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Original research

Diagnostic yield and cost analysis of electrocardiographic screening in Swiss paediatric athletes

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ABSTRACT

Objectives: Athletes performing sports on high level are at increased risk for sudden cardiac death. This includes paediatric athletes, even though data on screening strategies in this age group remain scarce. This study aimed to assess electrocardiogram interpretation criteria in paediatric athletes and to evaluate the cost of screening.
Methods: National, multicentre, retrospective, observational study on 891 athletes of paediatric age (<18 years) evaluated by history, physical examination and 12-lead electrocardiogram. The primary outcome measure was abnormal electrocardiogram findings according to the International Recommendations for Electrographic Interpretation in Athletes. The secondary outcome measure was cost of screening.
Results: 19 athletes (2.1%) presented abnormal electrocardiogram findings requiring further investigations, mainly abnormal T-wave inversion. These 19 athletes were predominantly males, performing endurance sports with a mean volume of 10 weekly hours for a mean duration of 6 years of training. Further investigations did not identify any relevant pathology. All athletes were cleared for competition with regular follow-up. Total costs of the screening were 108,860 USD (122 USD per athlete).
Conclusions: Our study using the International Recommendations for Electrographic Interpretation in Athletes identified a low count of abnormal findings in paediatric athletes, yet raising substantially the cost of screening. Hence, the utility of electrocardiogram-inclusive screening of paediatric athletes remains to be elucidated by longitudinal data.

Practical implications

- Of the 891 paediatric athletes (mean age 14 years), 3.8% had abnormal findings, identified by history, physical examination and 12-lead electrocardiogram (ECG).
- 2.1% presented abnormal ECG findings according to the International Recommendations for Electrographic Interpretation in Athletes, resulting in a low rate of subsequent downstream investigations.
- Subsequent assessment failed to identify any pathology questioning the utility of general ECG screening in the paediatric age range.
- The cost of screening was 122 USD per athlete.

1. Introduction

Pre-participation screening for athletes continues to be a matter of debate. Often cited arguments against routine electrocardiogram

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(ECG) screening include lack of definitive outcome data, imperfect sensitivity and specificity, cost, difficulties with quality control and ethical issues.[1] ECG criteria have been revised several times with the last version being published in 2017.[2] They now achieve high values of specificity and sensitivity in adults.[3] However data on paediatric athletes are sparse. A study from the Middle East cited a false-positive rate of 6.8%.[4]

During childhood and adolescence, the heart is continuously developing. Major steps in cardiovascular growth and development occur during puberty, resulting in slightly less pronounced cardiac adaptations to exercise in pre-pubertal athletes.[5,6] It therefore remains to elucidate whether diagnostic ECG criteria targeting adult athletes can be applied to the paediatric population. A meta-analysis demonstrated that paediatric athletes gather more training related and training unrelated ECG changes than non-athletes.[7] These modifications are mainly influenced by chronological age and ethnicity with more changes in athletes older than 14 years and of Afro-Caribbean ethnicity.[7] Male sex impacts on the prevalence of both, training-related and abnormal ECG changes in athletes of paediatric and adult age.[8,9]

Hence, this study aimed to determine the performance of the International Recommendations for Electrographic Interpretation in Athletes[2] in a paediatric population and to investigate the financial implications of this screening program. We hypothesised that due to the phenotypical emergence of SCD related disease with age, the rate of abnormal electrocardiographic findings in paediatric athletes would be lower compared to adult data with subsequently higher costs per finding.

2. Methods

We enrolled 891 athletes between 2011 and 2017 undergoing single, first-time preparticipation cardiovascular screening from six medical centres in Switzerland: Lausanne, Bern (in collaboration with the Swiss Federal Institute of Sports Magglingen), Geneva, Zurich, Bellinzona and Lugano. Inclusion criteria included age less than 18 years, sport participation at an international, national or regional level, and minimal training frequency of 6 h per week. We excluded individuals with known heart disease. The Swiss Ethics Committee approved the study protocol (Project No 2018-00121). Given the fact that the participants were included retrospectively, the Swiss Ethics Committee declared that no retroactive consent of the single participants was required.

The following parameters were collected: age, sex, ethnicity, weight, height, body mass index (BMI), body fat mass, sport type, training volume in weekly hours, duration in years of training, level of performance, sports category according to the Mitchell criteria,[10] personal and family medical history, physical examination, resting heart rate and resting blood pressure.

