

From Sudden Cardiac Death Prevention to Performance Optimization: A Conceptual Framework for Cardiovascular Assessment in Elite Athletes

REVIEW

ABSTRACT

Cardiovascular pre-participation evaluation in elite athletes primarily aims to identify cardiovascular conditions associated with sudden cardiac death. Current international recommendations emphasize comprehensive medical history, physical examination, and resting 12-lead electrocardiography (ECG), with additional investigations guided by clinical findings and individual risk. However, advances in sports cardiology, cardiovascular imaging, and exercise physiology provide opportunities to integrate cardiovascular risk assessment with physiological performance evaluation. This article proposes a conceptual, hypothesis-generating framework integrating structural, electrical, and functional cardiovascular assessment in elite athletes. The framework consists of 3 sequential components: comprehensive clinical assessment with resting ECG; transthoracic echocardiography for structural evaluation and longitudinal reference; and cardiopulmonary exercise testing (CPET) as an optional complementary investigation. Cardiopulmonary exercise testing may provide information on maximal oxygen uptake, ventilatory thresholds, oxygen pulse, ventilatory efficiency, heart rate recovery, and exercise-induced arrhythmias, potentially supporting individualized training prescription and longitudinal physiological monitoring. Cardiac magnetic resonance and coronary computed tomography angiography (CCTA) may be considered selectively when clinically indicated. A one-time CCTA strategy during an athlete's career is proposed as a research hypothesis requiring prospective assessment of clinical utility and cost-effectiveness. Importantly, CPET and CCTA are not proposed as universal screening requirements. This framework is intended to complement, rather than replace, current evidence-based international recommendations. As the proposed model is based on available literature and expert opinion and has not undergone prospective clinical validation, future multicenter studies are required to determine whether integrated cardiovascular assessment improves risk stratification, athlete safety, clinical decision-making, performance monitoring, and cost-effectiveness.

Keywords: Athlete, cardiopulmonary exercise testing, heart, preparticipation screening, sports cardiology, sudden cardiac deaths

INTRODUCTION

Participation in competitive sports induces a spectrum of structural, functional, and electrophysiological cardiac adaptations collectively referred to as the athlete's heart. Although these physiological changes are generally benign, a small proportion of athletes may harbor previously unrecognized cardiovascular disorders that predispose them to malignant ventricular arrhythmias and sudden cardiac death (SCD). The underlying causes of SCD vary according to age; inherited cardiomyopathies, primary electrical disorders, myocarditis, and congenital coronary artery anomalies predominate in athletes younger than 35 years, whereas atherosclerotic coronary artery disease is the leading cause in older athletes.^{1,2}

Accordingly, pre-participation cardiovascular evaluation has become an integral component of sports medicine, aiming primarily to identify individuals at increased risk of exercise-related adverse cardiovascular events before participation in competitive sports. Current international recommendations—including

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the 2020 European Society of Cardiology Guidelines on Sports Cardiology, the International Criteria for Electrocardiographic Interpretation in Athletes, and cardiovascular screening strategies adopted by organizations such as the International Olympic Committee and FIFA (Fédération Internationale de Football Association)—emphasize a structured assessment based on medical history, physical examination, and resting 12-lead electrocardiography (ECG), with additional investigations performed according to clinical findings and individual risk profiles.³⁻⁶

Despite these advances, several challenges remain. Cardiovascular screening in elite athletes is frequently performed using heterogeneous institutional protocols that vary according to available expertise, local resources, and national practice patterns. In many professional sports organizations, echocardiography has become a routine component of the evaluation despite differences among international recommendations regarding its universal application. Similarly, exercise testing is widely performed during pre-participation assessment; however, the incremental diagnostic value of conventional treadmill exercise testing in asymptomatic elite athletes with exceptionally high functional capacity remains uncertain.⁷

Beyond the identification of occult cardiovascular disease, modern elite sports increasingly require objective physiological assessment to support individualized training prescription and long-term performance monitoring. Cardiopulmonary exercise testing (CPET) provides comprehensive evaluation of cardiovascular, pulmonary, and metabolic responses to exercise and has become an established tool for performance assessment in elite athletes. Nevertheless, its role as a routine component of cardiovascular screening remains incompletely defined, and current international guidelines do not recommend universal implementation in all asymptomatic athletes.^{8,9}

Similarly, recent advances in cardiovascular imaging have renewed interest in the potential role of coronary computed tomography angiography (CCTA) for identifying congenital coronary anomalies and subclinical coronary artery disease in selected athletic populations. However, routine implementation of CCTA remains controversial because of radiation exposure, contrast administration, incidental findings, healthcare costs, and the absence of prospective evidence demonstrating improved clinical outcomes.^{10,11}

HIGHLIGHTS

- A multistage cardiovascular screening algorithm is proposed for elite athletes.
- Cardiopulmonary exercise testing improves the functional assessment of athletic cardiovascular performance.
- Selective use of coronary computed tomography angiography strengthens risk stratification within the step-wise approach.

