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REVIEW ARTICLE

# Primary Prevention of Sudden Cardiac Death of the Young Athlete: The Controversy About the Screening Electrocardiogram and Its Innovative Artificial Intelligence Solution

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**Abstract** The preparticipation screening for athlete participation in sports typically entails a comprehensive medical and family history and a complete physical examination. A 12-lead electrocardiogram (ECG) can increase the likelihood of detecting cardiac diagnoses such as hypertrophic cardiomyopathy, but this diagnostic test as part of the screening process has engendered considerable controversy. The pro position is supported by argument that international screening protocols support its use, positive diagnosis has multiple benefits, history and physical examination are inadequate, primary prevention is essential, and the cost effectiveness is justified. Although the aforementioned myriad of justifications for routine ECG screening of young athletes can be persuasive, several valid contentions oppose supporting such a policy, namely, that the sudden death incidence is very (too) low, the ECG screening will be too costly, the false-positive rate is too high, resources will be allocated away from other diseases, and manpower is insufficient for its execution. Clinicians, including pediatric cardiologists, have an understandable proclivity for avoiding this prodigious national endeavor. The controversy, however, should not be focused on whether an inexpensive, noninvasive test such as an ECG should be mandated but should instead be directed at just how these tests for young athletes can be performed in the clinical imbroglio of these disease states (with variable genetic penetrance and phenotypic expression) with concomitant fiscal accountability and logistical expediency in this era of economic restraint. This monumental endeavor in any city or region requires two crucial elements well known to business scholars: implementation and execution. The eventual solution for the screening ECG dilemma requires a truly innovative and systematic approach that will liberate us from inadequate conventional solutions. Artificial intelligence, specifically the process termed "machine learning" and "neural networking," involves complex algorithms that allow computers to improve the decision-making process based on repeated input of empirical data (e.g., databases and ECGs). These elements all can be improved with a national database, evidence-based medicine, and in the near future, innovation that entails a Kurzweilian artificial intelligence infrastructure with machine learning and neural networking that will construct the ultimate clinical decision-making algorithm.

**Keywords** Screening 12-lead electrocardiogram · Sudden cardiac death · Hypertrophic cardiomyopathy

> In the next 40 years, the pace of change is going to be so astonishingly quick that you won't be able to follow it unless you enhance your own intelligence by merging with the intelligent technology we are creating…
>
> Ray Kurzweil in *Singularity is Near*, 2005

The preparticipation screening for athlete participation in sports typically entails a comprehensive medical and family history as well as a complete physical examination. A 12-lead electrocardiogram (ECG) can increase the likelihood of detecting cardiac diagnoses such as hypertrophic cardiomyopathy, but this diagnostic test as part of the screening process has engendered considerable controversy [6, 20]. Whereas there are systematic reviews for fetal ECG

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monitoring, QTc interval in medications, ECG changes that occur in strokes, and accuracy of ECG for left ventricular hypertrophy (LVH), none exist for ECG screening to detect cardiovascular disease in young athletes.

Even more controversy surrounds the myriad of other available testing such as echocardiography, computed tomographic (CT) angiography and magnetic resonance imaging (MRI), exercise testing, and genetic testing. Due to the paucity of data on the cost effectiveness of these diagnostic methods for the prevention of sudden death in the young athlete, this discussion is limited to the ECG issue. The various pro and con aspects of this controversy are presented in this report followed by a description of a reconciliatory solution in the near future.

## The Screening Electrocardiogram

### The Pro Position

Cardiac diagnoses such as hypertrophic cardiomyopathy (HCM), arrhythmogenic right ventricular cardiomyopathy/dysplasia (ARVC/D) [15], and Brugada syndrome all can lead to sudden death of young athletes. Preparticipation history and physical examination have not yielded acceptable detection rates for these diseases, but a screening 12-lead ECG can have incremental diagnostic value (Table 1). The following are supportive arguments for the use of an ECG in the preparticipation evaluation.