Medical history consisted of screening for cardiovascular symptoms such as chest pain, palpitation, dyspnoea and prior syncope. Family history included structural heart disease, primary arrhythmia and sudden cardiac death (SCD). Physical examination aimed at the detection of Marfanoid features, arterial hypertension, cardiac murmurs, and aortic coarctation. Arterial hypertension was defined as proposed by the American Academy of Pediatrics.[11]

A 12-lead ECG was performed and analysed by the treating sports physician and/or cardiologist. All ECGs were reviewed in each centre by an experienced sports cardiologist. ECG analysis aimed to differentiate normal ECG adaptations from patterns suggestive of disease and was retrospectively analysed according to the International Recommendations for Electrocardiographic Interpretation in Athletes.[2]

Athletes with abnormal medical history, physical examination or ECG findings (two borderline or one abnormal) were subject to further investigations at the discretion of the treating physician, including transthoracic echocardiography, 24 h-Holter monitoring, maximal exercise stress testing, cardiac magnetic resonance imaging (MRI), 24 h blood pressure monitoring or ECG with pharmacological exposure. In cases where criteria for borderline or abnormal ECG findings were equivocal, the ECG was repeated on a different appointment. Further cardiology work-up was only performed if the initial finding could be reproduced. Even though ECG analysis by the time of medical consultation relied on the use of contemporary ECG criteria, retrospective analysis by the International Recommendations for Electrographic Interpretation in Athletes in our study did not show any case of false-positive ECG findings based on less specific prior criteria, requiring unnecessary secondary examinations. In each study centre, the need for follow-up testing was determined by the consulting physicians and was not standardised. Exclusion from sports participation was based on additional examinations and shared decision making involving the treating physician, a cardiologist and/or a paediatric cardiologist.

Costs were calculated in Swiss francs according to the data of Menafoglio[12] and are depicted in USD (conversion rate 1 US dollar = 0.95 Swiss franc) in Table 1.

Values are presented as either percentage or median with interquartile range [IQR]. In order to test the influence of quantitative variables on the percentage of ECG abnormalities, we used one-way ANOVA followed by Bonferroni multiple comparison procedure; or Kruskal-Wallis test followed by Dunn's test with Bonferroni procedure, if normality assumptions were not verified. For the influence of qualitative variable, as we expected small numbers of ECG abnormalities in our cohort, we used the Fisher's exact test for 2×2 tables and the Pearson $\chi 2$ test otherwise. Values of $p < 0.05$ were considered statistically significant. All statistical analysis was performed using NCSS (Number Cruncher Statistical System. 2013: Atlanta).

3. Results

We included 891 athletes with a mean age of 14.8 ± 1.6 (SD) years (range 8 to 17). Approximately two-thirds of the cohort were males (580; 65%) and nearly all were of Caucasian ethnicity (864; 97%). The 45 different sports represented all nine categories of the Mitchell classification.[10] High-dynamic moderate-static class sports (IIC) (366; 41%), and high-dynamic low-static class sports (IC) (194; 22%) accounted for the majority of athletes. Football was the most common single sport represented (158; 18%). The athletes performed on international (22%), national (34%) and regional (44%) level of competition. Training time was 10.8 ± 5.3 (SD) h per week and training duration was 6.5 ± 2.7 (SD) years.

History revealed cardiac symptoms in 15 athletes (1.7%) as follows at rest and/or with exertion: chest pain (n = 7), palpitation (n = 3), prior syncope (n = 3) and dyspnoea (n = 2). Family history of first-degree relatives was positive in 15 athletes (1.7%), thereof premature cardiac death (n = 1), dilated cardiomyopathy (n = 1) and Brugada syndrome (n = 1). Physical examination detected abnormalities suggestive of underlying cardiovascular disease in 19 athletes (2.1%) with the following findings: cardiac murmur (n = 10), arterial hypertension (n = 8), and irregular

Table 1
Costs for screening methods in US dollars, according to Menafoglio.[12]

Basic screening	
Medical history	35.05
Physical examination	44.79
12-Leads ECG	28.37
Total	108.21
Secondary investigations	
Transthoracic echocardiography	328.51
24 h-Holter monitoring	205.63
Exercise testing	165.21
Cardiac MRI	742.21
24 h-blood pressure monitoring	92.42
ECG with pharmacological exposure	163.95

ECG, electrocardiogram; MRI, magnetic resonance imaging.

Table 2
Detailed cohort characteristics of athletes with abnormal ECG findings.