Given these considerations, there remains an opportunity to explore more comprehensive approaches to cardiovascular assessment in elite athletes that integrate contemporary cardiovascular screening with physiological performance evaluation. Accordingly, this article presents a conceptual, hypothesis-generating framework based on current literature and expert opinion rather than a validated clinical recommendation. The proposed model is intended to stimulate discussion and future prospective research regarding the integration of structural, electrical, and functional cardiovascular assessment within elite sports medicine.

Proposal

Based on the current literature and existing international recommendations, the authors propose a conceptual multistage cardiovascular assessment framework for elite athletes that integrates conventional cardiovascular screening with functional physiological evaluation (Figure 1). Importantly, this framework should not be interpreted as a validated clinical algorithm or a replacement for current guideline recommendations. Rather, it represents an expert-opinion-based model intended to stimulate future prospective research and discussion regarding comprehensive cardiovascular assessment in elite sports.

The proposed framework consists of 3 sequential stages. While the first stage closely reflects established international recommendations, the subsequent components incorporate additional investigations that may be considered in selected settings depending on available resources, local expertise, and individual athlete characteristics.

The first stage represents the fundamental cardiovascular pre-participation evaluation and should include a comprehensive medical history, focused physical examination, and resting 12-lead ECG, consistent with current international recommendations. Particular attention should be directed toward exertional syncope or presyncope, chest pain, unexplained dyspnea, palpitations, previous myocarditis, and a family history of inherited cardiomyopathy or premature SCD.^{12,13}

Physical examination should include cardiac auscultation, blood pressure measurement, and assessment for phenotypic features suggestive of inherited connective tissue disorders or other systemic diseases. Resting ECG should be interpreted according to the International Criteria for Electrocardiographic Interpretation in Athletes, recognizing both physiological training-related adaptations and abnormalities warranting further evaluation.⁶

This first stage represents the evidence-supported cornerstone of contemporary cardiovascular pre-participation evaluation and remains the foundation of the proposed framework.

The second stage comprises transthoracic echocardiography, providing comprehensive structural assessment of the athlete's heart and facilitating identification of conditions associated with SCD, including hypertrophic cardiomyopathy, dilated cardiomyopathy, arrhythmogenic cardiomyopathy, valvular disease, and aortic pathology.¹⁴