#### *International Screening Protocols Support Its Use*

Both the European Society of Cardiology (ESC) and the International Olympic Committee (IOC) have already endorsed routine ECG screening for young athletes around the world [8, 12]. In addition, the Italian government passed a law in 1971 to protect the athlete and then subsequently in 1982 included physical examination, 12-lead ECG, and submaximal exercise testing. This public health policy caused the annual sudden death incidence to decrease from 3.6 (1979–1981) to 0.4 (2003–2004) per 100,000 person-years among athletes, a reduction of 89% in annual incidence (Fig. 1) [7] In this experience, involving more than 42,000 athletes, 9% of the athletes required additional cardiovascular testing, and 2% were prohibited from sports participation. The limitation of this population-based observational report was the absence of both a control group and screening. Finally, mass screening of school children for cardiovascular disease was in place as early as 1973 in Japan [22]. The American Heart Association, however, has been hesitant to adopt this international public health screening strategy for its young athletes [19] although ECG screening is now mandatory in some professional organizations such as the National Basketball Association.

**Table 1** Relative usefulness of the electrocardiogram (ECG)

| ECG may be useful | ECG may not be useful |
|---|---|
| HCM | Marfan's syndrome |
| ARVC | Coronary anomaly |
| SQTS or LQTS | CPVT |
| CHB | Aortic disease |
| Brugada | Ventricular arrhythmias |
| Preexcitation WPW | |

*HCM* hypertrophic cardiomyopathy, *ARVC* arrhythmogenic right ventricular dysplasia/cardiomyopathy, *SQTS* short QT syndrome, *LQTS* long QT syndrome, *CPVT* catecholaminergic polymorphic ventricular tachycardia, *CHB* complete heart block, *WPW* Wolff-Parkinson-White syndrome

#### *Positive Diagnosis Has Multiple Benefits*

Most of the cardiac diagnoses that predispose a young adult to sudden death can be treated with antiarrhythmic medications, cardioverter-defibrillator device implantation, or cardiac surgery with good results that can yield more life-years than for older adults with the same predisposition for sudden cardiac death. In addition, diseases such as hypertrophic cardiomyopathy and long QT syndrome have inheritance patterns affecting biologic siblings in the same family. A timely diagnosis of these clinically elusive cardiac diseases can prevent the same fate for the affected parents or siblings. The additional lives saved are particularly important in the calculation of life-years saved for cost effectiveness.

#### *History and Physical Examination Are Inadequate*

The subject's history (including the family history) often is incomplete, and the physical examination also is frequently suboptimal. Combined history and physical examination, even when performed competently, do not have an acceptable detection rate for cardiac disease that may lead to sudden death. Many diseases such as hypertrophic cardiomyopathy and ARVC as well as the arrhythmogenic diseases usually are clinically silent during auscultation and often are not manifested by affected family members in the family history. One large study of more than 5,000 students in Nevada showed that the sensitivity of ECG in identifying cardiovascular disease was 70%, whereas it was only 3% for history and physical examination alone [11]. This study thus demonstrated that the ECG has an independent added value for diagnosing cardiac disease that can lead to sudden cardiac death.

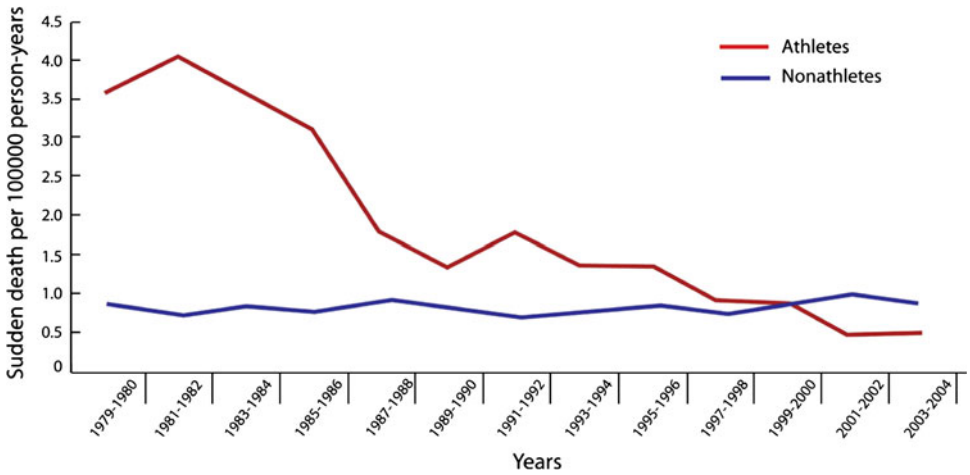


**Fig. 1** Incidence of cardiovascular death. The annual incidence in the Veneto region of Italy decreased 89% from 1979 to 2004 among screened athletes versus no change among nonscreened nonathletes during the same period. Note that the annual incidence of sudden cardiac death for screened athletes fell below that for nonscreened nonathletes by 1999–2000. From Corrado et al. [9]. Copyright © 2006 by the American Medical Association