	Age	Sex	Ethnicity	ECG criteria	BMI	P BMI	Weekly hours	Years of training	Sport type	Classification of sports[39]	Further investigations	Follow-up
1	16	Male	Caucasian	TWI, STD	21.8	50–75	11	8	Football	Mixed	Echo, Ex, H, MRI	Not available
2	12	Female	Caucasian	TWI	16.0	10	6	7	Football	Mixed	Echo	1 year (ECG): normal
3	14	Male	Caucasian	TWI	17.7	10–25	6	1	Football	Mixed	Echo, Ex	Not available
4	16	Male	Caucasian	TWI	24.8	75–90	10	5	Running	Endurance	Echo, Ex, H, MRI	Not available
5	16	Male	Caucasian	TWI	19.8	25–50	11	4	Judo	Power	Echo, Ex, H	7 years (ECG): normal
6	16	Male	Caucasian	TWI	22.9	75	12	7	Ice Hockey	Mixed	Echo	9 years (ECG, Echo, Ex, H, MRI): LVWT max. 14 mm
7	12	Female	Caucasian	TWI	18.4	50–75	12	8	Karate	Power	Echo	4 years (ECG): normal
8	16	Male	Caucasian	TWI	19.0	10–25	12	5	Triathlon	Endurance	Echo, MRI	2 years (ECG): normal
9	13	Female	Caucasian	PQW	21.7	75–90	15	3	Volleyball	Mixed	Follow-up ECG	Not available
10	14	Male	Caucasian	PQW	16.6	3–10	8	6	Football	Mixed	Follow-up ECG	3 years (ECG): normal
11	13	Male	Caucasian	PQW	20.7	50–75	9	3	Alpine skiing	Power	Follow-up ECG	2 years (ECG): normal
12	14	Female	Caucasian	PQT	21.9	75–90	7	5	Cross-country skiing	Endurance	Follow-up ECG	3 years (ECG): normal
13	14	Male	Caucasian	≥2 PVCs	18.7	25–50	6	1	Fencing	Mixed	Echo, Ex, H	1 year (ECG, Ex): normal
14	14	Male	Caucasian	≥2 PVCs	18.7	25–50	6	6	Football	Mixed	Echo, Ex, H	8 years (ECG, Echo, Ex, H): normal
15	16	Male	Asian	≥2 PVCs	18.4	10–25	15	8	Badminton	Mixed	Echo, H	4 years (ECG; Echo, Ex, H, MRI, implantable cardiac monitor, EP study): AVNRT
16	13	Male	Caucasian	≥2 PVCs	18.5	25–50	8	6	Cross-country skiing	Endurance	Echo, Ex, H	3 years (ECG, H): normal
17	10	Female	Caucasian	≥2 PVCs	19.4	75–90	24	8	Gymnastics	Mixed	Follow-up ECG	5 years (ECG): normal
18	15	Male	Caucasian	RAD, RBBB	19.1	25–50	13	9	Football	Mixed	Follow-up ECG	2 years (ECG): normal
19	16	Male	Caucasian	RAD, RBBB	20.5	25–50	12	8	Football	Mixed	Follow-up ECG	1 year (ECG): normal

Age in [years]. AVNRT, atrio-ventricular nodal re-entry tachycardia; BMI, body mass index; Echo, transthoracic echocardiography; EP study, electrophysiological study; Ex, exercise stress test; H, Holter ECG; LVWT, Left ventricular wall thickness; MRI = cardiac magnetic resonance imaging; P, percentile (WHO); PQT, prolonged QT interval; PQW, pathologic Q-waves; PVC, premature ventricular contractions; RAD, right axis deviation: RBBB, right bundle branch block; STD, ST-segment depression; TWI, T-wave inversion (excluding juvenile pattern).

cardiac rhythm (n = 1). One athlete had abnormal history and physical examination. Three athletes had abnormal history and family history. Four athletes had abnormal family history and physical examination. Overall, there were 36 athletes identified without ECG.

Of the 891 athletes, 672 (75.4%) demonstrated normal findings on standard 12-lead ECG according to the International Recommendations for Electrographic Interpretation in Athletes, thereof 12.8% a juvenile pattern, i.e., T-wave inversion in leads V1–V3 under the age of 16 years. Thirty-eight (4.3%) fulfilled borderline criteria. Only two (0.2%) of them had two borderline criteria requiring further investigations. 17 (2.1%) athletes presented at least one abnormal finding as detailed below. Of the 36 athletes with abnormal history and physical examination, three had one borderline finding and two had an abnormal ECG finding. 21 of the 36 athletes with abnormal history and physical examination were not further investigated, since the abnormal findings were not suggesting severe disease. Overall, 34 (3.8%) athletes were deemed to require post-screening investigation after integration of data from medical history, physical examination, and 12-lead ECG.

The 2 athletes with two borderline findings presented both right axis deviation and complete right bundle branch block (RBBB). Of the 17 athletes with abnormal findings, 8 (47%) had isolated T wave inversion while only 1 had two abnormal criteria: T wave inversion and ST segment depression. The remaining abnormal findings were distributed as follows: premature ventricular contractions (n = 5; 29%), pathologic Q waves (n = 3; 18%) and prolonged QT interval (n = 1; 6%) (Table 2).

All but one of the athletes with abnormal findings on ECG (two borderline or one abnormal) were of Caucasian ethnicity. Thirteen of the 19 athletes with abnormal ECG were males (68%) resulting in a similar male–female ratio compared to the whole cohort (65% male). The concerned athletes performed in 12 different types of sports. The predominant type of sport was football with 37% and thus twice more represented than in the whole cohort (18%).

When comparing athletes without ECG findings, training-related ECG, one borderline finding and abnormal ECG (including individuals with 2 borderline findings), the only differences were found for training volume and heart rate of athletes without ECG findings compared to training-related ECG (Table 3). When separating by age, we used a cut-off of 15 years to determine post-pubertal athletes, since Tanner stages were not available retrospectively. Athletes older than 15 years presented greater training volume (10.9 ± 5.3 vs 10.5 ± 5.4, $p < 0.05$) and duration of training (7.1 ± 2.7 vs 5.6 ± 2.5, $p < 0.05$).

