

Indications, protocols, and interpretation of cardiovascular imaging for the evaluation and management of athletes: a clinical consensus statement of the European Association of Preventive Cardiology (EAPC) and the European Association of Cardiovascular Imaging (EACVI) of the ESC: Part 1—Exercise imaging

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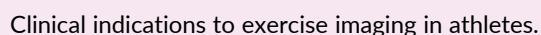
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Graphical Abstract



sports cardiology • athlete's heart • imaging • echocardiography • CMR • nuclear imaging • exercise echocardiography • stress echocardiography

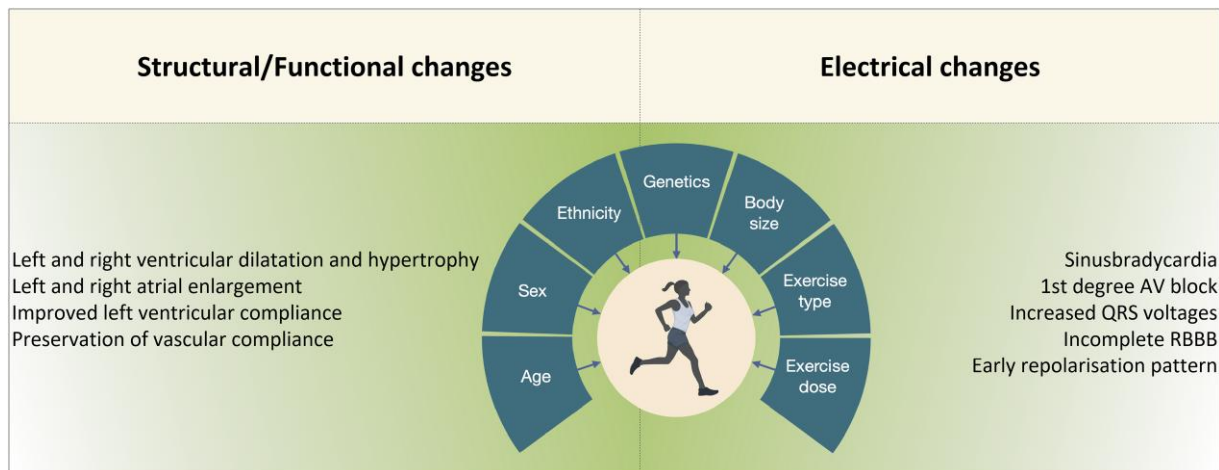


Figure 1 Determinants of exercise-induced cardiovascular adaptation. AV, atrioventricular; LBBB, left bundle branch block.

dimensions. Body surface area is a commonly used index for cardiac parameters, given the ease of measuring height and weight. Alternatively, fat-free mass can be used where available.¹⁹

- (7) Genetics. An important non-modifiable factor contributing to exercise-induced cardiac remodelling is the athlete's genetic signature. Certain signalling pathways for cardiac adaptations have been identified,²⁰ which may contribute to physiological vs. pathological remodelling processes, although scientific data are still relatively scarce. For example, a recent study on elite endurance athletes showed that a reduced LV ejection fraction (EF) may be determined by a combination of genetic predisposition and exercise training and is associated with an increased risk of ventricular arrhythmias.²¹

Exercise echocardiography

General principles: from physiology to clinical protocols

Athletic conditioning results in physiological cardiac chamber enlargement, which is ultimately aimed at generating the higher cardiac outputs required for improved performance. It has been observed that elite athletes may exhibit, in association with bradycardia, lower resting left and right ventricular (RV) function [mildly reduced EF, RV fractional area change, and global longitudinal strain (GLS)] compared to non-athletic individuals.^{22,23} This is a consequence of the enlarged chambers requiring a lower contractile state to deliver a sufficient stroke volume at rest. In association, the low resting HR is secondary to increased vagal tone.²⁴ The difference between resting and maximum LV contractility and HR increase is termed the cardiac reserve, and due to lower basal values, this reserve is greater in athletes than in non-athletes.²⁵ During exercise, the working myocardium is subjected to increased oxygen demand. A healthy, athletic individual with normal coronary arteries has full capacity to enhance the supply of blood flow to match the increasing demand for myocardial oxygen consumption and, hence, can meet the required cardiac reserve.

Athletic individuals with an underlying cardiac disease [e.g. inherited cardiomyopathy or underlying coronary artery

disease (CAD)] may have a compromised coronary reserve that may limit the heart's response to the increasing challenges of exercise.^{26–28} This can be observed as reduced cardiac reserve, with a blunted functional response and/or direct impairment and serves as the rationale for ESE. On the contrary, athletes with a normal coronary reserve have a normal inotropic response during exercise. Therefore, ESE is indicated to unmask the grey zone of the athlete's heart function and improve the diagnostic yield of underlying structural heart disease (SHD).

