Review article

Electrocardiogram in the pediatric athlete: physiological adaptations, borderline findings, and alarm criteria

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ABSTRACT

Electrocardiographic (ECG) interpretation in the pediatric athlete is clinically challenging due to the interaction between cardiovascular growth, electrophysiological maturation, and exercise-induced adaptations. Unlike adults, the electrical phenotype in children and adolescents reflects a dynamic developmental process, leading to greater variability in ECG patterns. Accurate differentiation between development-related findings, physiological adaptations to training, and alterations suggestive of structural or electrical heart disease is essential to optimize early detection of clinically relevant cardiovascular conditions while avoiding unnecessary restrictions on sports participation. This review summarizes the electrophysiological basis of ECG findings in young athletes and proposes a clinically oriented classification of findings into physiological, borderline, and abnormal categories, integrating contemporary interpretation criteria. A practical approach to ECG interpretation and the rational use of complementary diagnostic testing is also presented, aiming to improve diagnostic accuracy and support safe sports participation in pediatric populations.

Keywords: Electrocardiography, Pediatrics, Exercise; Death, Sudden, Cardiac; Risk Assessment (Source: MeSH-NLM).

RESUMEN

Electrocardiograma en el atleta pediátrico: adaptaciones fisiológicas, hallazgos *borderline* y criterios de alarma

La interpretación del electrocardiograma (ECG) en el atleta pediátrico representa un desafío clínico debido a la interacción entre los procesos de crecimiento cardiovascular, la maduración electrofisiológica y las adaptaciones inducidas por el entrenamiento físico. A diferencia del adulto, el fenotipo eléctrico en niños y adolescentes refleja un sistema en evolución, lo que condiciona una mayor variabilidad en los patrones electrocardiográficos observados. La correcta diferenciación entre hallazgos relacionados con el desarrollo, adaptaciones fisiológicas al ejercicio y alteraciones sugestivas de cardiopatía estructural o eléctrica resulta fundamental para optimizar la detección precoz de enfermedades cardiovasculares relevantes y evitar restricciones innecesarias de la práctica deportiva. Este artículo revisa los fundamentos electrofisiológicos del ECG en el atleta juvenil y propone una clasificación clínica de los hallazgos en fisiológicos, *borderline* y anormales, integrando criterios contemporáneos de interpretación. Se presenta, además, un enfoque práctico para la interpretación clínica del ECG y la indicación racional de estudios complementarios, con el objetivo de mejorar la precisión diagnóstica y favorecer una práctica deportiva segura en la población pediátrica.

Palabras clave: Electrocardiografía; Pediatría; Ejercicio Físico; Muerte Súbita Cardíaca; Estratificación del Riesgo (Fuente: DeCS-BIREME).

Introduction

The electrocardiogram (ECG) is a fundamental tool in the cardiovascular evaluation of athletes, particularly in the context of preparticipation screening aimed at detecting structural or electrical heart disease associated with an increased risk of adverse events during exercise [1,2]. Its incorporation has improved diagnostic capacity for identifying potentially silent cardiomyopathies, channelopathies, and conduction disorders, thereby helping to optimise cardiovascular safety in physically active young populations [2].

ECG interpretation in paediatric athletes represents a particular challenge because of the interaction between the cardiovascular maturation processes inherent to growth and the physiological adaptations induced by physical training. The cardiovascular system of children and adolescents undergoes continuous physiological development that differs substantially from that observed in adulthood, manifesting as progressive changes in ventricular geometry, cardiac electrical axis configuration, neuroautonomic modulation, and ventricular repolarisation patterns [3,4]. These changes generate greater variability in parameters considered normal, broadening the spectrum of physiological findings and increasing the complexity of differentiation [2,5].

Direct extrapolation of electrocardiographic criteria derived from adult populations may be limited in this context, as it does not fully account for the influence of biological age and training-related cardiovascular remodelling during the early stages of life. Consequently, paediatric ECG interpretation requires an integrated and individualised approach [1,2,6].

The aim of this article is to review the physiological basis of the ECG in paediatric athletes, describe variants considered normal, analyse borderline findings, and present warning criteria that indicate the need for further cardiovascular evaluation.