Among the athletes with abnormal personal or family history and/or physical examination but with normal ECG, further examinations were performed in 15 athletes including transthoracic echocardiography

Table 3
Demographic, anthropometric, sport-related and clinical data of athletes classified by ECG findings according to the International Recommendations for Electrographic Interpretation in Athletes.[2] Note that two borderline findings were defined as abnormal ECG.

	No ECG findings (n = 164)	Training-related ECG (n = 672)	1 borderline ECG finding (n = 36)	Abnormal ECG (n = 19)
Age [years]	14.6 ± 1.7	14.8 ± 1.5	14.4 ± 1.9	14.6 ± 1.8
Weight [kg]	58.0 ± 13.1	58.5 ± 12.3	59.3 ± 15.2	55.9 ± 11.2
Height [cm]	167.1 ± 11.6	168.3 ± 11.0	170.7 ± 13.6	167.9 ± 11.3
BMI [kg/m^2]	20.5 ± 2.7	20.4 ± 2.5	19.9 ± 2.8	19.6 ± 2.1
Body fat [%]	19.0 ± 6.3	17.2 ± 6.5	18.2 ± 6.0	16.7 ± 5.0
Weekly hours	9.9 ± 5.1*	11.1 ± 5.5*	9.7 ± 3.1	10.5 ± 4.3
Years of training	6.3 ± 2.9	6.6 ± 2.6	5.9 ± 2.7	5.9 ± 2.3
HR [bpm]	70.0 ± 8.0*	63.5 ± 10.1*	65.6 ± 10.4	64.4 ± 10.3
BP syst [mm Hg]	114.7 ± 11.0	116.6 ± 9.7	116.9 ± 11.8	115.0 ± 10.0
BP dias [mm Hg]	66.4 ± 8.5	65.1 ± 8.5	65.9 ± 10.2	65.9 ± 7.7
BP mean [mm Hg]	82.8 ± 8.1	83.5 ± 8.7	86.6 ± 14.1	89.5 ± 13.1

BMI, body mass index; BP, blood pressure; dias, diastolic; syst, systolic; HR, heart rate.
* Statistically significant ($p < 0.05$) between subgroups.

(n = 7), exercise testing (n = 6), 24 h blood pressure monitoring (n = 2), ECG with ajmaline challenge (n = 1), and 24 h-Holter monitoring (n = 1). No pathology was detected in any of these 15 athletes and all were cleared for sports participation.

The 19 athletes with abnormal ECG findings underwent transthoracic echocardiography (n = 12), 24 h-Holter (n = 7), exercise testing (n = 7) and cardiac MRI (n = 3). Athlete 8 (Table 2) with pathologic T wave inversion was found to have medio-mural apical fibrosis of the left ventricle on MRI which was considered an unspecific finding but could be suggestive of former myocarditis in an atypical localisation. Athlete 3 with pathologic T wave inversion had a mild posterior leaflet mitral prolapse with minimal insufficiency. Among the remaining 6 athletes with pathologic T wave inversion, including the one with additional ST segment depression, no diagnosis was established after comprehensive testing. Among the 5 athletes with premature ventricular contractions, no underlying cardiovascular disease was found. The remaining findings such as pathologic Q waves (n = 3), prolonged QT interval (n = 1), and two borderline ECG criteria (n = 2) could not be reproduced on follow-up ECG and long QT syndrome was ruled out. Consequently, no athletes in our cohort were excluded from competitive sport participation.

Follow-up data for athletes with abnormal history, physical examination and/or ECG were available for 24/34 (71%) of affected individuals with a mean duration of 3.8 years. Athlete 6 has been followed until now and recently had a wall thickness of maximally 14 mm. He was allowed to continue his sport with annual follow-up. Athlete 15 has been investigated for four years due to ventricular extrasystoles and a positive family history (premature SCD of his father). A recent electrophysiological study was performed because of palpitations and wide complex tachycardia on implantable cardiac monitor. It showed atrioventricular nodal re-entrant tachycardia with aberrant conduction enabling him to continue sport.

Costs for basic screening of the 891 athletes amounted to 96,416 USD (108 USD per athlete): history-taking 31,232 USD, clinical examination 39,907 USD, and 12-lead ECG 25,276 USD. Further examinations because of ECG findings increased the costs to 105,180 USD (118 USD per athlete). Further examinations because of abnormal history and physical examination amounted to 4157 USD (115 USD per athlete) (Fig. 1). Thus, the total costs of the program were 109,025 USD (122 USD per athlete). Screening confined to history and physical examination would have decreased the costs to 75,297 USD (85 USD per athlete) for basic screening excluding 12-lead ECG and further investigations.

