The multi-modality cardiac imaging approach to the Athlete’s heart: an expert consensus of the European Association of Cardiovascular Imaging

Maurizio Galderisi1*, (Chair), Nuno Cardim2, (Co-chair), Antonello D’Andrea3, Oliver Bruder4, Bernard Cosyns5, Laurent Davin6, Erwan Donal7, Thor Edvardsen8, Antonio Freitas9, Gilbert Habib10, Anastasia Kitsiou11, Sven Plein12, Steffen E. Petersen13, Bogdan A. Popescu14, Stephen Schroeder15, Christof Burgstahler16, and Patrizio Lancellotti17

Document Reviewers: Rosa Sicari, (Italy), Denisa Muraru, (Romania), Massimo Lombardi, (Italy), Raluca Dulgheru, (Romania), Andre La Gerche (Australa)

1Department of Advanced Biomedical Sciences, Federico II University Hospital, Naples, Italy; 2Cardiac Imaging Department, Hospital Da Luz, Lisbon, Portugal; 3Department of Cardiology, Second University of Naples, AORN des Colli, Monaldi Hospital, Naples, Italy; 4Department of Cardiology and Angiology, Contilia Heart and Vascular Center, Elisabeth Hospital Essen, Essen, Germany; 5Department of Cardiology, Universtair Ziekenhuis Brussel, Centrum Voor Hart-en Vaatziekten and CHIREC, Brussels, Belgium; 6Department of Cardiology, Interventional and Cardiovascular Imaging, University of Liege Hospital, Liege, Belgium; 7Department of Cardiology, Hospital Pontchaillou – University Medical Center, Rennes, France; 8Department of Cardiology, Center of Cardiologic Innovation, Oslo University Hospital & University of Oslo, Oslo, Norway; 9Cardiology Department, Hospital Fernando Fonseca, Amadora, Portugal; 10Cardiology Department, APHM, La Timone Hospital and Aix-Marseille Universite, Marseille, France; 11Cardiology Department, Sismanoglio Hospital, Athens, Greece; 12Multidisciplinary Cardiovascular Research Center & Leeds Institute of Cardiovascular and Metabolic Medicine, University of Leeds, Leeds, UK; 13NIHR Cardiovascular Biomedical Research Unit at Barts, William Harvey Research Institute, Queen Mary University of London, London, UK; 14University of Medicine and Pharmacy “Carol Davila” - Euroecolab, Institute of Cardiovascular Diseases “Prof. Dr. C. C. Iliescu”, Bucharest, Romania; 15Department of Cardiology, Alb-Fils-Kliniken Goepplinger, Germany; 16Department of Sports Medicine, Internal Medicine V, University of Tuebingen, Tuebingen, Germany; and 17Department of Cardiology, University of Liege Hospital, GICA Cardiovascular Sciences, Heart Valve Clinic, CHU Sart Tilman, Liege, Belgium

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The term ‘athlete’s heart’ refers to a clinical picture characterized by a slow heart rate and enlargement of the heart. A multi-modality imaging approach to the athlete’s heart aims to differentiate physiological changes due to intensive training in the athlete’s heart from serious cardiac diseases with similar morphological features. Imaging assessment of the athlete’s heart should begin with a thorough echocardiographic examination. Left ventricular (LV) wall thickness by echocardiography can contribute to the distinction between athlete’s LV hypertrophy and hypertrophic cardiomyopathy (HCM). LV end-diastolic diameter becomes larger (>55 mm) than the normal limits only in end-stage HCM patients when the LV ejection fraction is <50%. Patients with HCM also show early impairment of LV diastolic function, whereas athletes have normal diastolic function. When echocardiography cannot provide a clear differential diagnosis, cardiac magnetic resonance (CMR) imaging should be performed. With CMR, accurate morphological and functional assessment can be made. Tissue characterization by late gadolinium enhancement may show a distinctive, non-ischaemic pattern in HCM and a variety of other myocardial conditions such as idiopathic dilated cardiomyopathy or myocarditis.