For the purposes of this review, the term paediatric athlete will be used mainly to refer to older children, preadolescents, and adolescents who are physically active or competitive athletes, approximately between 8 and 18 years of age. This definition reflects the fact that most of the available evidence on electrocardiographic interpretation in young athletes, as well as contemporary cardiovascular screening criteria, has been developed and validated predominantly in these developmental stages. Accordingly, the findings and recommendations presented should be interpreted within this context and should not be directly extrapolated to infants or young children.

Throughout the manuscript, the terms paediatric athlete, youth athlete, and young athlete will be used interchangeably to refer to this same population, except when specific age groups reported in the cited studies are explicitly mentioned.

Fundamentals of cardiac electrophysiology in childhood

The electrocardiogram in the paediatric population reflects a continuously developing cardiovascular system, characterised by progressive changes in myocardial structure, the spatial orientation of the heart, the functional organisation of the conduction system, and autonomic regulation [5,7]. The paediatric electrocardiographic tracing is characterised by marked variability related to the structural, functional, and neuroautonomic changes that accompany growth. This heterogeneity reflects the progressive reorganisation of myocardial mass, ventricular activation vectors, and cardiac regulatory mechanisms, all of which drive continuous changes in the electrical parameters observed during childhood and adolescence [8].

During the early stages of life, there is a relative predominance of the right ventricle, derived from the characteristics of fetal and neonatal circulation. With growth, a gradual transition occurs towards structural and functional predominance of the left ventricle, related to the progressive increase in systemic vascular resistance and to changes in cardiac and thoracic geometry [1,4,7]. This process involves modifications in the distribution of myocardial mass, the orientation of electrical vectors, and the sequence of ventricular activation, reflecting the physiological reorganisation of the cardiovascular system throughout somatic development [8,9].

The cardiac conduction system also undergoes progressive maturation during childhood and adolescence. Functional development of the atrioventricular node, the His bundle, and the Purkinje network is accompanied by changes in conduction velocity and in the synchronisation of myocardial activation. In parallel, development of the autonomic nervous system leads to changes in the sympathetic-parasympathetic balance, influencing heart rate regulation and modulation of atrioventricular conduction [9,10]. These transformations represent the physiological adaptation of the neurocardiac system as the organism progresses through biological maturation.

Ventricular repolarisation also shows age-dependent characteristics, related to the evolution of transmural electrophysiological gradients and the relative distribution of ventricular masses. Changes in myocardial architecture, the organisation of muscle fibres, and the cellular properties of cardiac tissue influence the temporal sequence of ventricular depolarisation and repolarisation, shaping electrical patterns that evolve throughout development [3,7].

In paediatric athletes, physical training acts as an additional modulator of a maturing cardiovascular system. Repeated haemodynamic stimuli, autonomic adaptation, and the interaction between functional load and biological growth contribute to the complexity of the electrical phenotype at these ages [6,9]. Understanding the electrophysiological foundations of development allows the paediatric ECG to be interpreted within a dynamic framework, in which observed changes should be analysed in the context of the structural and functional evolution of the heart throughout growth.

Electrical adaptation to training in young athletes

Systematic physical training during childhood and adolescence induces a series of cardiovascular adaptations that are expressed at both structural and functional levels, shaping a physiological phenotype known as athlete's cardiac remodelling [5,7]. In the paediatric context, these changes are particularly complex because they interact with processes of somatic growth and cardiovascular maturation, generating a spectrum of electrocardiographic findings that may differ from those observed in adult athletes. The ECG of the paediatric athlete, therefore, represents the integrated expression of repeated haemodynamic stimuli acting on a developing cardiovascular system, in which physiological adaptive mechanisms may modify conduction, voltage, and repolarisation parameters without necessarily implying structural disease [11,12].

Dynamic exercise, particularly predominantly aerobic exercise, produces a sustained increase in venous return and stroke volume, resulting in a physiological volume overload that promotes myocardial adaptations characterised by improved ventricular compliance and optimisation of cardiac mechanical efficiency. These changes may be associated with modest increases in cardiac chamber dimensions and alterations in the synchrony of ventricular activation, contributing to high QRS voltages, which, in the absence of other findings, generally represent a manifestation of functional adaptation to training [8,9,12]. In the paediatric population, these changes should be interpreted with caution, considering that the progressive increase in ventricular mass is also part of the physiological process of growth.