CARDIOVASCULAR EVALUATION ALGORITHM IN ELITE ATHLETES

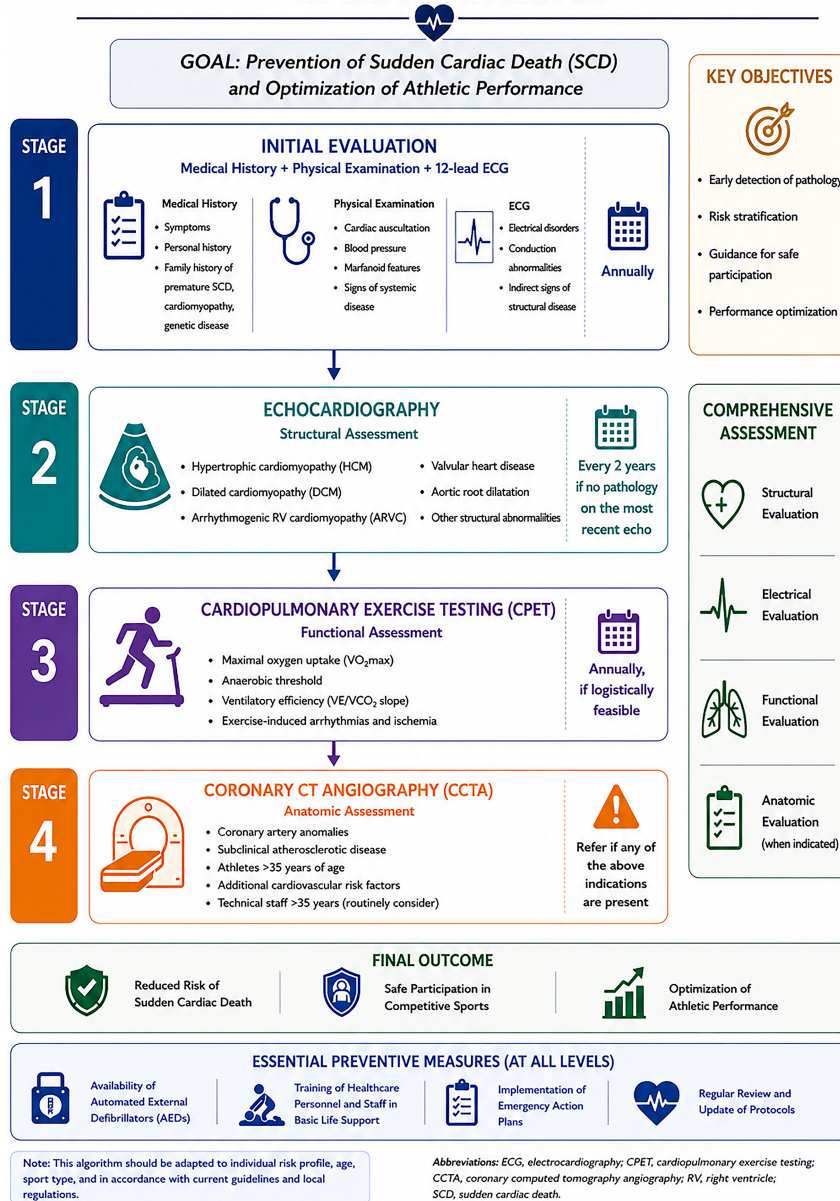


Figure 1. Schematic Flowchart of the Athlete Medical Assessment

Interpretation requires careful differentiation between physiological remodeling and pathological cardiac disease. When standard echocardiographic findings remain inconclusive, cardiac magnetic resonance imaging may provide complementary tissue characterization and improve diagnostic confidence, particularly in suspected cardiomyopathy, myocarditis, myocardial fibrosis, or arrhythmogenic cardiomyopathy.^{15,16}

Because routine echocardiographic screening practices differ among healthcare systems and sports organizations, their implementation should remain consistent with local expertise and current institutional practice. Nevertheless, a baseline echocardiographic examination may provide

valuable reference data for longitudinal follow-up in elite athletes.

The third stage incorporates CPET to provide a comprehensive assessment of the integrated cardiovascular, pulmonary, and metabolic responses to exercise. In addition to maximal oxygen uptake (VO_{2max}), CPET provides clinically relevant physiological parameters including ventilatory thresholds, oxygen pulse, ventilatory efficiency (VE/VCO_2 slope), heart rate recovery, and exercise-induced arrhythmias.^{4,17}

These variables may assist sports physicians, cardiologists, and performance teams in individualizing aerobic training intensity, monitoring physiological adaptation throughout

the competitive season, identifying inadequate recovery, and recognizing unexpected reductions in exercise capacity that may warrant further cardiovascular investigation.

However, current international guidelines do not recommend routine CPET as a universal cardiovascular screening test for all asymptomatic elite athletes. Consequently, within the present framework, CPET should be regarded as an optional complementary investigation that may provide additional physiological and performance-related information when appropriate expertise, equipment, and resources are available.^{18,19}

Furthermore, the incremental diagnostic value of routine CPET beyond conventional cardiovascular screening has not yet been established in prospective outcome studies. Practical considerations—including availability, financial cost, specialized personnel, and laboratory infrastructure—should therefore be considered before widespread implementation.

Accordingly, the inclusion of CPET in the proposed framework reflects expert opinion supported by physiological rationale rather than evidence sufficient to justify universal implementation. Prospective studies are needed to determine whether CPET-guided assessment improves cardiovascular outcomes, clinical decision-making, or athletic performance.

Advanced Imaging

In selected athletes, additional cardiovascular imaging may be appropriate after individualized clinical assessment. Among these modalities, CCTA has demonstrated excellent diagnostic performance for identifying congenital coronary artery anomalies and excluding obstructive coronary artery disease.^{20,21} Importantly, the true prevalence of congenital coronary artery anomalies may be underestimated in living populations, as many anomalies remain clinically silent and are only identified through advanced imaging or post-mortem examination. Autopsy-based studies have demonstrated a notable prevalence of anomalous coronary artery origins among young individuals and competitive athletes who died suddenly, highlighting the possibility that the burden of these abnormalities may be greater than suggested by clinically detected cases alone.^{22,23}

In the proposed conceptual framework, routine CCTA screening for all elite athletes is not recommended. Instead, CCTA may be considered in carefully selected individuals when congenital coronary anomalies are suspected, when symptoms or abnormal investigations require further anatomical clarification, or in older athletes with elevated cardiovascular risk consistent with current guideline recommendations. Nevertheless, within this conceptual framework, the potential value of performing a one-time CCTA examination during the career of an elite athlete warrants further investigation. Future prospective studies should specifically evaluate the clinical utility, feasibility, and cost-effectiveness of a one-time CCTA strategy in elite athletes, particularly in those without a previous coronary anatomical assessment. Such research may determine

whether a single baseline CCTA examination provides sufficient incremental diagnostic and preventive value to justify its incorporation into routine cardiovascular assessment. Importantly, this concept should not be interpreted as a current recommendation for universal CCTA screening, but rather as a research hypothesis that could be considered for future clinical implementation if supported by prospective evidence demonstrating clinical benefit, feasibility, and cost-effectiveness.