The cost of post-screening investigations for the 19 athletes with ECG included: transthoracic echocardiography = 3942 USD, exercise testing = 1156 USD, 24 h-Holter monitoring = 1439 USD, and cardiac MRI = 2227 USD. This represented 10 USD per athlete or 461 USD per athlete with abnormal ECG. Since there were no diagnoses associated with sudden cardiac death (SCD), costs per finding could not be calculated.

4. Discussion

This study was designed to determine the diagnostic yield and financial implications of ECG-inclusive screening among paediatric competitive Swiss athletes. Key findings can be summarised as follows: First, the rate of abnormal ECG findings based upon the International Recommendations for Electrographic Interpretation in Athletes requiring further investigations was low amounting to 2.1%. Second, none of the further evaluated athletes were diagnosed with an SCD related pathology. Thus, all athletes were cleared for competition. Third, ECG inclusion raised the costs per athlete by more than 30% compared to a screening program based on history and physical examination.

The guidelines of the Swiss Society of Sports Medicine for athletes screening were published first in 1998 and reinforced in 2010.[13] They target athletes above 14 years and suggest preparticipation screening every 1–2 years including ECG, based on the fact that ECG was shown

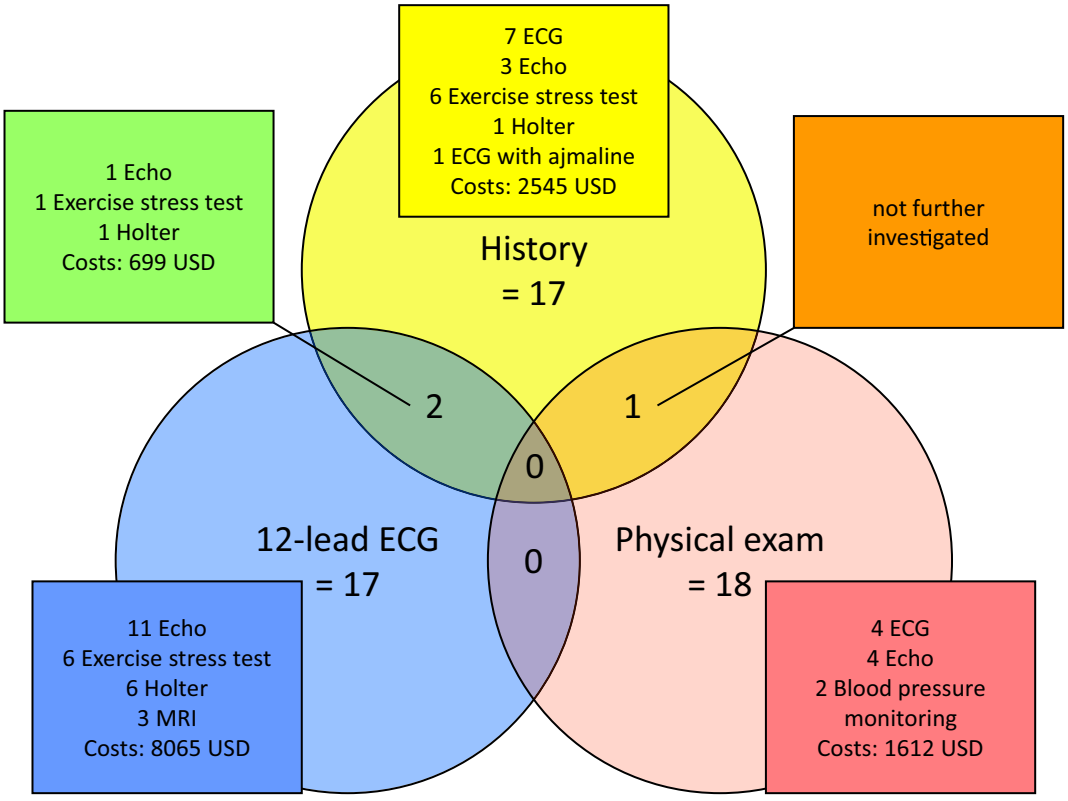

Fig. 1. Abnormal findings identified by history, physical examination and/or 12-lead ECG with cost calculation.
Echo, transthoracic echocardiography; Ex, exercise stress test; H, Holter ECG; MRI = cardiac magnetic resonance imaging.

to detect conditions accounting for SCD in athletes in approximately two thirds of all cases.[14]

History and physical examination remain the cornerstones of athlete screening. Nevertheless, at least 60% of conditions predisposing to SCD in young athletes are detected on ECG.[15,16] ECG screening is superior to history and physical examination in the detection of SCD-associated disease.[17] In contrast, the global incidence of sports-related SCD in athletes is low.[18] This implies a risk for inappropriate restriction of athletes with false-positive results.[19] The Swiss guidelines currently follow the European recommendations that include routine screening with ECG.[20] The recently published Canadian statement is an intermediary approach that argues against routine ECG and suggests a tiered approach in evaluating athletes.[19] It limits ECG to athletes with positive findings in history and physical examination.[19] Consequently, costs are reduced at the price of a higher rate of missed SCD related diseases.