*Primary Prevention Is Essential*

Primary prevention focuses on timely diagnosis instead of relying on resuscitative efforts considered secondary prevention. This is true especially for hypertrophic cardiomyopathy, which is the most common cause of sudden cardiac death of young athletes, with a 1 in 500 incidence in the general population, and the first event often is fatal [16]. Resuscitation of individuals with hypertrophic cardiomyopathy does not have a high success rate even with competent emergency resuscitation. Therefore, hypertrophic cardiomyopathy is best treated by primary prevention during screening. Other diseases such as ARVC/D and Brugada and long QTc syndromes all have characteristic ECG findings that can confirm their diagnosis. The various diseases that lead to sudden cardiac death thus create the need for a multidimensional set of solutions that involve primary and secondary prevention measures. Commotio cordis, a ventricular fibrillation resulting from a sudden impact on the chest, is a cardiac death diagnosis that obviously is not amenable to screening as a primary prevention because it is an accidental hit, although appropriate protective gear should be implemented.

*Cost Effectiveness Is Justified*

The screening ECG can be performed with adequate cost effectiveness. Studies have shown it to have a relatively justifiable cost effectiveness compared with other medical conditions. In Orange County with its high school athlete population of 75,000 and with an ECG cost of about $25, the estimated total cost would be $1.875 million. If even one life is saved (that of either the high school athlete screened or a family member) and an additional 50 years of life is expected, then each quality-adjusted life-year (QALY) is calculated to be $1.875 million, with 50 life years equal to $37,500 per QALY. This amount is relatively low compared with the $50,000 per QALY cost of renal dialysis.

The Con Position

Although the aforementioned myriad of justifications for routine ECG screening of young athletes can be persuasive, several valid contentions oppose supporting such a policy.

*The Sudden Death Incidence Is Very (Too) Low*

The overall incidence of sudden death among young athletes is thought to be low, at 0.8 to 6.2 per 100,000, with sudden death claiming the lives of 1,000 to 7,000 children and adolescents each year in the United States [3]. This probably inaccurate perception is mainly due to lack of a national registry, thereby resulting in the "tip of the iceberg" epidemiologic phenomenon, in which the known disease burden is not reflective of all the disease burden. In addition, near misses occur that are not reported in the media, so these cases are lost in the medical database. Finally, it should be noted that the incidence of hypertrophic cardiomyopathy is 1 in 500, with a sudden death incidence of 2% or higher among affected children [17].

*The ECG Screening Will Be Too Costly*

At $25 per ECG and with an estimated 1 to 2 million new high school athletes in the United States per annum, a total of $25–50 million will be spent for a one-time screening, which may be justified in the context of our national cost of health care at nearly $2 trillion (or about 0.01% of the total). With cost effectiveness defined in the United States as a QALY of $50,000 or less, if 500 life-years are saved, then the $25 million cost can be justified. However, ECG

may be the most cost effective in the list of interventions for sudden death prevention (Table 2).

*The False-Positive Rate Is Too High*

The sensitivity and specificity of any diagnostic test depends not only on the quality of the test (which can be improved) but also on the definition of what constitutes an abnormal test. Although the 12-lead ECG results are abnormal for up to 95% of individuals with hypertrophic cardiomyopathy [18], the current established criteria for LVH may be outdated and may need to be modified further to increase its positive predictive value for hypertrophic cardiomyopathy compared with left ventricular remodeling associated with athletes. The accuracy profile can be improved easily with a national cumulative ECG database and ongoing Bayesian statistical analysis with receiver operating characteristic curves to maximize positive and negative predictive rates based on the individuals who had positive diagnoses.