The work-up of athletes with suspected coronary artery disease should start with an exercise ECG. In athletes with inconclusive exercise ECG results, exercise stress echocardiography should be considered. Nuclear cardiology techniques, coronary cardiac tomography (CCT) and/or CMR may be performed in selected cases. Owing to radiation exposure and the young age of most athletes, the use of CCT and nuclear cardiology techniques should be restricted to athletes with unclear stress echocardiography or CMR.

Keywords

- Athlete’s heart
- Left ventricular hypertrophy
- Hypertrophic cardiomyopathy
- Idiopathic dilated cardiomyopathy
- Arrhythmogenic right ventricular cardiomyopathy
- Echocardiography
- Cardiac magnetic resonance
- Coronary cardiac CT
- Nuclear cardiology

* Corresponding author. Tel: +39 081 7464749; Fax: +39 081 5466152; Email: mgalderi@unina.it

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The approach to the athlete’s heart

Definition of the athlete’s heart and physiological left ventricular hypertrophy

The term ‘athlete’s heart’ refers to a clinical picture characterized by two distinct and specific cardiac effects induced by a sustained and regular physical training programme, namely, slow heart rate (HR) and enlargement of the heart.\(^1\) This is the result of haemodynamic changes corresponding to HR reduction and stroke volume (SV) increase along with the reduction in systemic vascular resistance. Further haemodynamic changes include a slight elevation of cardiac output (= SV × HR) during exercise and a more pronounced increase in blood pressure. From a physiological point of view, in the long-run haemodynamic changes during exercise lead to an increase in both left ventricular (LV) internal size (LV dilation) and LV hypertrophy (LVH) which is generated in order to normalize LV wall stress. Cardiac response to training is also influenced by additional factors including hormonal stimuli and genetic susceptibility. LV dilation and LVH may be pronounced enough to mimic a pathological state, but LV systolic and diastolic function are normal or even supra-normal, a feature which is the very nature of the athlete’s heart.

Of interest, in the athlete’s heart ejection fraction (EF), i.e. the percentage of blood in the left ventricle at-end-diastole, which is ejected per beat, remains normal or can be even marginally reduced at rest.\(^3\) This perhaps surprising finding can be ascribed to different factors. First of all, the formula used to calculate EF (100 × SV/LV end-diastolic volume) is designed for individuals with normal sized LV and can produce an intrinsic mathematical underestimation of LV performance in the hearts of the athletes who generally have increased LV end-diastolic volume. Furthermore, EF is an estimate of the LV chamber function and not of myocardial contractility itself; it can therefore underestimate LV ability to increase SV during strenuous exercise. Finally and more importantly, EF of the athletes increases markedly during effort when larger LV end-diastolic volume allows to best utilize the Frank–Starling mechanism (the higher preload, the more rapid diastolic filling, and the smaller LV end-systolic volume) and increase SV compared with non-athletes.\(^1,4\)

Accordingly, a truly comprehensive assessment of LV systolic function in athletes should be performed not only at rest but also during exercise with standard echocardiography, advanced ultrasound techniques and other non-invasive cardiac imaging modalities. However, despite these theoretical incentives to measure LV function and myocardial mechanics during exercise, the majority of the studies have evaluated the athlete’s heart only at rest.

Differential impact of endurance and strength training on the heart (Morganroth hypothesis)