If ECG screening is still a matter of debate in the adult population, there is no established strategy for children yet. With only 2.1% of abnormal ECG in our cohort we can conclude that the false positive rate is low and similar to older athletes.[21,22] In addition, the fact that non-invasive additional investigations allowed to clear all athletes is encouraging. Data from other studies on paediatric athletes confirm the trend of a low rate of abnormal findings in athletes under 18 years: Calo demonstrated in Italian male paediatric football players 2.9% of abnormal ECG.[23] In football players aged 15 to 17 years from the UK, the rate of SCD related cardiac disorders was 0.38%.[24] This suggests that adult diagnostic criteria can be used in children without an unacceptable amount of false positive results. However, a study on paediatric athletes from the Middle East identified 8.2% of abnormal findings by ECG.[4] Of note, this study was performed in athletes from different ethnic backgrounds who are known to exhibit more abnormal ECG findings.[25] Given the lack of generalised follow-up in our cohort and the absence of universal imaging to exclude or detect occult disease we cannot comment on sensitivity and false negative rate. Nevertheless, the International Recommendations for Electrographic Interpretation in Athletes achieved high accuracy rates in adolescent football players.[26]

None of the 891 athletes screened had a diagnosis associated with SCD. It therefore raises the question whether ECG screening is efficient in the paediatric population. The heart continues to develop during growth and ECG reflects dynamic changes during this period. Structural heart diseases are conditions that develop with age. Hypertrophic cardiomyopathy (HCM) and arrhythmogenic right ventricular cardiomyopathy (ARVC) are the most frequent SCD related structural diseases.[27] The genetic predisposition to develop these conditions is present at birth, but the morphological and electrical manifestation are often absent in children and young adults. This may require regular ECG in the screening strategy of this population. The best example for the emergence of cardiomyopathies with age is shown by athlete number 6 from Table 2. Based on his initially abnormal ECG, it took nine years of yearly follow-up to identify a left ventricular wall thickness (14 mm) which raised the suspicion of HCM, yet not confirmed. Of note, serial screening proved to increase the diagnostic yield of SCD related conditions by factor three compared to single screening.[28]

It is worth to mention that the incidence of inherited heart disease varies between different countries. In the Italian study that had presented a decline of 89% in SCD after implementation of a mandatory ECG-inclusive screening for athletes, ARVC was the predominantly diagnosed condition.[29] Populations of other countries, like the US, seem to bare another genetic profile with HCM being the most common identified cause for SCD in the young athlete.[14] In a study on SCD in Switzerland, HCM was also the major cardiomyopathy.[30] These geographical differences need to be taken into account before implementing a general screening program in a paediatric population. It is not appropriate to screen children for a condition that does not manifest before adulthood. However, in recent series of SCD, the origin remained predominantly undetermined with a structurally normal heart at autopsy.[31]

All of the athletes were screened first by history and physical examination. Interestingly, between the 36 athletes with abnormal history and physical examination and the 19 athletes with abnormal ECG, there were only two overlapping. One may argue that limiting ECG screening to athletes with positive history and physical examination might have reduced our rate of false-positive findings, thus reducing cost. However, the sensitivity of clinical parameters alone to detect sinister conditions is insufficient.[32] Even though SCD victims might present cardiovascular symptoms before a fatal event,[33] the majority of cases occurs in the absence of symptoms.[14] Besides, the training load of young competitive athletes is equivalent to that reported in adults.[5] Therefore, early identification of underlying (cardiac) disease also allows guiding young individuals towards their future career.

As stated in the above-mentioned study by Malhotra on adolescent football players in the UK, the rate of SCD related disorders on one-time screening was very low.[24] Comparable to our study, for 2% of abnormal findings on initial screening, no diagnosis could be established. However, long-term follow-up (mean 10.6 years) demonstrated several missed fatalities, resulting in an SCD-rate in screened athletes of 6.8/100,000 athletes. We therefore believe that follow-up is of paramount importance in screening athletes in the paediatric age range, notably in post-pubertal individuals.

In this controversial debate on ECG inclusion, cost is often cited as an additional concern: according to reports from the US, nationwide inclusion of ECG would increase the costs to several billions of dollars.[34] However, these calculations do not consider the increased sensitivity and specificity of the most recent International Recommendations for Electrographic Interpretation in Athletes.[2] A study from the UK demonstrated a 27% cost reduction by the International Recommendations for Electrographic Interpretation in Athletes compared to the 2010 ESC criteria.[22] In 42% of abnormal history and physical examination in our cohort, further investigations other than ECG were performed. This contrasted to 63% in the group of abnormal ECGs who had at least one further investigation. Even though ECG increases the absolute cost of screening, it proved to be more cost-effective than history and physical examination only.[35–37]

Another important factor to be considered is the timing of secondary investigations, keeping athletes away from training and thus potentially interfering with their sports career. In this ongoing debate, it should be emphasised that screening young athletes, in addition to risk stratification, offers a unique opportunity to address the specific issues of athletes' health like injury prevention, overtraining, doping and to assess potential problems of the adolescent population like eating disorders or fatigue.

