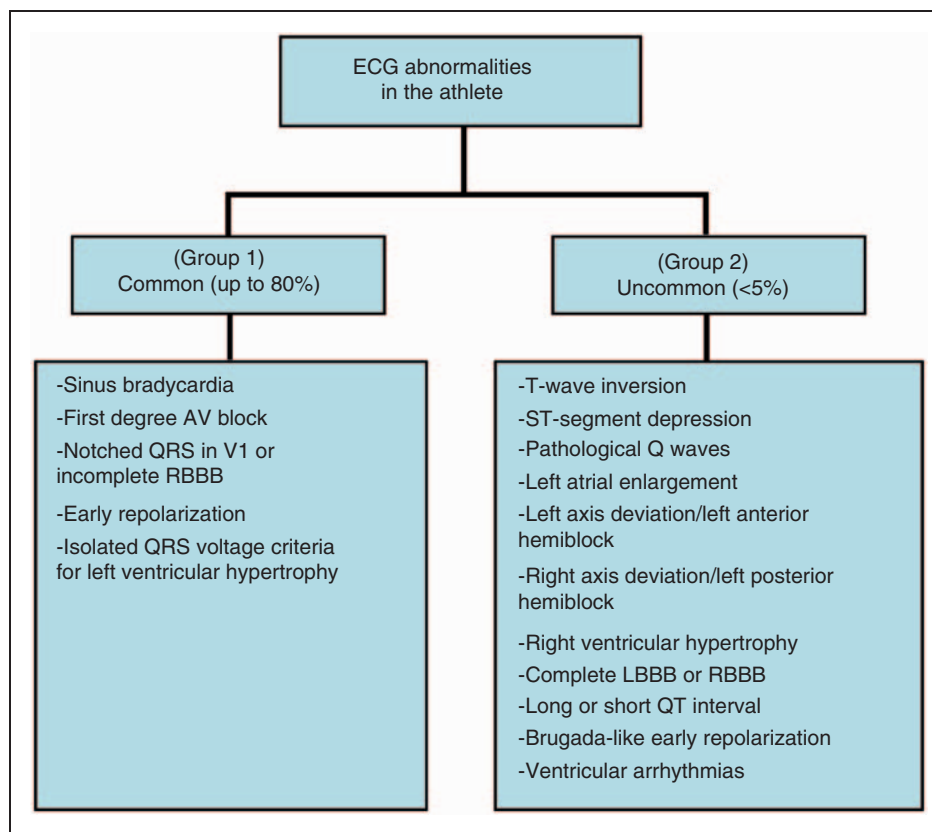
89%, from 3.6 per 100,000 person-years during the pre-screening period to 0.4 per 100,000 person-years during the late-screening period. By comparison, the incidence of SCD in the unscreened non-athletic population of the same age did not change significantly over that time (Figure 6). The decline in death rate started after mandatory screening was launched and persisted to the late screening period. Compared with the pre-screening period (1979–1981), the relative risk of SCD was 44% lower in the early-screening period (1982–1992) and 79% lower in the late-screening period (1993–2004). It is noteworthy that most of the reduced death rate was due to fewer cases of SCD from cardiomyopathies. Most of the reduction was attributable to fewer deaths from HCM and arrhythmogenic right ventricular cardiomyopathy/dysplasia. A parallel analysis of the causes of disqualifications from competitive sports at the Center for Sports Medicine in the Padua country area showed that the proportion of athletes identified and disqualified for cardiomyopathies doubled from the early- to the late-screening period. This indicates that mortality reduction was a reflection of a lower incidence of SCD from cardiomyopathies, as a result of increasing identification over time of affected athletes at preparticipation screening.