*Endurance sports* (dynamic (isotonic) exercise, e.g., running, walking, cycling, swimming, rowing, and skiing) imply an aerobic training in which the goal is prolonged athletic output over an extended distance or for a long period of time. *Strength training* (isometric exercise, e.g., wrestling, weightlifting) is a type of physical exercise specializing in the use of resistance to induce muscular contraction which builds the strength, anaerobic endurance, and size of skeletal muscles. Morganroth et al.\(^5\) hypothesized that morphological adaptations in athletes correspond with the type of haemodynamic overload imposed on the heart during exercise (Figure 1). Endurance training would lead, as a consequence of volume overload and increased diastolic wall stress, to eccentric LVH (LV mass increase with increased LV cavity dimension). In contrast, strength training leads, as a consequence of pressure overload and increased systolic wall stress, to concentric LVH (increased wall thickness with no change in cavity size). The ‘Morganroth hypothesis’ is not without its critics. Plenty of evidence supported this hypothesis for endurance training, while several studies failed to support the cardiac phenotype expected in strength training.\(^6\) This may at least in part be explained by the fact that some sports (soccer, rugby, hockey, etc.) include both endurance and strength training programmes. Other factors include the absence of standardized measurements, some degree of inaccuracy of M-mode and 2D echocardiographic measurements and the confounding effect of the performance-enhancing substances abuse. In addition, most of the studies challenging the ‘Morganroth hypothesis’ are cross-sectional by design. Figure 2 depicts two different types of echocardiographically detected LVH in an endurance athlete and in an athlete exerting mixed training, respectively. The ‘Morganroth hypothesis’ needs therefore to be restested in longitudinal studies, assessing well-defined exercise protocols and using standardized measurements ideally with cardiac magnetic resonance (CMR) and/or 3D echocardiography. It is noteworthy that a meta-analysis of 66 echocardiographic studies comparing 1451 athletes and 813 control subjects showed significantly larger LV diameters and greater wall thickness, with a relatively balanced LVH, in endurance athletes as well as in strength and combined (endurance + strength) training athletes.\(^7\)

Data from the Italian pre-participation screening programmes reported LV dilatation and LVH in large cohorts of young athletes assessed by echocardiography. LV end-diastolic diameters varied widely, but were found to be above normal in the majority of athletes, whereas LV wall thickness > 12 mm was found only in a small percentage.\(^1\) EF LV is preserved (i.e. > 50%) in the most of but not in
all endurance athletes, and marginally low EF at rest does not equal LV systolic dysfunction in athletes. LV diastolic function remains also normal, independent of the training type. The volume load of endurance training also influences the right ventricle, which is commonly enlarged in endurance athletes.

**EACVI expert consensus key points**

- The original Morganroth hypothesis differentiates eccentric LVH seen in athletes performing endurance training from concentric LVH in athletes undergoing strength training.

### Sudden cardiac death in athletes

The cardiovascular benefits of regular exercise are established and most sports activities are presumed to be good for health. The effects of competitive sports and vigorous exercise training and longevity are, however, uncertain. Excessive training should, therefore, not be regarded as a negligible risk. Although sudden cardiac death (SCD) in athletes is rare, sport activity in adolescent and young athletes is associated with an increased risk of SCD, which has an incidence ranging between 0.5 and 2.3 per 100,000 person-years and is more common in males. However, incidence and numbers might be underestimated. The aetiology of SCD in athletes, 35 years is mostly inherited, it being due to structural heart disease (mainly HCM and ARVC). In contrast, the vast majority of SCD in athletes >35 years is a consequence of acquired disease, in particular CAD.

EACVI expert consensus key points:

- Intense sport activity in adolescent and young athletes is associated with an increased risk of SCD, which has an incidence ranging between 0.5 and 2.3 per 100,000 person-years and is more common in males. However, incidence and numbers might be underestimated.
- The aetiology of SCD in athletes <35 years is mostly inherited, it being due to structural heart disease (mainly HCM and ARVC). In contrast, the vast majority of SCD in athletes >35 years is a consequence of acquired disease, in particular CAD.
Cardiovascular effects of performance-enhancing substances

The use of performance enhancing, illicit substances is an important problem not only in competitive athletes. The list of drugs which are banned is annually updated by the World Anti-Doping Agency and includes anabolic agents and corticosteroids, peptide hormones, growth factors and erythropoietin, β-2 agonists, hormone and metabolic modulators, diuretics and masking agents, stimulants (amphetamine, cocaine), and cannabinoids. Their cardiac effects can include the development of myocardial fibrosis and blunt the late cellular protein synthesis through adrenergic receptors and promote growth factors and erythropoietin, human chorionic gonadotropin, erythropoietin, and selective androgen receptor modulators. Although it is well known that the chronic use of these drugs can induce LVH and LV diastolic dysfunction, their effects in competitive athletes is poorly investigated by cardiac imaging. All stimulants structurally related to amphetamine can cause catecholamine-mediated cardiotoxicity (vasospasm, vasoconstriction, tachycardia, arterial hypertension). As a consequence, the heart is compromised resulting in LVH, myocardial fibrosis, and necrosis. The use of cocaine is associated with acute and/or chronic cardiac disease, but it may also induce regional wall motion abnormalities mimicking premature CAD, aortic dissection, vasculitis, and stroke.