Interpretation of exercise imaging in competitive and recreational athletes should primarily be based on the direction and magnitude of change from resting conditions rather than on isolated absolute values obtained at peak exercise. Resting imaging provides the essential anatomical and functional reference, while exercise imaging allows assessment of ventricular reserve, haemodynamic adaptation, and appropriateness of the cardiovascular response to physiological stress.²⁹

There is currently no consensus on the specific protocols to be employed for ESE in an athletic population. However, there are general principles hence it is reasonable to propose: that an athletic individual undergo an exercise protocol (rather than a pharmacological stimulus) on a dedicated supine/semi-supine cycle ergometer. This allows for true physiological stress, whilst enabling diagnostic-quality echocardiographic images. The protocol design should aim to push the athlete to the maximum effort possible. This is achieved by gradually increasing the intensity of exercise through incremental increases in workload, with the magnitude and timing of these increments flexible and dependent on the athlete's cardiorespiratory fitness. The protocol should always include a recovery period to allow the HR and cardiac contractile state to return to baseline levels. Echocardiographic images should be acquired at baseline, throughout the protocol at each workload increment and into recovery.

Exercise stress echocardiography can be performed using a semi-supine position, or images can be collected during upright cycling, particularly among young athletes, in whom the echocardiographic windows may be permissive. echocardiographic images and data, the latter is more physiological, particularly for athletes accustomed to cycling, and usually yields a higher heart rate (HR)_{peak} and, in a combined evaluation with CPET, a

higher VO_{2peak} .^{30,31} Sometimes, ESE on the treadmill has also been applied, particularly in runners. With the latter approaches, athletes usually reach higher HR_{peak} and develop their full potential exercise capacity better than on recumbent cycling, therefore increasing the sensitivity of the ESE. However, echocardiographic acquisition and image quality may be significantly affected. Therefore, the protocol choice should be tailored to each individual and not separated from the resources and expertise available at each centre.

Alternative methods have been proposed, such as acquiring images at a percentage of the athlete's HR reserve (defined as the difference between *maximum HR* and *basal HR*). It is important to note that athletes often exceed their age-predicted maximum HR; therefore, the use of peak HR as a test endpoint should be limited to cases where it has been pre-calculated at VO_{2peak} .

Further research is warranted to validate the current protocols in different settings, balancing their clinical value with time and costs. Alongside acquiring the echocardiographic images (with inherent rhythm ECG), systemic blood pressure, HR, and symptoms should be recorded. *Figure 2* provides an exemplar protocol for ESE in an athletic individual.

How to image the right ventricle during exercise

Evaluating the right ventricle (RV) by transthoracic echocardiography is quite challenging during exercise due to the complex RV geometry and the high heart and respiratory rates. Guidelines recommend a graded, semi-supine exercise protocol, with imaging acquisition at each stage of stress, to support the performance, interpretation, and application of stress echocardiography in ischaemic heart disease.³² Conventional long and inflow parasternal views, the latter obtained with anterior tilting of the probe from a conventional long parasternal view, provide a qualitative assessment of RV size. Doppler interrogation can be performed in parallel to a typically mild tricuspid regurgitation (TR) jet at the RV inflow in the parasternal view to estimate pulmonary artery pressure. Also, a transition view from the short-axis view at the level of the great vessels to the four-chamber view could allow parallel alignment with a tiny TR jet, particularly during exercise. Intravenous administration of agitated saline or ultrasound contrast can improve the detectability of the TR Doppler signal when it is weak and help confirm a valid velocity envelope³³; however, this should be used selectively and interpreted with caution, as contrast-enhanced Doppler envelopes may sometimes appear more diffuse and could potentially overestimate peak TR velocity if not carefully aligned and analysed.³⁴ Finally, the four-chamber apical view focused on the RV is crucial, particularly for ensuring correct endocardial delineation and adequate myocardial tracking to measure RV volumes and strain. This view can be obtained from the apex lateral tilting of the probe. Comparison of exercise and baseline images is maximized when reproducible views are acquired.

A comprehensive evaluation of the RV in the athlete should include tricuspid annular motion, lateral annular tissue Doppler velocities, strain imaging, and 2D assessment of RV size and function from an RV-focused apical four-chamber view.³⁵ Three-dimensional echocardiography provides more accurate RV volumetric assessment at rest and may be considered during exercise in selected cases when image quality, HR, and local expertise allow. However, due to technical limitations during exercise, 2D parameters and qualitative assessment remain the primary tools for RV evaluation in most athletic settings.

Accordingly, practical approaches to RV assessment during exercise rely primarily on focused RV apical views, real-time, or multi-beat acquisitions when feasible, and consistent use of the same software platform for baseline and exercise measurements. When comprehensive volumetric analysis cannot be reliably obtained, functional indices such as fractional area change and longitudinal strain provide robust and clinically meaningful information. Reference values for RV size and function at rest³⁶ and during exercise³⁷ are available for athletes involved in high-dynamic sports and should be used to support accurate interpretation in this specific population.