Potential advantages of CCTA should always be balanced against important limitations, including radiation exposure, iodinated contrast administration, incidental findings, false-positive results, downstream diagnostic testing, and healthcare costs. Therefore, the decision to perform CCTA should remain individualized and based on shared clinical decision-making rather than routine protocolized screening.

Feasibility and Practical Considerations

The feasibility of implementing comprehensive cardiovascular assessment varies considerably across healthcare systems, sports organizations, and countries. While professional clubs and national sports federations may have access to advanced imaging and CPET laboratories, such resources are not universally available.

Consequently, the present framework should be viewed as a flexible model rather than a mandatory screening protocol. The extent of cardiovascular evaluation should remain proportional to local expertise, available infrastructure, economic considerations, and individual clinical circumstances.

DISCUSSION

The present manuscript proposes a conceptual framework that integrates established cardiovascular pre-participation screening with selected physiological assessment tools that may contribute to individualized athlete management. Unlike current evidence-based guideline recommendations, this framework is intended to stimulate discussion regarding future directions in sports cardiology rather than to establish a new standard of care.

Comparison with Current International Recommendations

Current international recommendations—including the 2020 ESC Guidelines on Sports Cardiology, the International ECG Criteria, and cardiovascular screening approaches adopted by the IOC and FIFA—consistently emphasize structured medical history, physical examination, resting ECG, and targeted additional investigations according to clinical suspicion (Table 1).^{6,24-26} Echocardiography is widely incorporated into elite sports medicine practice, although its routine use varies among healthcare systems.

The present framework is largely consistent with these recommendations in its initial assessment. However, it extends current practice by proposing the selective incorporation of functional physiological assessment using CPET and individualized use of advanced imaging where clinically appropriate. These additional components should be regarded as complementary rather than replacement investigations and currently remain supported primarily by physiological

Table 1. Comparison of the Proposed Conceptual Cardiovascular Assessment Framework with Current International Recommendations for Pre-Participation Cardiovascular Evaluation in Elite Athletes

Component	ESC 2020	IOC/FIFA	Proposed Framework
Medical history	✓	✓	✓
Physical examination	✓	✓	✓
Resting ECG	✓	✓	✓
Echocardiography	Selective / Local practice	Frequently used	Baseline recommended where available
Conventional exercise test	Selected cases	Variable	Limited value in asymptomatic elite athletes
CPET	Not routine	Not routine	Optional complementary assessment
CMR	Selected cases	Selected cases	Recommended when echocardiography is inconclusive
CCTA	Selected cases	Selected cases	Individualized consideration

The table summarizes the principal components of the 2020 ESC Guidelines on Sports Cardiology, the International Criteria for Electrocardiographic Interpretation in Athletes, and cardiovascular screening approaches commonly adopted by the IOC and FIFA/UEFA. The proposed framework extends current practice by incorporating optional functional assessment with CPET and individualized use of advanced imaging modalities, including cardiac CMR and CCTA, when clinically appropriate. These additional components represent expert-opinion-based recommendations intended to complement, rather than replace, current evidence-based guideline recommendations, and require prospective clinical validation before routine implementation.

CCTA, coronary computed tomography angiography; CMR, cardiac magnetic resonance imaging; CPET, cardiopulmonary exercise testing; ECG, electrocardiography; ESC, European Society of Cardiology; FIFA, Fédération Internationale de Football Association; IOC, International Olympic Committee.

rationale and expert opinion rather than prospective outcome evidence.

Performance Optimization Beyond Cardiovascular Screening

Although prevention of SCD remains the principal objective of cardiovascular screening, elite sport increasingly requires integration of cardiovascular evaluation with performance medicine.