In this study, we respond to the urgent demand for more data on ECG screening in young athletes.[1] However, we admit several limitations. Firstly, only athletes who were part of an organised screening program were included. This may cause a selection bias. Secondly, nearly all athletes included were Caucasians. Thus, the often-addressed ethnical impact on electrocardiographic findings could not be evaluated.[7] Thirdly, due to the retrospective, multicentre nature of the study, we did not use standardised medical history, physical examination or ECG protocols and moreover referral and choice of further investigations were based on local attitude. Fourthly, although this is one of the biggest studies in elite paediatric athletes, still the number is small when considering the prevalence of SCD related conditions in young individuals, reported as 1 in 300.[38] Finally, we were unable to obtain follow-up data in a significant proportion of athletes referred for further evaluation, raising the possibility that we may have missed some diagnoses.

In conclusion, the low rate of abnormal ECG findings suggests that adult criteria can be used in paediatric athletes. The lack of correlation with the presence of relevant disease in a broad paediatric population and the absence of diagnosis of SCD related conditions on single screening underline the need for regular follow-up. With further investigations taken into account, adding ECG to history and physical examination increased the cost of screening from 85 to 122 USD. Our data may be

helpful in the development of cardiac screening programs in paediatric athletes. Future policy makers should carefully assess the diagnostic yield and costs of individual screening modalities and adopt the most cost-efficient strategy. Prospective follow-up data are needed to elucidate long-term evolution of these athletes starting their sports career in early life.

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Declaration of interest statement

The authors have no interest to declare.

Confirmation of ethical compliance

The authors followed the WMA Declaration of Helsinki – Ethical Principles For Medical Research Involving Human Subjects.

The Swiss Ethics Committee approved the study protocol (Project No 2018-00121).