Autonomic modulation is another fundamental component of exercise adaptation in young athletes. Regular training favours predominance of parasympathetic tone and a relative reduction in sympathetic activity at rest, a phenomenon that is reflected electrocardiographically by a lower resting heart rate, increased sinus variability, and mild prolongation of atrioventricular conduction intervals [13,14]. Sinus bradycardia and respiratory sinus arrhythmia are frequent findings in trained paediatric athletes and reflect greater cardiovascular efficiency and an adaptive response of the autonomic nervous system. In the absence of symptoms or suggestive clinical history, these patterns are usually considered physiological variants [5,10,11].

Ventricular repolarisation may also be influenced by physical training [4,8,15]. These changes are associated with modifications in the heterogeneity of myocardial repolarisation times and are usually interpreted as benign findings in the context of the young athlete. Nevertheless, differentiation between physiological variants and potentially pathological abnormalities requires a comprehensive assessment that considers age, type of sport, training intensity, and the coexistence of other electrocardiographic findings **(Table 1)**.

Overall, the ECG of the paediatric athlete should be interpreted as the manifestation of a dynamic adaptive process in which training acts as a modulator of a cardiovascular system that is still developing [2,8,9]. Integrating the principles of exercise physiology with knowledge of paediatric electrophysiology allows benign adaptive patterns to be recognised, optimising diagnostic accuracy and reducing the risk of misinterpretation that could lead to unnecessary investigations or inappropriate restriction from physical activity.

Maturational variation of the electrocardiogram in childhood

ECG interpretation in children and adolescents requires consideration of the physiological changes that accompany cardiovascular maturation [6,16,17]. Progressive changes in myocardial structure, the spatial orientation of the heart, and the functional organisation of the conduction system generate expected variations in multiple electrocardiographic parameters throughout development. This maturational variability explains why certain electrical patterns may differ substantially from those observed in adults without necessarily indicating the presence of cardiovascular disease [9,13,18].

One of the most relevant developmental changes is the progressive transition from relative right ventricular predominance in the early stages of life to structural and functional left ventricular predominance during adolescence. This process is associated with changes in the direction of ventricular depolarisation vectors, resulting in variations in the electrical axis and changes in QRS complex voltages. The orientation of the heart within the thoracic cavity also changes with somatic growth, particularly in relation to thoracic development and diaphragmatic position, contributing to variability in the electrocardiographic expression of electrical vectors [4,9,11].

The cardiac conduction system also undergoes progressive maturation. Functional development of the atrioventricular node and the His-Purkinje system, together with the increasing influence of the autonomic nervous system, leads to changes in conduction intervals and resting heart rate [5,9,19]. During adolescence, increased parasympathetic tone and greater cardiovascular efficiency contribute to greater sinus variability

Table 1. Electrocardiographic findings in young athletes aged 8-18 years: classification and clinical interpretation.

Category	Electrocardiographic finding	Definition	Clinical interpretation	Considerations according to age and development
	Juvenile T-wave pattern	T-wave inversion in V1–V3 in athletes younger than 16 years	Variación fisiológica del desarrollo ventricular	Frecuente en niños y preadolescentes; disminuye progresivamente durante la adolescencia.
	First-degree AV block	PR interval >200 ms and <300 ms	Training-associated vagal modulation of the AV node	More frequent in trained adolescents because of vagal predominance.
	Increased QRS voltages	Isolated voltage criteria for left ventricular hypertrophy (SV1 + RV5 or RV6 >3 mV) or right ventricular hypertrophy (RV1 + SV5 or SV6 >0.8 mV)	Physiological cardiac remodelling	Voltages increase progressively with growth and physiological training-induced remodelling.
Borderline finding	Incomplete right bundle branch block	rSR’ pattern in V1 with QRS complex <100 ms	Possible right ventricular adaptation	May be observed as a physiological variant in young athletes.
	Left axis deviation	−9° to −90°	Interpret according to the clinical context	Should be interpreted considering age and the evolution of ventricular dominance.
	Right axis deviation	>110°	May reflect anatomical variation or adaptation to training	May be physiological in young children, but is less frequent in adolescents.
	Left atrial enlargement	P wave ≥120 ms or increased terminal negative component in V1	Structural or haemodynamic variation; interpret according to context	Clinical relevance increases when associated with other findings.
	Right atrial enlargement	P wave ≥2.5 mm in the inferior leads	Possible haemodynamic adaptation or anatomical variation	Should be assessed together with clinical features and other ECG findings.
Abnormal finding	Short PR interval	PR ≤90 ms	Suspected pre-excitation	Values below those expected for age and sex suggest pre-excitation.
	Complete right bundle branch block (RBBB)	rSR’ pattern in V1 with an S wave larger than the R wave in V6 and QRS ≥100 ms	Significant conduction abnormality	Not considered a physiological adaptation to training.
	Complete left bundle branch block (LBBB)	QRS ≥100 ms with a predominantly negative complex in V1 and positive R wave in I and V6	Suggestive of structural heart disease	Infrequent and potentially pathological at any paediatric age.
	Prolonged QTc interval	QTc ≥460 ms or ≥470 ms in high-level young athletes	Suspected long QT syndrome	Should be interpreted considering age, sex, and reference percentiles; values above the 95th percentile require additional evaluation.
	Profound sinus bradycardia	Heart rate <40 bpm or sinus pauses ≥3 s	Possible sinus node dysfunction	Usually not explained by training alone.
	Ventricular pre-excitation	PR ≤90 ms with delta wave and QRS ≥90 ms	Wolff–Parkinson–White syndrome	Requires specific evaluation regardless of age.
	Non-specific intraventricular conduction delay	QRS ≥130 ms	Possible myocardial disease	Clearly exceeds expected values for any paediatric age group.
	Profound first-degree AV block	PR ≥300 ms	Significant atrioventricular conduction abnormality	Abnormal finding regardless of age.
	Pathological T-wave inversion	≥1 mm in ≥2 contiguous leads, except aVR, III, and V1	Suspected structural heart disease or cardiomyopathy	Should be differentiated from the physiological juvenile pattern in children younger than 16 years.