The results of the Italian study have raised an intensive debate. It has been argued that the Italian study was not a randomized trial comparing screening versus non-screening of young competitive athletes, and, thus, definitive conclusions that the reduced mortality was solely the consequence of the screening process cannot be drawn.<sup>43</sup> However, the strong cause–effect relationship between implementation of the screening programme and the substantial reduction (by 89%) of SCD in Italian athletes should remove all doubt of the efficacy of screening to identify athletes with at-risk cardiovascular conditions and its ability to save lives. The study<sup>18</sup> showed that: (1) there was a coincident timing between decline of SCD in young competitive athletes and screening implementation in Italy; (2) most of the reduced incidence of SCD was due to fewer deaths from cardiomyopathies and was accompanied by the concomitant increase of the proportion of young competitive athletes with cardiomyopathies who were identified and disqualified from competition at the Center for Sports Medicine in Padua during the same time interval; and (3) during the study period, the incidence of SCD did not change among the unscreened non-athletic population of the Veneto region of the same age range.

### Cost–benefit considerations

The long-term Italian experience indicates that screening is made feasible because of its limited costs in the





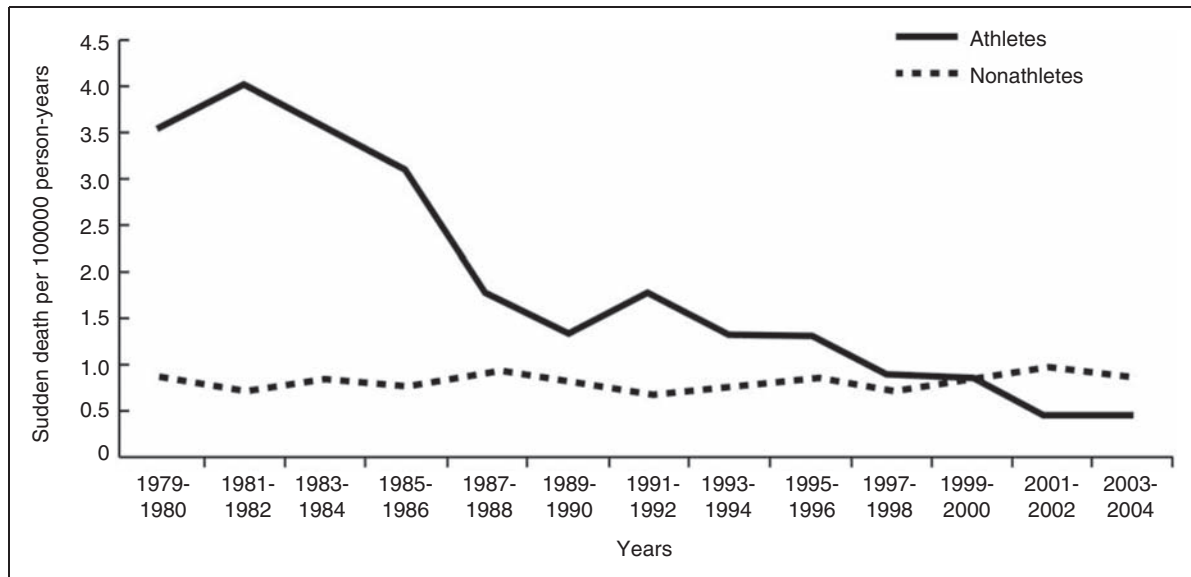
**Figure 5.** The abnormalities of athlete's electrocardiogram (ECG) are divided in two groups according to their prevalence, relation to exercise training, association with an increased cardiovascular risk, and need for further clinical investigation to confirm (or exclude) an underlying cardiovascular disease. Athlete heart is commonly (up to 80%) associated with ECG changes (Group 1) such as sinus bradycardia, first-degree atrioventricular block, and early repolarization resulting from physiological adaptation of cardiac autonomic nervous system to training, i.e. increased vagal tone and/or withdrawal of sympathetic activity. Moreover, the ECG of trained athletes often exhibits pure voltage criteria for left ventricular hypertrophy that reflect the physiological left ventricular remodelling, consisting of increased left ventricular wall thickness and chamber size. These ECG abnormalities should be clearly separated from uncommon ECG patterns (<5%) (Group 2) such as ST-segment and T-wave repolarization abnormalities, pathological Q waves, intraventricular conduction defects, ventricular pre-excitation, and long and short QT interval, which are unrelated to athlete training and may be an expression of cardiovascular disorders, notably cardiomyopathies and cardiac ion channel diseases, at risk of sudden arrhythmic death during sports. LBBB, left bundle branch block; RBBB, right bundle branch block. Adapted from Corrado et al.<sup>41</sup>