Generally, screening of athletes by cardiac imaging can raise suspicion about this kind of cardiotoxicity (Table 2) but cannot reliably unmask the cardiotoxic effects of banned substances. This lack of reliability is also related to the fact that the use of these drugs is often characterized by periods of abuse and intervals of abstinence in order to maximize their performance-enhancing effects while limiting the negative cardiac consequences. Furthermore, additional drugs can be used to limit side effects and mask the doping effects. However, the combination of LVH with diastolic dysfunction and/or subclinical alteration of systolic function may raise suspicion of a doping effect on the heart when other primary pathologies, mainly HCM and arterial hypertension, have been excluded. In this context, CMR can provide further information about the presence of myocardial fibrosis as a main determinant of diastolic dysfunction but cannot be considered conclusive.

EACVI expert consensus key points:

- Drugs increasing lean muscle mass and enhancing performance as well as non-steroid agents producing anabolic effects may induce myocardial fibrosis, which is consistent with LVH and alterations of LV diastolic function.
- The use of cocaine is associated with acute and chronic cardiac disease but may also induce regional wall motion abnormalities suggestive of premature CAD.
- Cardiac imaging cannot prove or rule out illicit substance abuse. However, the combination of clear-cut LVH with diastolic dysfunction and/or subclinical alteration of systolic function may raise the suspicion of illicit substance abuse when other primary pathologies (HCM or arterial hypertension) are excluded. CMR can provide additional information about the presence of myocardial fibrosis but cannot be considered always conclusive.

### Table 2  Power of cardiac imaging for suspected diagnosis performance-enhancing substances involvement

<table>
<thead>
<tr>
<th>Prohibited substances</th>
<th>Cardiac effect</th>
<th>Demonstration by cardiac imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anabolic androgenic substances</td>
<td>LVH, LV diastolic dysfunction, reduction of EF, reduction of longitudinal strain</td>
<td>+++</td>
</tr>
<tr>
<td>Non-steroids anabolic agents (B2 agonists, peptide hormones, growth factors, recombinant human erythropoietin)</td>
<td>LVH, LV diastolic dysfunction</td>
<td>+</td>
</tr>
<tr>
<td>Stimulants (amphetamine, methamphetamine and cocaine)</td>
<td>Acute and chronic CAD, Aortic dissection</td>
<td>++</td>
</tr>
</tbody>
</table>

+++, largely demonstrated; ++, well demonstrated; +, poorly demonstrated.

The assessment of anatomy and function

**Differential diagnosis of athlete’s heart from pathological remodelling of the left ventricle**

**The role of echocardiography**

Standard echocardiography has a pivotal role in differentiating physiological and pathological LVH. In a series of 1309 athletes of different disciplines, 55% had increased LV end-diastolic diameter and only 15% of the endurance athletes demonstrated values > 60 mm, always in the presence of a normal EF. However, in a study of Abergel et al., the majority of elite cyclists had LV end-diastolic diameter > 60 mm. Cardiac size should be therefore considered in the
context of exercise capacity given its robust association with VO₂ max. A LV end-diastolic diameter >60 mm should therefore raise the suspicion of an idiopathic dilated cardiomyopathy (IDCM) when the LV dilation is out of proportion to the athlete’s conditioning. In 947 elite athletes, maximal end-diastolic septal wall thickness was ≤12 mm in most. Only 1.7% had septal thickness >13 mm (range = 13–16 mm). Septal thickness was lower in women (average = 9 mm, upper limits = 12 mm) compared with men of the same age and body size. Moreover, LV remodelling in Afro-caribbean athletes is characterized by similar cavity size but a disproportionate wall thickening compared with Caucasians. In athletes LVH involves equally the septal and the other LV walls. Conversely, in HCM increased wall thickness (>15 mm) involves mainly the basal septum, and in 20% of HCM cases is associated with additional features, i.e. systolic anterior motion (SAM) of the mitral valve or aortic valve mid-systolic closure. After cessation of exercise training (‘physical deconditioning’) for about 3 months a reduction of maximum septal wall thickness (of about 15–33%) can be observed in healthy athletes, whereas the reduction involving both septal thickness (by 15%) and LV cavity dimension (by 7%) occurs after 1–13 years of training cessation. However, in 20% of the athletes increased LV end-diastolic diameter was persistent even after an average of 5 years of inactivity, despite normal LV function and no occurrence of adverse cardiac events. Conversely, reverse LV remodelling (both LV wall thickness and LV cavity dilation) does not occur in pathological LVH. Likewise, LVH related to anabolic substance abuse is typically not reversible even after 12 months of deconditioning.