*Resources Will Be Allocated Away From Other Diseases*

According to this objection, mandatory ECG screening would result in an unfair resource allocation, with funds directed away from more common diseases such as diabetes, obesity, and hypertension. One ethical justification is that these sudden death cardiac diagnoses usually are congenital and not the result of poor health habits.

*Lack of Sufficient Manpower to Execute the ECG*

The manpower needs for ECG reading and interpretation would be 500 ECGs per board-certified pediatric cardiologist in the United States. The average seasoned pediatric cardiologist should be able to interpret an ECG in 60 s or less, so this would require fewer than 20 h of total time per annum. In the future, qualified pediatric sports medicine specialists also can contribute to the qualified manpower needs to meet this task.

**Table 2** Cost per quality-adjusted Life Years (QALY) of interventions

| Disease or intervention | Cost per QALY ($) | ($) |
|---|---|---|
| ECG screening | 8,800–44,000 | 89 per athlete |
| ICD | 34,000–70,000 | |
| CPR | 75,000 | |
| AED | 55,000–162,000 | |
| History and physical exam | >84,000 | |
| Renal dialysis | 50,000 | |

*ECG* electrocardiogram, *ICD* implantable cardioverter-defibrillator, *CPR* cardiopulmonary resuscitation, *AED* automated external defibrillator

Adapted from Wheeler et al. [23]

Implementation and Execution

Clinicians, including pediatric cardiologists, have an understandable proclivity for avoiding the prodigious national ECG screening endeavor with unclear benefit. The controversy, however, should not be focused on whether an inexpensive noninvasive test such as an ECG should be mandated but should instead be directed at just how these tests can be performed for young athletes in the context of the clinical imbroglio of these disease states (with variable genetic penetrance and phenotypic expression) with concomitant fiscal accountability and logistical expediency in this era of economic restraint. In addition, the eventual ECG screening should be extended to all high school students (an estimated 3 million per annum) [10] and not simply to the athletes. This monumental endeavor in any city or region would require two crucial elements well known to business scholars: implementation and execution.

*Implementation*

Change is at times difficult to implement even if the logistical and theoretical concerns are successfully overcome. In Kotter's [13] model for implementing change, small changes involving a few schools are preferred before a broad-scale implementation across large regions. In addition, a sense of urgency shared by a powerful and committed coalition is essential. For example, a few model schools were initially selected to be part of the Orange County ECG screening initiative. Buy-in from not merely the parents but also the school leadership as well as the athletic directors was essential to ensure the success of this screening process.

*Execution*

The other component of the success dyad for project management is execution [5]. Most clinicians and lay personnel may not fully appreciate the impact from proper execution of a major project and often wonder why these projects fail despite genuine enthusiasm, collective expertise, and a grand vision. The treatise on execution by Larry Bossidy and the legendary business advisor Ram Charan emphasizes the culture of execution in terms of continual prioritization and accountability in an organized group. In the Orange County effort to reduce sudden death of young athletes, the many interfaces of the ECG screening process were assigned separate working groups, each with a leader accountable to the entire coalition.

## The Future Solution: Use of Artificial Intelligence

The eventual solution for the screening ECG dilemma requires a truly innovative and systematic approach that will liberate us from inadequate conventional solutions. Artificial intelligence, specifically the process termed "machine learning" and "neural networking," involves complex algorithms that will allow computers to improve the decision-making process based on repeated input of empirical data (such as databases) [1].

A raw form of this artificial intelligence usage was aptly demonstrated by the IBM *Big Blue* chess-playing feat and by an even more sophisticated showing during the recent *Jeopardy*! contest, during which the computer named Watson defeated its human counterparts. Additional techniques such as data mining, multiobjective optimization, probabilistic modeling, and pattern recognition further increase the capability of decision making. In short, artificial intelligence is a computational process that can be modeled after the brain itself but with an even more robust database and accurate pattern recognition.