setting of a mass programme.<sup>5,28</sup> The cost of performing a preparticipation cardiac history/physical examination by qualified physicians has been estimated to be about 20 Euro per athlete and rises to about 30 Euro per athlete if a 12-lead ECG is added. The screening cost is covered by the athlete or by the athletic team, except for athletes younger than 18 years, for whom the expense is supported by the National Health System.

The cost of further evaluation of athletes with positive findings at first-line examination is smaller than expected on the basis of the presumed low specificity of athlete's ECG. The long-running Italian screening programme showed that the percentage of false-positive results (i.e., athletes with a normal heart but positive screening findings) requiring additional

testing, mainly echocardiography, did not exceed 9%, with a modest proportional impact on cost (Figure 4).<sup>18</sup>

The demographics of the screened athletic population, consisting of adolescents and young adults, as well as the genetic nature of the leading causes of SCD in this age group, profoundly impacts cost-benefit considerations.<sup>5,44</sup> Unlike older patients with coronary artery diseases or heart failure, young individuals diagnosed with a genetic disease at risk of arrhythmic cardiac arrest will survive for many decades with normal or nearly normal life expectancy, thanks to restriction from competition and prophylactic therapy against life-threatening arrhythmias.<sup>5</sup> This large amount of life-years saved favourably influences cost-effectiveness analysis of the screening process.<sup>45,46</sup>



**Figure 6.** Annual incidence rates of sudden cardiovascular death (SCD) per 100,000 person, among screened competitive athletes and unscreened non-athletes 12–35 years of age in the Veneto region of Italy, 1979–2004. During the study period (the nationwide preparticipation screening programme was launched in 1982), the annual incidence of SCD declined by 89% in screened athletes ( $p$  for trend  $<0.001$ ). In contrast, the incidence rate of SCD did not demonstrate consistent changes over time in unscreened non-athletes. Adapted from Corrado et al.<sup>18</sup>

A recent US analysis estimated that adding ECG to history and physical examination to screen athletes aged 14–22 years saves 2.06 life-years per 1,000 athletes screened at an incremental total cost of US\$89 per athlete, yielding a cost-effectiveness ratio... of US\$42,000 per life-year saved.<sup>47</sup> The addition of ECG remained cost-effective in a range of sensitivity analyses.

The benefit of preparticipation evaluation goes beyond the detection of index athletes with an inherited heart disease because it enables cascade screening of relatives and results in a multiplier effect for identifying other affected family members and saving additional lives.<sup>5,44</sup>

## Secondary prevention of sudden death

The screening ability to detect young competitive athletes with either premature coronary atherosclerosis or anomalous coronary artery is limited by the scarcity of baseline ECG signs of myocardial ischaemia.<sup>15,48–51</sup> Moreover, SCD during sports may be the result of non-penetrating chest injury (commotio cordis) which cannot be prevented by screening.<sup>27</sup> This justifies the growing efforts to implement secondary prevention strategy based on early external defibrillation of unpredictable SCA.

## Early defibrillation for SCA

The most important factor influencing survival from SCA is the access to rapid defibrillation through