In athletes, LV mass increase is usually combined with normal EF at rest, whereas SV is normal or even augmented, as a result of increased preload (LV end-diastolic volume). Pulsed tissue Doppler provides additional information for a comprehensive assessment of functional properties of the athlete’s heart showing normal or supranormal myocardial systolic performance at rest. Accordingly, a cut-off value <9 cm/s of systolic peak velocity (s’, average of four mitral annular sites) demonstrated 87% sensitivity and 97% specificity in distinguishing pathological LVH (arterial hypertension or HCM) from athlete’s LVH.

Also LV diastolic function at rest can appear normal but is often supranormal when compared with no trained individuals, in particular in endurance-trained athletes. Typically, the transmitral E/A ratio is >2 in athletes (Figure 3). This feature helps to distinguish physiological from pathological LVH, which is characterized by an
Table 3  Key echocardiographic measurements to be measured in athletes

<table>
<thead>
<tr>
<th>LV mass index (g/m²)</th>
<th>RV free wall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV end-diastolic volume (mL)</td>
<td>RV basal diameter (mm)</td>
</tr>
<tr>
<td>Septal wall thickness (mm)</td>
<td>RV base to apex diameter (mm)</td>
</tr>
<tr>
<td>LV EF (%)</td>
<td>TAPSE (mm)</td>
</tr>
<tr>
<td>LV SV (mL)</td>
<td>IVC size (mm)</td>
</tr>
<tr>
<td>LV CO (L/min)</td>
<td>IVC respiratory reactivity (%)</td>
</tr>
</tbody>
</table>

A, transmirtal atrial velocity; a, annular atrial velocity (pulsed tissue Doppler); CO, cardiac output; E, transmirtal early-diastolic velocity; e', annular early-diastolic velocity (pulsed tissue Doppler); EF, ejection fraction; IVC, inferior vena cava; LV, left ventricular; RV, right ventricular; s, annular systolic velocity (pulsed tissue Doppler); TAPSE, tricuspid annular plane systolic excursion.

E/A ratio < 1 and a prolonged E velocity deceleration time. Pulsed tissue Doppler-derived early-diastolic myocardial velocity (e') (Figure 3) and e'/a' ratio of basal septal and basal lateral wall were found to be increased in athletes. Of interest, e' velocity of the LV inferior wall was positively correlated with LV end-diastolic diameter in endurance athletes since the predominant pre-load increase of isotonic training induces a proportional improvement of myocardial relaxation. Conversely, in patients with HCM, e' velocity reduction occurred in both the hypertrophic septum and the normal thickness of lateral wall. Regional diastolic dysfunction (e'/a' < 1) was detected in 25% of the myocardial segments of HCM patients (including the non-hypertrophic walls) but was not present in any segments of athletes. Also in hypertensive patients a reduction of the septal e'/a' ratio was observed, in particular in those with clear-cut LVH. Increased E/e' ratio at rest was found to correlate with NYHA class and exercise capacity in HCM patients, whereas it was found to be normal in athletes. However, there are few descriptions of athletes with pathology and we cannot assume that athletes with cardiomyopathies will exhibit the typical pathological features seen in non-athletes with cardiomyopathies. Table 3 summarizes LV key parameters, which should be measured by standard echo Doppler examination in the athletes.