AV: atrioventricular. RBBB: right bundle branch block. LBBB: left bundle branch block. QTc: corrected QT interval.

and mild changes in conduction intervals, which may fall within the normal spectrum in the absence of other findings suggestive of pathology.

Ventricular repolarisation also has age-dependent characteristics. The so-called juvenile repolarisation pattern, characterised by T-wave inversion in the right precordial leads, may be observed in children and adolescents as a consequence of physiological gradients in ventricular repolarisation times and the relative distribution of myocardial mass [6,12]. This pattern may persist into mid-adolescence and should be interpreted within the context of normal cardiovascular development.

Recognition of maturational variation in the ECG is essential to avoid misinterpreting growth-related patterns as pathological findings. In paediatric athletes, these changes overlap with adaptations induced by physical training, increasing the interpretative complexity of the electrocardiographic tracing [1,8,11]. Therefore, ECG assessment in this population requires integration of developmental physiology principles with the clinical context and level of physical activity, enabling distinction between normal variability, physiological adaptation, and findings that require further evaluation.

Physiological electrocardiographic features in young athletes

The electrocardiogram of young athletes may show various findings that reflect physiological adaptations of the cardiovascular system to regular physical training. These changes form part of the so-called electrical phenotype of the athlete's heart and, in most cases, represent benign manifestations of the interaction between cardiovascular maturation and exercise-induced remodelling [4,12,20]. Recognition of these physiological patterns is essential to avoid misinterpretation that could lead to unnecessary diagnostic evaluation or unjustified restriction from sports participation.

One of the most frequent findings is sinus bradycardia, defined as a resting heart rate lower than expected for age. This phenomenon is mainly explained by increased parasympathetic tone associated with regular aerobic training, which modulates sinus node activity and reduces the spontaneous discharge rate of pacemaker cells [7,11,14]. In trained adolescents, bradycardia may be marked and accompanied by high heart rate variability, reflecting efficient autonomic regulation.

Respiratory sinus arrhythmia is another common finding. This pattern is characterised by cyclical variations in heart rate related to the respiratory cycle and represents a physiological manifestation of vagal predominance. In young athletes, it is usually more evident because of greater baroreceptor sensitivity and increased parasympathetic tone [12,15,16].

Benign abnormalities of atrioventricular conduction are also relatively frequent. First-degree atrioventricular block, defined by a PR interval greater than 200 ms, may be observed as a consequence of increased vagal tone modulating conduction through the AV node. In some cases, particularly at rest or during sleep, second-degree Mobitz type I atrioventricular block (Wenckebach) may occur and typically disappears with exercise or sympathetic stimulation [4,12,17].