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References

1. Lampert R. ECG screening in athletes: differing views from two sides of the Atlantic. *Heart* 2018;104(12):1037-1043.
2. Sharma S, Drezner JA, Baggish A et al. International recommendations for electrocardiographic interpretation in athletes. *Eur Heart J* 2018;39(16):1466-1480.
3. Zorzi A, Calore C, Vio R et al. Accuracy of the ECG for differential diagnosis between hypertrophic cardiomyopathy and athlete's heart: comparison between the European Society of Cardiology (2010) and International (2017) criteria. *Br J Sports Med* 2018;52(10):667-673.
4. McClean G, Riding NR, Pieles G et al. Diagnostic accuracy and Bayesian analysis of new international ECG recommendations in paediatric athletes. *Heart* 2019;105(2):152-159.
5. Pieles GE, Oberhoffer R. The Assessment of the Paediatric Athlete. *J Cardiovasc Transl Res* 2020;13(3):306-312.
6. Rowland T. Morphologic features of the “athlete's heart” in children: a contemporary review. *Pediatr Exerc Sci* 2016;28(3):345-352.
7. McClean G, Riding NR, Ardern CL et al. Electrical and structural adaptations of the paediatric athlete's heart: a systematic review with meta-analysis. *Br J Sports Med* 2018;52(4):230.
8. Finocchiaro G, Dhutia H, D'Silva A et al. Effect of sex and sporting discipline on LV adaptation to exercise. *JACC Cardiovasc Imaging* 2017;10(9):965-972.
9. Pela G, Crocamo A, Li Calzi M et al. Sex-related differences in left ventricular structure in early adolescent non-professional athletes. *Eur J Prev Cardiol* 2016;23(7):777-784.
10. Mitchell JH, Haskell W, Snell P et al. Task Force 8: classification of sports. *J Am Coll Cardiol* 2005;45(8):1364-1367.
11. Flynn JT, Falkner BE. New clinical practice guideline for the management of high blood pressure in children and adolescents. *Hypertension* 2017;70(4):683-686.
12. Menafoglio A, Di Valentino M, Segatto JM et al. Costs and yield of a 15-month preparticipation cardiovascular examination with ECG in 1070 young athletes in Switzerland: implications for routine ECG screening. *Br J Sports Med* 2014;48(15):1157-1161.
13. Villiger BHM, Goerre S, Kriemler S et al. Task Force “Prevention of Sudden Death in Elite Sport” SGSM/SSMS 2010; the sudden cardiac death of a young athlete: recommendations for a sensible and effective preventive exam. *Schweizerische Zeitschrift für “Sportmedizin und Sporttraumatologie”* 2011;2(58):108-109.
14. Finocchiaro G, Papadakis M, Robertus JL et al. Etiology of sudden death in sports: insights from a United Kingdom regional registry. *J Am Coll Cardiol* 2016;67(18):2108-2115.
15. Mont L, Pelliccia A, Sharma S et al. 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. *Europace* 2017;19(1):139-163.
16. Maron BJ, Haas TS, Murphy CJ et al. Incidence and causes of sudden death in U.S. college athletes. *J Am Coll Cardiol* 2014;63(16):1636-1643.
17. Harmon KG, Zigman M, Drezner JA. The effectiveness of screening history, physical exam, and ECG to detect potentially lethal cardiac disorders in athletes: a systematic review/meta-analysis. *J Electrocardiol* 2015;48(3):329-338.
18. Mohananey D, Masri A, Desai RM et al. Global incidence of sports-related sudden cardiac death. *J Am Coll Cardiol* 2017;69(21):2672-2673.
19. Johri AM, Poirier P, Dorian P et al. Canadian Cardiovascular Society/Canadian Heart Rhythm Society joint position statement on the cardiovascular screening of competitive athletes. *Can J Cardiol* 2019;35(1):1-11.
20. Musso P, Carballo S. Current practice for the prevention of sudden death in young athletes. *Rev Med Suisse* 2018;14(623):1849-1853.
21. Dhutia H, Malhotra A, Gabus V et al. Cost implications of using different ECG criteria for screening young athletes in the United Kingdom. *J Am Coll Cardiol* 2016;68(7):702-711.
22. Dhutia H, Malhotra A, Finocchiaro G et al. Impact of the international recommendations for electrocardiographic interpretation on cardiovascular screening in young athletes. *J Am Coll Cardiol* 2017;70(6):805-807.
23. Calo L, Martino A, Tranchita E et al. Electrocardiographic and echocardiographic evaluation of a large cohort of peri-pubertal soccer players during pre-participation screening. *Eur J Prev Cardiol* 2019;26(13):1444-1455.
24. Malhotra A, Dhutia H, Finocchiaro G et al. Outcomes of cardiac screening in adolescent soccer players. *N Engl J Med* 2018;379(6):524-534.
25. Riding NR, Sheikh N, Adamuz C et al. Comparison of three current sets of electrocardiographic interpretation criteria for use in screening athletes. *Heart* 2015;101(5):384-390.
26. Malhotra A, Dhutia H, Yeo TJ et al. Accuracy of the 2017 international recommendations for clinicians who interpret adolescent athletes' ECGs: a cohort study of 11 168 British white and black soccer players. *Br J Sports Med* 2020;54(12):739-745.
27. Firoozi S, Sharma S, Hamid MS et al. Sudden death in young athletes: HCM or ARVC? *Cardiovasc Drugs Ther* 2002;16(1):11-17.
28. Sarto P, Zorzi A, Merlo L et al. Serial versus single cardiovascular screening of adolescent athletes. *Circulation* 2021;143(17):1729-1731.
29. Corrado D, Basso C, Pavei A et al. Trends in sudden cardiovascular death in young competitive athletes after implementation of a preparticipation screening program. *JAMA* 2006;296(13):1593-1601.
30. Asatryan B, Vital C, Kellerhals C et al. Sports-related sudden cardiac deaths in the young population of Switzerland. *PLoS One* 2017;12(3):e0174434.
31. Bagnall RD, Weintraub RG, Ingles J et al. A prospective study of sudden cardiac death among children and young adults. *N Engl J Med* 2016;374(25):2441-2452.
32. Williams EA, Pelto HF, Toresdahl BG et al. Performance of the American Heart Association (AHA) 14-point evaluation versus electrocardiography for the cardiovascular screening of high school athletes: a prospective study. *J Am Heart Assoc* 2019;8(14):e012235.
33. Drezner JA, Fudge J, Harmon KG et al. Warning symptoms and family history in children and young adults with sudden cardiac arrest. *J Am Board Fam Med* 2012;25(4):408-415.
34. Maron BJ, Friedman RA, Kligfield P et al. Assessment of the 12-lead ECG as a screening test for detection of cardiovascular disease in healthy general populations of young people (12–25 years of age): a scientific statement from the American Heart Association and the American College of Cardiology. *Circulation* 2014;130(15):1303-1334.
35. Papadakis M, Sharma S. Electrocardiographic screening in athletes: the time is now for universal screening. *Br J Sports Med* 2009;43(9):663-668.
36. Harmon KG, Suchsland MZ, Prutkin JM et al. Comparison of cardiovascular screening in college athletes by history and physical examination with and without an electrocardiogram: efficacy and cost. *Heart Rhythm* 2020;17(10):1649-1655.
37. Dhutia H, Malhotra A, Finocchiaro G et al. Diagnostic yield and financial implications of a nationwide electrocardiographic screening programme to detect cardiac disease in the young. *Europace* 2021;23(8):1295-1301.
38. Schmied C, Borjesson M. Sudden cardiac death in athletes. *J Intern Med* 2014;275(2):93-103.
39. Niebauer J, Borjesson M, Carre F et al. Recommendations for participation in competitive sports of athletes with arterial hypertension: a position statement from the sports cardiology section of the European Association of Preventive Cardiology (EAPC). *Eur Heart J* 2018;39(40):3664-3671.