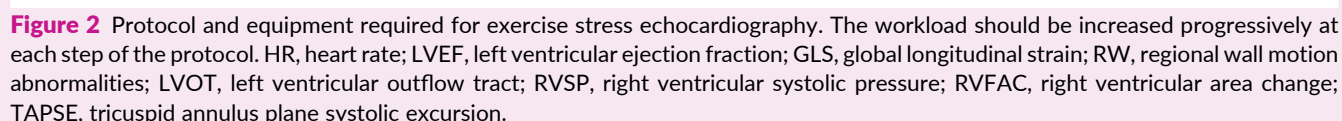
Acquisition of RV volumes during exercise is technically feasible but remains challenging due to high HR, respiratory motion, and the complex geometry of the RV. In addition, volumetric quantification during exercise is highly dependent on acquisition strategy and post-processing software, which may limit reproducibility across centres. Practical approaches to RV assessment during exercise therefore rely on focused RV apical views, real-time, multi-beat acquisitions (at least five consecutive cardiac cycles recorded whenever feasible), and consistent use of the same software platform for baseline and exercise measurements. When comprehensive volumetric analysis cannot be reliably obtained, functional indices such as fractional area change and longitudinal strain provide robust and clinically meaningful information.

Interpretation of RV dimensions and function during exercise should primarily focus on dynamic changes relative to baseline rather than on isolated absolute values. In healthy athletes, mild RV dilatation or borderline functional parameters at rest often normalize or improve during exercise, reflecting preserved RV functional reserve. Conversely, a blunted, absent, or paradoxical RV response during exercise supports the presence of an underlying pathological substrate and should be interpreted in conjunction with resting imaging findings and the overall clinical context.³⁸

How to image the left ventricle during exercise

Imaging the LV during exercise presents both opportunities and challenges, offering insights into dynamic cardiac changes during physical activity. Exercise tests enable accurate quantification of LV volumes, mass, and function during training, providing a comprehensive assessment of cardiac performance. During exercise, the heart undergoes dynamic changes in size and function, necessitating precise imaging techniques. Echocardiography facilitates real-time visualization of LV function and has the potential to provide a more comprehensive understanding of cardiac responses to stress.³⁹ Imaging the LV during exercise might also reveal differences between physiological adaptations to exercise and pathological changes in the heart, aiding in the early detection of cardiac abnormalities in athletes.⁴⁰ The ESE indication would define the exercise protocol to use and the views to prioritize when acquiring images. Standardizing image acquisition is essential to obtain consistent images, and ideally, the same sonographer should assess them to limit inter-observer variability.⁴¹

A graded semi-supine exercise with imaging acquisition at each stage of stress is the first recommendation of the American Society of Echocardiography (ASE) guidelines on stress echocardiography in ischaemic and non-ischaemic heart disease^{1,32} for the evaluation of LV global and segmental contractility reserve and LV diastolic functional reserve. Treadmill exercise should be considered an alternative, as both diastolic and systolic abnormalities may persist after exercise, according



For the evaluation of dynamic LV obstruction, either in the context of hypertrophic cardiomyopathy (HCM) or not, an ESE

Imaging the LV during exercise requires a balance between practicality and diagnostic accuracy. Data obtained from imaging the LV during exercise can contribute to future research on physiological adaptations to exercise and may have clinical applications in assessing cardiovascular risk profiles and guiding exercise-based interventions.³⁹

Imaging the right and left atrium (RA and LA) with transthoracic echocardiography during exercise should include conventional apical four- and two-chamber views with dedicated acquisitions

aimed at measuring biatrial size at end-systole, avoiding foreshortening.^{1,44} Notably, atrial enlargement, a physiologic adaptation to exercise conditioning, is usually observed in athletes, particularly endurance athletes, even in the early phases of their careers.^{45–47} This physiological remodelling is confirmed by the characterization of the biatrial function using speckle-tracking echocardiography (STE), demonstrating normal reservoir function at rest⁴⁸ and normal stiffness.^{49–51} Two techniques have been described for analysing atrial function at rest,^{52,53} using the QRS or P wave as a reference point, respectively, with the former offering slightly higher feasibility and less time-wasting than the latter.

Speckle-tracking echocardiography can also be applied to assess biatrial function during exercise. Exercise stress echocardiography, with an accurate analysis of phasic volumes and STE, provides crucial information on changes in atrial function and filling pressure during exercise⁵⁴ that can be particularly useful in individuals with valvular heart disease, atrial fibrillation (AF), and heart failure.^{55–57} In healthy individuals, atrial function increases at low- and moderate-intensity exercise and remains unchanged at high-intensity exercise, in which the increase in cardiac output relies more on the rise in HR.⁵⁸ As such, similarly to the protocol applied for the ventricles, atrial function should be assessed at each step of exercise and not just at peak effort.

Exercise nuclear imaging

Indication

Competitive and recreational athletes may undergo nuclear cardiac imaging for selected clinical indications, most commonly myocardial perfusion imaging (MPI) for the evaluation of suspected CAD or, less commonly, for the assessment of congenital coronary anomalies. Because athletes—particularly younger individuals—may undergo repeated imaging over the course of their careers, careful attention to cumulative radiation exposure is essential, and strategies to reduce radiation dose are warranted.