The ECG of young athletes may also show increased QRS complex voltages, particularly in the precordial leads. These findings are related to the physiological increase in ventricular mass and exercise-induced cardiac remodelling (6,9). For this reason, classic electrocardiographic criteria for ventricular hypertrophy have limited specificity when applied to young athletes.

Variations in ventricular repolarisation are another relevant feature. These include early repolarisation, characterised by elevation of the J point and ST segment in the inferior or lateral leads, often accompanied by positive T waves. This pattern is observed more frequently in physically active individuals and has been related to the influence of vagal predominance on myocardial repolarisation mechanisms [2,21,22].

Finally, a characteristic finding in children and adolescents is the juvenile T-wave pattern, consisting of T-wave inversion in the right precordial leads, especially V1-V3. This pattern reflects regional differences in right ventricular repolarisation during the early stages of cardiac development and usually disappears progressively with age [7,11,21].

Overall, these electrocardiographic features represent physiological expressions of exercise-induced cardiovascular remodelling and of the electrophysiological particularities of the developing heart. Their correct identification allows normal cardiovascular adaptations to be distinguished from findings that could suggest underlying cardiac disease.

The "grey zone": physiological and pathophysiological basis of borderline electrocardiographic findings

Between clearly physiological electrocardiographic adaptations in athletes and unequivocally pathological patterns, there is an intermediate group of findings whose interpretation is more complex. These changes, known as borderline electrocardiographic findings, represent abnormalities that lie at a transitional point between physiological variability of the cardiovascular system and the possible early manifestations of structural heart disease or conduction disorders [5,9,11]. In many cases, they can be explained by changes in cardiac geometry, heart-thorax interaction, or propagation of the electrical impulse associated with growth and training. However, from a pathophysiological perspective, they may also reflect early changes in myocardial architecture or in the conduction system, which explains their role as a diagnostic "grey zone".

One of the most representative examples is incomplete right bundle branch block. Electrocardiographically, it appears as an rSR' pattern in lead V1, with a QRS complex duration of less than 100 ms. In young athletes, this pattern may reflect slight prolongation of right ventricular activation secondary to exercise-induced haemodynamic adaptations (5,9,23). The chronic increase in venous return and preload during aerobic training favours physiological enlargement of the right-sided cardiac chambers, which may subtly modify the sequence of ventricular activation. This phenomenon produces a mild delay in right ventricular activation, without structural abnormality of the conduction system. However, a similar pattern may also be observed in diseases affecting the right ventricle, such as congenital heart disease or the early stages of arrhythmogenic cardiomyopathy, in which the presence of fibrosis or structural remodelling slows propagation of the electrical impulse (6,18,24).

Electrical axis deviation is another example of a borderline finding. The QRS axis reflects the predominant direction of ventricular depolarisation and depends on the geometric relationship between both ventricles, as well as the orientation of the heart within the thorax. During growth, progressive changes occur in ventricular dominance and cardiac position. At younger ages, there is relative right ventricular predominance, which gradually decreases with development. In addition, physical training may modify ventricular geometry and the orientation of the heart within the thoracic cavity (4,9,11). These anatomical and functional variations may generate moderate axis deviations without necessarily indicating structural disease. However, more marked deviations may also reflect alterations in the distribution of myocardial mass or in impulse propagation, as occurs in some congenital heart diseases, conduction disorders, or early cardiomyopathies.

The borderline nature of these findings is explained by the overlap between physiological mechanisms and early pathological processes. Many inherited or structural heart diseases begin with subtle abnormalities of myocardial architecture or the conduction system that initially produce discrete electrical changes. These abnormalities may not be sufficient to generate clearly abnormal electrocardiographic patterns, but they may slightly alter the direction or propagation of electrical vectors (9,11,25). Therefore, borderline findings may be interpreted as possible electrical manifestations of an intermediate phase between physiological adaptation and subclinical disease.

Another factor contributing to these patterns is the influence of the autonomic nervous system. Regular physical training produces predominance of parasympathetic tone and a relative reduction in sympathetic activity at rest. This autonomic modulation may affect not only heart rate and atrioventricular conduction, but also myocardial excitability and impulse propagation within ventricular tissue (9,13,18). As a result, subtle variations in the sequence of electrical activation may appear, expressed electrocardiographically as mild conduction or axis abnormalities.