Cardiopulmonary exercise testing-derived physiological variables may provide valuable information for multidisciplinary performance teams beyond cardiovascular risk assessment.²⁷ Parameters such as maximal oxygen uptake, ventilatory thresholds, oxygen pulse, ventilatory efficiency, and heart rate recovery can facilitate the optimization of aerobic training intensity, support individualized exercise prescription, and enable longitudinal monitoring of physiological adaptation throughout the competitive season.²⁸ Furthermore, serial CPET assessments may assist in identifying inadequate recovery or unexpected reductions in exercise capacity, thereby prompting further cardiovascular evaluation when clinically indicated. Nevertheless, current evidence demonstrating that CPET-guided interventions improve competitive performance remains limited, and prospective studies are required before routine implementation can be recommended solely for performance optimization.²⁹

Feasibility, Cost-effectiveness, and Limitations

The implementation of comprehensive cardiovascular assessment varies considerably across countries, healthcare systems, and sporting organizations. Although professional clubs, Olympic training centers, and national sports federations often have access to advanced cardiovascular imaging modalities and CPET laboratories, these resources are not universally available. Consequently, the widespread adoption of a multistage assessment model may be constrained by differences in equipment availability, the need for

specialized personnel, laboratory infrastructure, financial costs, and healthcare resource allocation. These practical considerations may substantially influence the feasibility of implementing such an approach in routine clinical practice, particularly outside elite professional sports environments. Accordingly, the proposed framework should be interpreted as a flexible model whose implementation should be adapted to local clinical practice, available resources, and individual athlete characteristics.

An additional limitation is the absence of prospective clinical validation. At present, no randomized or prospective cohort studies have demonstrated that incorporation of CPET or selective advanced imaging into routine cardiovascular screening reduces SCD, improves long-term cardiovascular outcomes, or enhances athletic performance compared with current screening strategies. Therefore, the proposed framework should not be interpreted as an evidence-based clinical recommendation but rather as an expert-opinion-based conceptual model requiring further scientific validation.

Future Research Directions

Future multicenter prospective studies are required to determine whether integrating structural, electrical, and functional cardiovascular assessment into a comprehensive screening strategy improves clinical outcomes in elite athletes. Particular emphasis should be placed on prospectively validating the proposed multistage framework, clarifying the incremental diagnostic value of CPET beyond conventional screening modalities, and identifying the athlete populations most likely to benefit from advanced imaging techniques. Furthermore, health-economic analyses are needed to evaluate the cost-effectiveness of incorporating additional diagnostic modalities into routine pre-participation cardiovascular assessment, while long-term follow-up studies should investigate their impact on cardiovascular outcomes, athlete safety, and clinical decision-making. Finally, prospective research should examine whether CPET-guided

physiological monitoring and individualized exercise prescription translate into measurable improvements in athletic performance. Collectively, such investigations will help determine whether a more comprehensive cardiovascular assessment strategy can simultaneously enhance athlete safety and performance while remaining practical, economically sustainable, and applicable across diverse healthcare systems and sporting environments.

CONCLUSION

Cardiovascular pre-participation evaluation in elite athletes continues to evolve as advances in sports cardiology, cardiovascular imaging, and exercise physiology expand the range of available diagnostic tools. While current international recommendations provide a robust evidence-based foundation for cardiovascular screening, opportunities remain to explore complementary strategies that integrate structural, electrical, and functional cardiovascular assessment within selected elite athletic populations.

The conceptual framework presented in this review combines established screening modalities with optional physiological and advanced imaging investigations that may contribute to individualized athlete evaluation in appropriately selected settings. Importantly, this proposal should not be interpreted as a validated clinical screening algorithm or as a replacement for existing international guideline recommendations. Rather, it represents an expert-opinion-based synthesis of the currently available evidence that is intended to stimulate scientific discussion and future prospective investigation.

The selective incorporation of CPET may provide additional physiological information capable of supporting individualized exercise prescription, longitudinal performance monitoring, and comprehensive cardiovascular evaluation in elite athletes. Likewise, advanced imaging techniques such as cardiac CMR and CCTA may offer incremental diagnostic value in carefully selected athletes when clinically indicated. However, the routine implementation of these modalities should be balanced against practical considerations including resource availability, financial cost, specialized expertise, and the current lack of prospective outcome-based evidence supporting their universal use.

Future multicenter prospective studies are warranted to determine whether this integrated assessment strategy improves cardiovascular risk stratification, clinical decision-making, athlete safety, and performance optimization beyond current standard practice. In addition, cost-effectiveness analyses and implementation studies across different healthcare systems will be essential to evaluate the feasibility of incorporating advanced physiological and imaging modalities into routine pre-participation cardiovascular screening. Until such evidence becomes available, the proposed framework should be regarded as a hypothesis-generating conceptual model that complements—rather than replaces—existing evidence-based cardiovascular screening recommendations.

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