Modern nuclear cardiology technologies, such as cadmium zinc telluride cameras, offer higher sensitivity and spatial resolution, enabling substantial reductions in radiation dose compared with conventional systems. Several studies have shown up to a 50% dose reduction without compromising diagnostic accuracy.^{59,60} In addition, the use of stress-first (or stress-only) protocols can further limit exposure by avoiding unnecessary rest imaging.²

Age and clinical profile remain key determinants of imaging choice. Younger athletes, who may require long-term surveillance or repeated imaging, benefit from stricter dose-minimization strategies. Conversely, master athletes—particularly recreational athletes—often present with multiple cardiovascular risk factors, making nuclear imaging more frequently indicated. Tailoring nuclear cardiology protocols to age, sporting history, cardiovascular risk, and expected lifetime radiation exposure is therefore essential to ensure safe and effective cardiac assessment.

Protocols

Whenever feasible, competitive and recreational athletes should be stressed using physical exercise, as it provides several advantages over pharmacological vasodilators. Exercise stress improves image quality by diverting blood from the gastrointestinal tract to the heart muscle, and it allows superior risk stratification for coronary anomalies and myocardial bridging, as it better reflects the true haemodynamic impact of exertion than

vasodilators. On the contrary, vasodilator stress may be preferred in AF and left bundle branch block, as exercise can be limited by submaximal effort, and arrhythmias may complicate interpretation. Vasodilators do not require an increase in HR, minimizing LV dyssynchrony and allowing for more reliable imaging.⁶¹ Additionally, hybrid imaging approaches, such as calcium scoring or computed tomography angiography (CTA) integrated with single photon emission computed tomography (SPECT)/CT or positron emission tomography (PET)/CT, may be considered to improve patient stratification (Figure 3).

As recommended by the 2024 ESC Guidelines on Chronic Coronary Syndrome,⁶² competitive and recreational athletes may also undergo stress cardiac PET imaging, which offers superior sensitivity for detecting myocardial perfusion abnormalities and viability, and, as previously discussed, provides a more targeted approach to reduce radiation exposure compared with conventional nuclear techniques.

Finally, the selection of exercise nuclear imaging protocols should be individualized for each athlete, taking into account age, the likelihood of repeated imaging over the course of their life and the reliability of the chosen modality for specific cardiac conditions. Tailoring nuclear cardiology protocols to individual athlete profiles, as in the study's clinical objectives, is essential to ensure cardiac assessment and optimize safety.

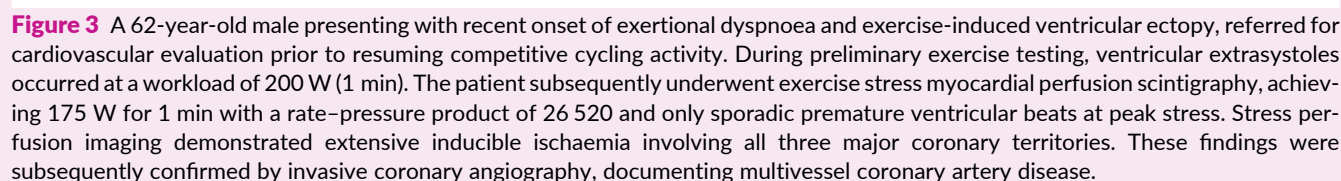
Common clinical scenarios: putting theory into practice

These scenarios are intended to reflect a continuum of clinical presentations and exercise imaging responses, including borderline or equivocal findings, emphasizing interpretation within the broader clinical, electrocardiographic, and physiological context rather than reliance on isolated thresholds.

T-wave inversion at rest

T-wave inversion (TWI) at rest preceded by convex ST-segment elevation in V1–V4 is common in black/African athletes and in V1–V3 in children and adolescent athletes; therefore, according to the current recommendations, further assessment is not required in this scenario if there are no symptoms, no positive family history, or no abnormal physical examination.²² Conversely, TWI involving the inferior and/or lateral leads, or pathological anterior TWI, warrants comprehensive investigation and surveillance to exclude an underlying cardiomyopathy, as these patterns may represent the earliest manifestation of SHD.²² T-wave inversion can be accompanied by LV remodelling; an accurate analysis of cardiac function during exercise may help distinguish between an athlete's heart and SHD, providing information on electrical and functional responses to this stimulus. Athletes demonstrate greater contractile reserve, with a larger increase in stroke volume and LVEF during exercise and only a small increase in HR.^{63–66} Exercise stress echocardiography with STE analysis demonstrates that a <2% increase in GLS during exercise indicates limited contractile reserve, which is more suggestive of cardiomyopathy.⁶⁷ Combined with CPET, a $\text{VO}_{2\text{max}}$ >50 mL/kg/min or >20% above the predicted value may help differentiate between an athlete's heart and pathological hypertrophy, although some athletes with morphologically mild HCM may achieve higher values.⁶⁸

T-wave inversion may also raise suspicion of myocarditis. Resting wall motion abnormalities may be absent, and mildly reduced LVEF can be seen even in healthy athletes, making diagnosis challenging. Speckle-tracking echocardiography can reveal



In contrast to the low prevalence of physiological LV hypertrophy, a larger proportion of male athletes exhibit an LV cavity ≥ 60 mm,⁸⁸ occasionally associated with a concomitant, mildly depressed resting LV EF of 48–54%.^{17,89} The prevalence of an enlarged LV cavity >60 mm ranges from 14 to 50%^{19,78} and is most