From a clinical perspective, the relevance of borderline findings depends on the context in which they occur. When they appear in isolation in asymptomatic young athletes, without a family history of heart disease or sudden cardiac death and without other associated electrocardiographic findings, they usually represent physiological variations related to cardiovascular development or adaptation to training (11,15,17). However, the presence of two or more borderline electrocardiographic findings significantly increases the likelihood of underlying heart disease. This principle has a pathophysiological and probabilistic basis: multiple subtle abnormalities in conduction or in the orientation of electrical vectors may reflect more extensive structural changes that are not yet manifested as pathological electrocardiographic abnormalities (6,12,19). For this reason, contemporary recommendations for ECG interpretation in athletes state that identification of two or more borderline findings should prompt additional cardiological evaluation, which may include echocardiography, ambulatory electrocardiographic monitoring, or exercise testing.

Abnormal electrocardiographic findings: clinical relevance and warning criteria

In paediatric athletes, abnormal electrocardiographic findings correspond to electrical patterns whose presence cannot be explained by cardiovascular maturation or physiological adaptation to physical training, and which are associated with a higher likelihood of structural heart disease or primary electrical disorders (6,27,28). Identification of these findings is essential in the context of cardiovascular screening, as various inherited or acquired cardiac diseases may remain clinically silent during their early stages and manifest only through abnormalities in myocardial depolarisation, repolarisation, or electrical conduction (6,15,17).

Findings considered abnormal include abnormalities of ventricular repolarisation, particularly T-wave inversion in the lateral or inferolateral leads, as well as significant ST-segment depression. These patterns may reflect changes in myocardial architecture, fibrosis, or structural disarray that generate heterogeneity in ventricular repolarisation times. Similarly, the presence of pathological Q waves may suggest abnormalities in the distribution of myocardial mass or in the sequence of ventricular activation (4,11,14,29). Abnormal variations in QT interval duration, including both prolongation and marked shortening, may indicate alterations in the function of ion channels responsible for the cardiac action potential, which are associated with increased susceptibility to potentially malignant ventricular arrhythmias (11,15,30). In the paediatric population, interpretation of the corrected QT interval (QTc) should take into account age, sex, and maturational stage because of the physiological variations observed during growth. From a clinical perspective, values above the 95th percentile for age and sex should be considered potentially abnormal. In practical terms, contemporary criteria suggest that a QTc ≥460 ms warrants additional cardiovascular evaluation, whereas values ≥470 ms in high-level young athletes represent a warning finding that requires exclusion of inherited channelopathies, particularly long QT syndrome.

Abnormalities of atrioventricular and intraventricular conduction constitute another relevant group of abnormal findings. Advanced atrioventricular block, complete right bundle branch block, complete left bundle branch block, and non-specific intraventricular conduction delays reflect abnormalities in electrical impulse propagation that may be related to conduction system disease or structural myocardial changes [(8,12,19)]. The presence of markedly short PR intervals associated with delta waves is suggestive of ventricular pre-excitation secondary to accessory atrioventricular pathways, which may predispose to the development of supraventricular tachyarrhythmias.

Other findings that should be considered abnormal include profound sinus bradycardia accompanied by prolonged sinus pauses, as well as complex ventricular arrhythmias, defined by multifocal, paired, or exercise-induced premature ventricular contractions [(3,5,6,31)]. These patterns may indicate abnormalities in automaticity or myocardial electrical stability, particularly when associated with symptoms or a relevant family history.

The clinical relevance of these findings lies in the fact that they may represent the electrical expression of diseases such as hypertrophic cardiomyopathy, arrhythmogenic cardiomyopathy, inherited channelopathies, congenital heart disease, or myocardial inflammatory processes. In the context of exercise, increased sympathetic activity, heart rate, and metabolic demand may facilitate the occurrence of arrhythmias in the presence of a vulnerable electrical substrate [(4,7,32,33)]. Therefore, identification of abnormal electrocardiographic findings in paediatric athletes justifies complementary investigations aimed at characterising cardiac structure and function, enabling more accurate risk stratification and contributing to safe sports participation **(Table 2)**.

ECG interpretation and complementary investigations

Interpretation of the electrocardiogram in paediatric athletes should follow a systematic approach that integrates the tracing findings with the individual clinical context. Evaluation should not be limited to the isolated analysis of electrical parameters, but should also consider biological age, personal and family history, the presence of symptoms, and the type of sports participation [(4,9,19,34)]. This approach allows patterns that may be observed in the context of cardiovascular development and training to be distinguished from those that may suggest underlying disease and require more detailed assessment.