Although the use of artificial intelligence is in its nascent stages in clinical medicine, the preparticipation evaluation for the athlete is well situated for its exploration [2, 21]. With a national registry database as an initial step, artificial intelligence can be empowered and eventually can surpass seasoned cardiologists' capabilities in making the appropriate clinical decisions and diagnoses while concomitantly considering variables and nuances such as gender, race, and type of sports. Individuals with positive diagnoses for diseases such as HCM and ARVC can provide valuable data that enable the computer and its artificial intelligence to be "smarter" at interpreting ECGs via machine learning. For example, while cardiologists are interpreting ECGs with traditional LVH criteria, artificial intelligence can be used to incorporate multiple LVH criteria as well as additional nuances such as T wave inversions and other ST segment abnormalities.

The computer will eventually be very "smart" in recognizing the myriad of ECG "signatures" for HCM (vs athlete's heart). In addition, the computer will eventually be able to mass screen the entire U.S. population in a very short time. This will be necessary given that some diseases such as long QTc syndrome may require serial ECGs for definitive diagnosis and others such as ARVC/D also may need multiple ECGs due to their presentation at an older age.

Computers with artificial intelligence thus have an insurmountable advantage of continually evolving its decision-making process. The most ideal solution may be collaboration between the smart computer with its machine learning capability and the astute clinician with human intuition (Fig. 2). This concept is akin to what the venerable futurist Ray Kurzweil has previously described as "singularity"—a future period in which technological change will be so rapid and its impact so profound that every aspect of human life will be irreversibly transformed [14].

## Conclusion

The 12-lead ECG, albeit controversial, can be both cost effective and acceptable in its sensitivity and specificity as well as its positive and negative predictive value profiles. The question is not whether the screening should be performed but how this endeavor can be carried out using strategic vision and exemplary execution with cost

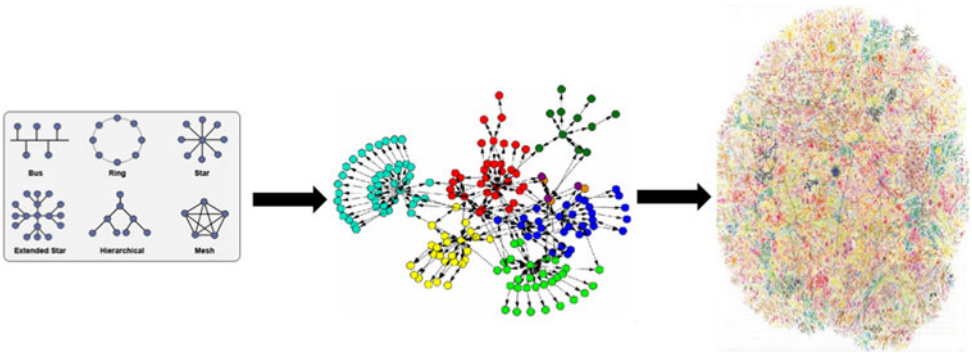


**Fig. 2** Use of artificial intelligence. Researchers from Boston Children's Hospital and Harvard Medical School used machine learning algorithms to delineate the complexity profile of resting electroencephalographic (EEG) signals for a group of infants at risk for autism based on family history. The degree of randomness in the signal, called "modified multiscale entropy," enabled the researchers to predict autism accurately for infants before clinical manifestations of the disease. This is a landmark breakthrough in the use of information theoretic analysis of EEG data to predict neurologic disease. A similar model can be applied to ECG screening for high-risk cardiac diseases in older children and young adults. From Bosl et al. [4]

effectiveness and fiscal accountability. These elements all can be improved with a national database, evidence-based medicine, and in the near future, innovation involving a Kurzweilian artificial intelligence infrastructure with machine learning and neural networking that will construct the ultimate clinical decision-making algorithm.

Cardiologists should consider ECG screening not solely as a clinical scientist but also as a guardian and parent while they answer the clarion call to reduce sudden death among young athletes. It is of paramount importance for us to develop patience and resolve to achieve universal ECG screening for our young athletes, especially because the current status quo is unacceptable. This quality and safety paradigm shift can perhaps even evolve into a separate clinical discipline (adolescent sports cardiology) with its own specialized training in the near future. With increasingly limited resources and a lack of sufficient manpower, the sudden death prevention clinical arena can become the perfect crucible for quality and safety concerns, not only for our highest-risk subpopulation, the athletes, but also for all of us.

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