Although data are limited by small cohorts, the evaluation of LV contractile reserve by exercise echocardiography has demonstrated promising results in this scenario. A study comparing 35 highly active individuals with DCM and 25 athletes with a dilated LV and mildly depressed baseline LVEF revealed that failure to increase the LVEF by $\geq 11\%$ from baseline to peak exercise had a sensitivity of 77.1% and a specificity of 96% in predicting DCM.²¹ Furthermore, failure to achieve a peak LVEF $>63\%$ had a sensitivity of 82.9% and a specificity

of 92% for predicting DCM. Collectively, these two parameters increased the sensitivity to 86% for detecting DCM.²¹ Adding contrast when assessing ventricular function during exercise further enhances diagnostic accuracy by improving delineation of endocardial borders, particularly in athletes with suboptimal acoustic windows.⁹¹ Further studies in larger cohorts are required to realize the full potential of myocardial reserve in differentiating between physiological LV enlargement with mildly depressed LVEF and morphologically mild DCM.

Extreme right ventricular remodelling

The RV of athletes requires specific attention because there can be significant overlap between a healthy and diseased RV, particularly among those undergoing the highest volumes of intense endurance exercise training. Marked RV dilation is common in elite endurance athletes, and, although remodelling associated with 'athlete's heart' is symmetrical mainly, there is a slight increase in the RV:LV ratio that should be seen as part of the normal spectrum of athletic conditioning.^{92,93} Similarly, slight reductions in RV strain, fractional area change, and EF are common in ostensibly healthy athletes and need to be carefully differentiated from disease.^{17,94}

In the athlete with marked remodelling of the RV, exercise can be an invaluable tool to assist in differentiating between health and disease. When considering athletic remodelling, the main differential diagnoses are ACM, DCM, and an intracardiac shunt, such as an atrial septal defect (ASD). Although exercise RV imaging can be abnormal in patients with ASD,^{95,96} this is rarely an indication for exercise imaging and is best evaluated with resting imaging, including transoesophageal echocardiography.

The rationale for using exercise RV imaging to differentiate between athletic remodelling and cardiomyopathy is based on the observation that subtle RV dysfunction may become pronounced during severe, prolonged exercise and remain so for more than 24 h.³⁶ Furthermore, the process of exercising the athlete under observation provides an opportunity to assess the incidence and pattern of arrhythmias. Exercise imaging can be achieved with echocardiography or cardiac CMR (which will be described in more detail later). Exercise stress echocardiography has demonstrated utility in identifying pathological attenuations in contractile augmentation.^{95,96} It has been established that although resting function may be low-normal or mildly reduced in healthy endurance athletes, it normalizes with exercise when measured as either fractional area change or longitudinal strain.⁹⁴ Conversely, in athletes with pathology (RV arrhythmias and/or cardiomyopathy), there may be a slight increase, or even a paradoxical decrement, in these measures.^{95,96} All studies to date that have assessed contractile reserve in athletes have used semi-supine bicycle ergometry to acquire real-time imaging during exercise at each stage of stress. Formal quantification of RV measures is recommended according to the guidelines on the clinical use of stress echocardiography in non-ischaemic heart disease from the ASE, and as advised by international experts^{40,95,96} (with care taken to maximize the RV dimensions), but sometimes, the failure of augmentation is profound and can be readily identified with a qualitative appraisal.

Atrial remodelling

The atria of well-trained athletes are enlarged and have slightly decreased reservoir and contractile functions but reduced stiffness in resting conditions.⁵¹ Atria serve as reservoirs for filling the ventricles, and these physiological adaptations enable athletes' atria to accommodate the massive increase in stroke

volume during high-intensity aerobic exercise. While the enlargement of the atria supposes an enhanced volume reserve, the slight decrease in atrial function at rest supposes a greater margin for atrial function to rise during exercise; in other words, it supposes an enhanced atrial contractile reserve.⁹⁷ Recent data in elite athletic populations further support this concept, demonstrating that left and right atrial reservoir, conduit, and contractile strain assessed by STE are closely related to the extent of LV remodelling, to cardiorespiratory fitness and vary according to sex and sporting discipline.⁹⁸

Atrial strain in resting conditions has been demonstrated to be a predictor of the occurrence of AF in different clinical scenarios, such as hypertension⁹⁹ or HCM.¹⁰⁰ In addition, atrial function at rest has been shown to predict exercise capacity in patients with heart failure.^{101,102} Recently, evaluation of atrial functional reserve has emerged as a promising marker for early detection of atrial cardiomyopathy. In the general population, an impaired LA functional reserve could distinguish individuals with paroxysmal AF from healthy individuals, even when the atria were not yet enlarged.¹⁰³ Furthermore, an impaired LA functional reserve was associated with a greater risk of cardiovascular events in DCM patients.¹⁰⁴ In addition, a limited RA reservoir and contractile reserve were associated with poor cardiac output and depressed exercise capacity in heart failure with preserved EF,¹⁰⁵ while impaired LA reserve was identified as an early sign of transition from the asymptomatic phase to overt heart failure with preserved EF.¹⁰² In the athlete's clinical scenario, a recent study in master athletes confirmed what had already been shown in the general population: an impaired LA functional reserve might be an early predictor of paroxysmal AF.¹⁰⁶