on-site AED. Public access to AED has been successful in improving survival (up to 52%) from out-of-hospital cardiac arrest in many setting including casino, airlines, and airports.<sup>6–9</sup> These favourable results were obtained in individuals with a mean age  $>60$  years that most likely experienced an ischaemic cardiac arrest due to atherosclerotic coronary artery disease. Limited research is available regarding early defibrillation programmes in the athletic setting. Concerns have been raised about the effectiveness of early defibrillation of SCA occurring in the young athletic population with different causes of cardiac arrest, mostly consisting of cardiomyopathies, compared with older people suffering ventricular fibrillation from coronary artery disease.<sup>52–55</sup> Original research on the use of AED at the college athletic venue did not demonstrate a significant success in a small number of intercollegiate athletes with SCA, although an overall resuscitation rate of 54% was found in older non-students.<sup>52,53</sup> Drezner and Rogers<sup>54</sup> showed that chances for on-field successful resuscitation in intercollegiate athletes with SCA are remote. Despite a witnessed collapse, timely cardiopulmonary resuscitation, and prompt defibrillation in most cases (average time from cardiac arrest to defibrillation of 3.1 minutes), only one out of nine athletes (11%) in this study survived. However, a closer scrutiny of the emergency responses in this series, revealed that the reported response time may have been underestimated. Moreover, five out of nine athletes (55%) with SCA had an underlying hypertrophic

cardiomyopathy, which likely influenced the low survival rate. It is noteworthy that ventricular tachycardia/fibrillation may be more resistant to defibrillation (specially if non-immediate) in patients with a cardiomyopathy. Other factors that may decrease the efficacy of defibrillation in athletes include the high catecholamine levels and metabolic changes occurring during strenuous physical exercise and interacting unfavourably with the underlying structural substrate. Other studies have also found the survival rates after SCA in young athletes to be lower than expected. Maron et al.<sup>27</sup> analysed 128 cases from the USA Commotio Cordis Registry and found an overall survival rate of 16%. Drezner et al.<sup>55</sup> reported a 7-year (2000–2006) analysis showing an overall survival rate of 11% per year following exercise-related SCA in US young people (5–22 years).

### Improved survival by early defibrillation in young athletes

A more recent research by Drezner et al.<sup>10</sup> on a cohort of 1,710 US high schools with free-standing AED programme demonstrated for the first time an improved survival rate for young athletes with SCA if early defibrillation is achieved. Twenty-three of the 36 SCA victims (64%) survived to hospital discharge, including nine of 14 students-athletes and 14 of 22 older non-students. Although this was a retrospective cohort study, the consistent reported use of on-site school-based AEDs makes this the largest study on successful early defibrillation to treat SCA in the school or athletic setting. Compared with previous studies in intercollegiate athletes, the higher survival rates reported in high school athletes may be explained by the higher proportion of SCA victims treated with AED and the smaller proportion of victims with HCM. An on-site AED was used in the resuscitation of students-athletes in 11 of 14 cases (79%) cases, and HCM was only found in three of 14 (21%) cases.

### Future directions and conclusions

The long-term Italian experience with preparticipation screening of millions of athletes has demonstrated that such a population-based prevention strategy allows the successful identification of athletes affected by potentially malignant cardiovascular diseases and to substantial reduction of mortality.<sup>56</sup> Until other studies, either observational or randomized, on athletic populations of comparable size and follow-up are conducted, the existing data provide good evidence that ECG screening decreases the risk of SCD in athletes. Accordingly, preparticipation ECG screening is currently recommended by the International Olympic Committee (Lausanne Recommendations)<sup>57</sup> as well as by most

European Cardiologic Societies and Sports Medical Federations.<sup>5</sup> Recent research reports an improved survival rate for young athletes who experience a SCA if early defibrillation is delivered by on-site AED.<sup>10</sup> Although the presence of a free-standing AED at sporting events is a valuable back up for life-threatening conditions that are unrecognized by ECG screening such as atherosclerotic coronary artery disease, congenital coronary anomalies, or commotio cordis, it should not be considered neither a substitute of preparticipation evaluation nor a justification for participation in competitive sports of athletes with at-risk heart diseases. Preparticipation ECG screening and early defibrillation by AED should not be considered alternative prevention strategies; rather, they should be used synergistically in order to combine primary prevention of SCD during sports by preparticipation identification of athletes affected by potentially lethal heart diseases and secondary prevention with back-up defibrillation of unpredictable arrhythmic cardiac arrest in the athletic field.

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### Conflict of interest

There are no conflicts of interest.

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