The initial analysis should identify the presence of findings classified as training-related, borderline, or abnormal, according to contemporary criteria for ECG interpretation in athletes [(7,15,35,36)]. When the ECG shows only training-related findings and the athlete is asymptomatic, with no family history of inherited heart disease or sudden cardiac death, no additional investigations are required and usual clinical follow-up may be maintained [(6,37)].

In the presence of borderline findings, interpretation should consider their number and the clinical context in which they occur. A single isolated borderline finding, in the absence of symptoms or relevant history, generally does not justify immediate complementary investigations [(9,15,38)]. However, the coexistence of two or more borderline findings may increase the likelihood of underlying heart disease; therefore, additional evaluation aimed at characterising cardiac structure and function is reasonable [(3,6,7,39)].

When abnormal electrocardiographic findings are identified, targeted cardiovascular evaluation is recommended, even in the absence of symptoms [(15,18,40)]. The selection of complementary investigations should be individualised according to the predominant finding and may include transthoracic echocardiography as the initial tool for structural assessment, ambulatory electrocardiographic monitoring for arrhythmia detection, exercise testing to assess the electrical response to exercise, and, in selected cases, cardiac magnetic resonance imaging for more precise tissue characterisation [(4,9,11)].

ECG interpretation should be integrated with the clinical history and physical examination. Symptoms such as syncope, exertional chest pain, disproportionate dyspnoea, or palpitations, as well as a family history of sudden cardiac death or inherited heart disease, may modify the clinical relevance of electrocardiographic findings and justify a broader evaluation. This integrated approach can improve diagnostic accuracy and support safe sports participation [(2,6,10,41)].

Conclusion

The electrocardiogram is a key tool in the cardiovascular evaluation of young athletes as part of preparticipation screening. Its interpretation requires consideration of the interaction between electrophysiological maturation of the developing heart and the adaptations induced by physical

Table 2. Recommended diagnostic evaluation according to electrocardiographic findings in young athletes aged 8-18 years.

Electrocardiographic finding	Possible underlying condition	Recommended complementary investigations
T-wave inversion in the lateral leads (I, aVL, V5–V6)	Hypertrophic cardiomyopathy	Echocardiography, cardiac magnetic resonance imaging
Deep anterior T-wave inversion (V2–V4)	Arrhythmogenic right ventricular cardiomyopathy	Echocardiography, cardiac magnetic resonance imaging, Holter monitoring
ST-segment depression	Cardiomyopathy or repolarisation abnormality	Echocardiography, exercise testing
Prolonged QT interval	Long QT syndrome	Holter monitoring, exercise testing, genetic testing
Short QT interval	Short QT syndrome	Holter monitoring, genetic evaluation
Ventricular pre-excitation (delta wave)	Wolff–Parkinson–White syndrome	Electrophysiological study, exercise testing
Profound sinus bradycardia or sinus pauses	Sinus node dysfunction	Holter monitoring, exercise testing
Complete left bundle branch block	Structural heart disease	Echocardiography, cardiac magnetic resonance imaging
Significant intraventricular conduction delay (QRS ≥130 ms)	Myocardial disease	Echocardiography, cardiac magnetic resonance imaging
Frequent premature ventricular contractions	Arrhythmogenic cardiomyopathy, myocarditis, structural heart disease	Holter monitoring, exercise testing, cardiac magnetic resonance imaging
Ventricular tachycardia	Structural heart disease or channelopathy	Complete cardiological evaluation

training. In this context, it is essential to distinguish between physiological findings, borderline patterns, and clearly abnormal changes.

Whereas physiological changes usually reflect benign adaptations to exercise, borderline findings require contextual assessment, and abnormal changes should prompt a more comprehensive cardiological evaluation. The application of contemporary ECG interpretation criteria, integrated with clinical history and physical examination, can improve diagnostic accuracy and facilitate the early detection of clinically relevant heart disease.

Author contributions

AGY: conceptualisation, methodology, analysis and interpretation, writing—original draft, supervision, and final approval of the manuscript. **MMMS:** conceptualisation, data curation, writing—review and editing, and final approval of the manuscript. **KVL:** literature search, analysis and interpretation, visualisation (tables, figures, and diagrams), and final approval of the manuscript. **HBA:** literature search, writing—review and editing, and final approval of the manuscript.

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