Mild-to-moderate valvular heart disease

Mitral valve

Competitive and recreational athletes with moderate-to-severe or severe primary MR^{3,107} may refer to themselves as 'asymptomatic', so the use of ESE is helpful to unmask reduced functional capacity, a considerable increase in systolic pulmonary artery pressure (sPAP), changes in mitral regurgitant volume and the occurrence of symptoms during exercise. The latter and the baseline effective orifice area are independent predictors of symptoms at rest at 2 years.¹⁰⁸ Moreover, an early increase in sPAP during exercise (>15 mmHg at the first exercise stage) was independently associated with an increased risk of cardiovascular events at 3-year follow-up.¹⁰⁹ The indication for surgery in asymptomatic individuals with severe MR is based on the presence of LV dysfunction (LVEF ≤60%) and significant LV dilation (LV end-systolic diameter ≥40 mm); however, lifelong endurance athletes can exhibit marked exercise-induced LV remodelling and overlap with these parameters.^{110,111} Therefore, ESE helps demonstrate a normal increase in LVEF at peak exercise and identifies a specific subset of asymptomatic but high-risk athletes who will benefit from early surgery, as well as those with discordance between symptoms and MR grade.

In addition, after a successful mitral valve repair and in competitive and recreational athletes with significant MR but without indications for surgery, ESE provides useful information for exercise prescription and sports eligibility, including biventricular contractile reserve, valvular gradients, regurgitations, pulmonary artery pressure, and diastolic function.^{8,112} The evaluation of diastolic function during exercise is challenging after mitral repair surgery, as Doppler parameters may be affected by the procedure and the presence of a prosthetic material. In fact, after surgical implantation of a ring or a prosthetic valve, mitral *E* velocity increases and *e'* velocity decreases,

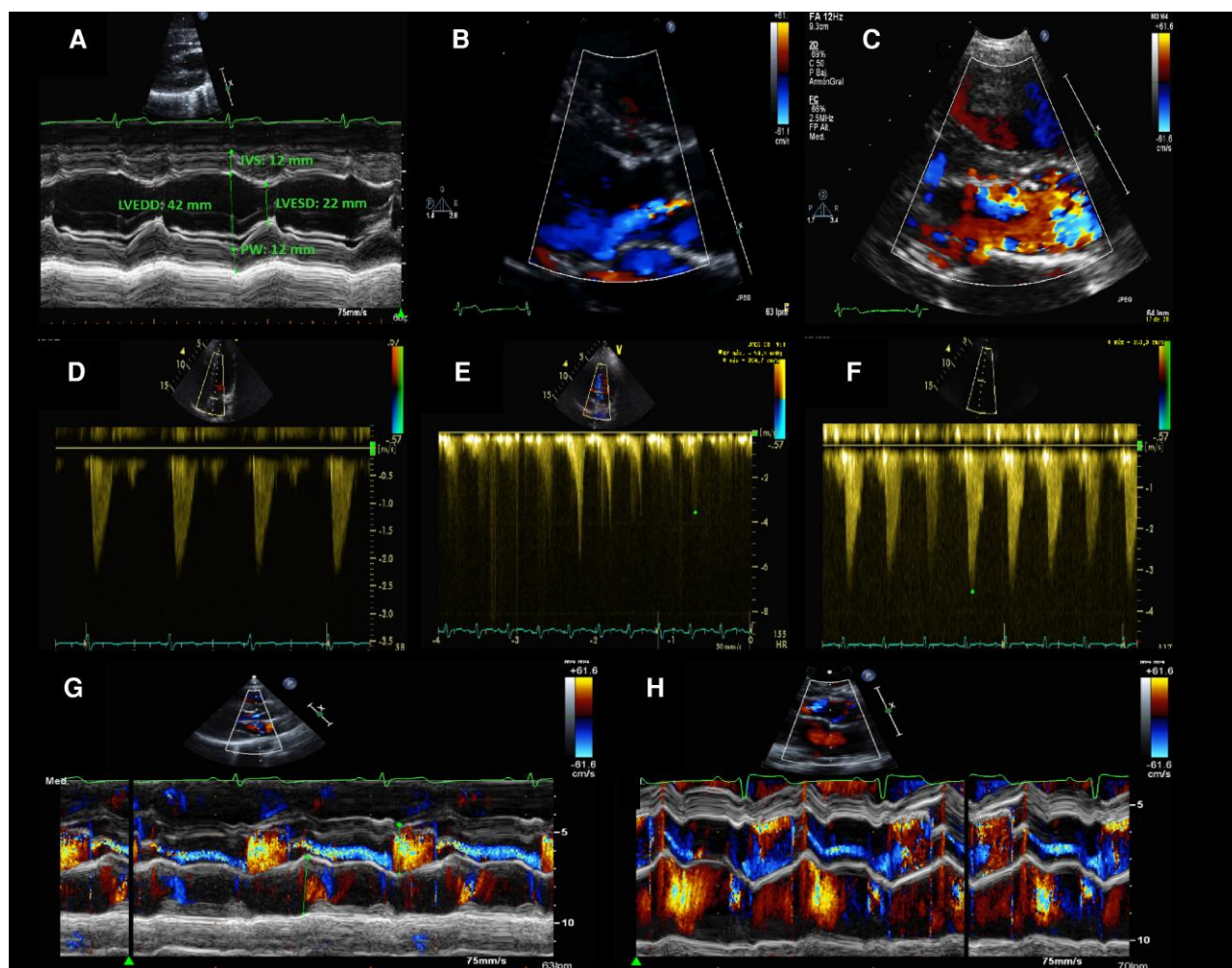


Figure 4 Clinical case example illustrating the incremental diagnostic value of exercise stress echocardiography in an athlete with exertional pre-syncope due to a subaortic membrane: exercise stress echocardiography was performed in an adolescent basketball player who complained of dizziness while performing intense aerobic exercise. The resting 2D echocardiography showed mild left ventricular hypertrophy (interventricular septum and posterior wall were 12 mm) with a relatively low LV cavity (LV end-diastolic diameter was 42 mm). The Doppler evaluation revealed mild aortic regurgitation (A) and aliasing immediately before the aortic valve, suggesting a subaortic membrane (B). During exercise, stress echocardiography demonstrated a progressive increase in the subaortic gradient, associated with the development of a dynamic component of the left ventricular outflow tract obstruction (C–E), reproducing the patient's symptoms. Surgical resection of the subaortic membrane and localized septal myomectomy were subsequently performed. Post-operative imaging demonstrated complete resolution of the colour Doppler aliasing and mild aortic regurgitation, confirming the haemodynamic significance of the subaortic obstruction identified during exercise stress echocardiography. (F and G) Comparative preoperative and postoperative images, respectively.

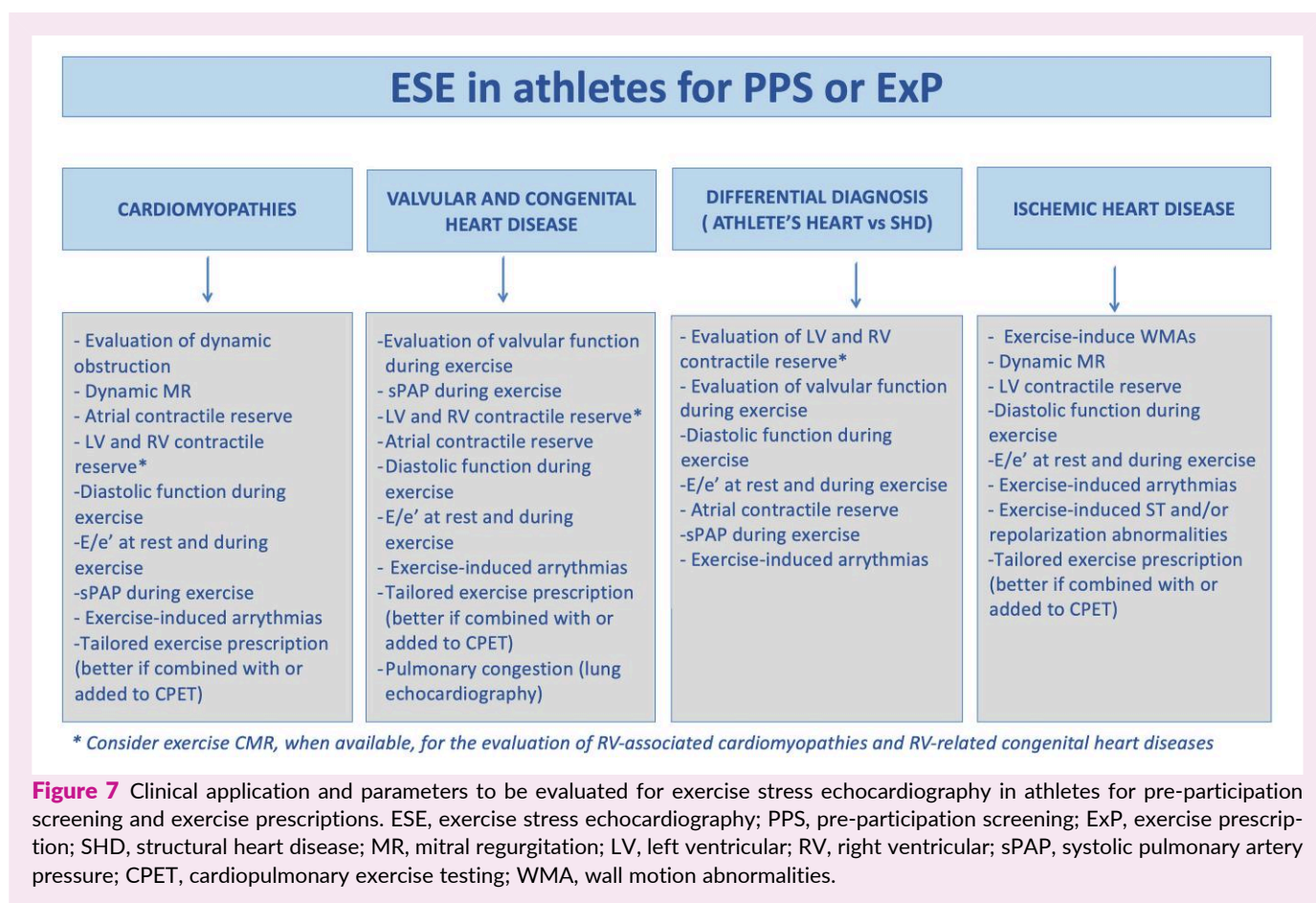
and superimposed pathophysiological findings in competitive and recreational athletes, particularly when combined with stress imaging techniques, e.g. echocardiography or cardiac CMR. In this context, CPET has the advantage of providing contributory information on gas exchange and imaging techniques to implement knowledge of the haemodynamic response by assessing the progressive cardiac and circulatory coupling during physical performance.

The applications of CPET imaging have been proposed in several settings, especially in heart failure diagnostics and pathophysiology, as this may relate cardiac function to clearly defined CPET exercise references, e.g. pre-test, ventilatory thresholds (VT_1 and VT_2) and maximal exercise (VO_{2peak} or

VO_{2max}).^{143,144} The experience and data combining both methods in athletes with and without cardiopulmonary disease are still rare, and it seems quite early to include the simultaneous application into routine diagnostic recommendations. However, CPET and ESE, when performed separately, can significantly yield individual information for exercise prescription regarding upper limits of endurance exercise intensities and exercise prescriptions according to VTs ,^{145,146} particularly in patients under beta-blocker therapy. Both methods, when combined, retrieve information from ECG recordings on exercise-induced arrhythmias, blood pressure during increased exercise, O_2 -diffusion capacity, potential deterioration of myocardial and valvular function, LVOTO in HCM patients,¹⁴⁷ or changes in pulmonary



Figure 6 (A and B) Clinical advice for the use of exercise imaging techniques in athletes. ESE, exercise stress echocardiography; HCM, hypertrophic cardiomyopathy; LVOTO, left ventricular outflow tract obstruction; LV, left ventricular; DCM, dilated cardiomyopathy; EF, ejection fraction; RV, right ventricular; LA, left atrium; CPET, cardiopulmonary exercise testing; CMR, cardiac magnetic resonance.



to echocardiography; however, analysing volumes and derived measures such as stroke volume and EF remains laborious and requires manual contouring and compensation for respiratory motion.¹³⁹ Future developments in artificial intelligence may overcome this limitation. The magnitude of physiological adaptation to supine exercise in the CMR bore depends on the type of exercise used: bicycle ergometer, stepper-stress, or post-exercise imaging. Irrespective of the exercise modality, stroke volume, and EF are expected to increase during exercise due to progressive reductions in end-systolic volume, with no change in end-diastolic volume. In well-trained athletes, EF typically increases by more than 10% during exercise, whereas individuals with underlying cardiomyopathy exhibit an attenuated increase in EF.²⁵

Due to its superior accuracy in assessing the right ventricle, exercise cardiac CMR could benefit the evaluation of congenital heart disease,¹⁵⁰ pulmonary hypertension, or when right heart pathology is suspected in athletic individuals (e.g. ACM).¹⁵² In the context of left-sided disease, exercise-cardiac CMR has shown promising results in evaluating patients with CAD. However, ESE is the preferred technique for evaluating valvular heart disease, with superior ability to assess haemodynamics (e.g. pulmonary and arterial pressures, tissue Doppler imaging, and regurgitation jets) during exercise.¹⁴⁹ Currently, the use and dissemination of exercise cardiac CMR is challenged by the need for a CMR-compatible ergometer, the lack of standardized protocols and cumbersome offline analysis. Future technical development and artificial intelligence could help simplify this test, which can be considered a downstream modality for specific indications, mainly when volumetric assessment is of primary importance.

Clinical advice for the use of exercise imaging techniques in athletes is summarized in Figure 6A and B, while the clinical application and parameters to be evaluated for ESE in athletes for pre-participation screening and exercise prescriptions are reported in Figure 7.

Conclusions and future perspectives

Stress imaging techniques have emerged as reliable, comprehensive tests to obtain diagnostic and prognostic information in competitive and recreational athletes with suspected or established cardiovascular disease, providing information that complements resting and anatomical evaluations. Exercise stress echocardiography is currently the most widely available and clinically applicable modality. Advanced functional approaches, including CPET imaging and stress CMR may offer complementary information in selected clinical scenarios, further enhancing the understanding of cardiovascular responses to exercise (*Graphical Abstract*).

This document emphasizes the need for future research to focus on the standardization and validation of exercise imaging protocols specific to athletic populations. In addition, it underscores the need for large prospective studies to define normal reference values during exercise across sex, age, ethnicity, and sports discipline as well as to clarify the prognostic implications of exercise-derived functional parameters. Finally, it encourages the application of technological advances, particularly artificial intelligence-assisted image acquisition and analysis for enhancing feasibility, reproducibility, and broader clinical adoption of exercise imaging techniques in clinical practice.

Author contributions

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Data availability

No new data were generated or analysed in support of this research.

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