Advanced echocardiographic technologies have been used to characterize the athlete's heart and to distinguish physiological and pathological LVH. Some studies analysed athlete's heart by STE. One of these studies found a slight reduction in global longitudinal strain (GLS) at rest that was compensated by an increase of radial and circumferential strain in professional soccer players. Lower apical radial strain and lower LV twisting at rest were also observed in cyclists than in sedentary controls. These reports suggest LV adaptation of athletes at rest and also highlight the load dependency of strain measurement. Athlete's heart is in fact a very interesting model of strain variation at loading conditions. In another study a significant reduction of systolic and diastolic strain and strain rate was found in hypertensives—but not in athletes—with clear-cut LVH in comparison with normal sedentary controls. An e'/a' ratio > 1 was found in 100% of a large population of competitive athletes, 90% of subjects had e' ≥ 16 cm/s, s' ≥ 10 cm/s, and GLS ≤ −16%. GLS was also found to be lower in 18 hypertensive patients (−17.5 ± 2.8%) than in 22 elite rowers (−22.2 ± 2.7%) and in 19 sedentary controls (−21.1 ± 2.0%) (P < 0.0001). In a study comparing soccer players with HCM patients, radial strain—but not longitudinal strain or pulsed tissue Doppler-derived annular systolic velocities—differentiated the two groups. Very recently, the combination of 2D STE and 3D volumetric assessment allowed identifying different LV remodelling patterns in endurance-trained (increased LV twisting), strength-trained, and mixed-trained athletes. Albeit promising and useful to gain physiological information on the athlete's heart, the experience with STE is still preliminary and does not yet support its routine use for the differential diagnosis of athlete's heart from pathologic LVH.

EACVI expert consensus key points:

- Standard echocardiography is the first-line exam for differentiating athlete's heart from pathologic LVH.
- In elite athletes the LV end-diastolic diameter is not frequently increased > 60 mm. A LV end-diastolic diameter > 60 mm—when combined with reduced EF and abnormal diastolic function—should raise suspicion of IDCM.
- In elite athletes LVH involves typically all myocardial segments and the maximal septal thickness is usually ≤ 12 mm. Septal wall thickness is lower in female athletes and more pronounced in African than in Caucasian athletes.
- In HCM increased wall thickness (> 15 mm) involves mainly the basal septum and in 20% of HCM cases is associated with additional features, such as SAM or aortic valve mid-systolic closure.
- After physical deconditioning of three months, a reduction of LV wall thickness can be observed in athletes but not in HCM.
- In athletes LVH is combined with normal EF, normal, or even increased SV and s' velocity > 9 cm/s, whereas s' is < 9 cm/s in HCM. EF is normal or high in early stages and possibly reduced in advanced stages of HCM.
- LV diastolic function is often supranormal in athletes (E/A ratio > 2, increased e' velocity, low E/e' ratio). In the HCM E/A ratio is < 1, E velocity deceleration time is prolonged, e' velocity and e'/a' ratio are low. However, normal LV diastolic filling pattern does not exclude pathological LVH.

The role of CMR

LV and RV volumes and mass as well as global and regional contractile function can be accurately assessed with steady state free precession (SSFP) cine CMR. The excellent inter-study reproducibility of cine CMR can be relevant when assessing not only the features of the athlete's heart but also individual changes, such as reduction of LV wall thickness following training cessation. Quantification of LV contraction and relaxation through measurements of myocardial strain and strain-rate can be obtained by CMR tagging, but recently introduced CMR feature of tissue tracking techniques allows derivation of such parameters also from routine SSFP cine images. Contrast enhanced CMR, using the late gadolinium enhancement (LGE) imaging, enables differentiation of ischaemic from non-ischaemic patterns of myocardial damage.
patterns of myocardial damage include a subendocardial ring of enhancement (myocardial amyloid), patchy enhancement (HCM), or mid-myocardial and epicardial hyper-enhancement (myocarditis or Anderson Fabry’s disease). A more recent and promising CMR methodology, T1 mapping, provides the assessment of diffuse myocardial fibrosis either using native T1 values or through quantification of the extracellular volume from pre- and post-contrast T1 mapping, which cannot be visualized using LGE. This may further increase the diagnostic accuracy to identify pathological LVH.

Cine CMR was used to differentiate athlete’s heart from pathological LVH using multiple geometric measures. Twenty-eight normal controls, 25 elite athletes, 35 patients with HCM, 18 hypertensive patients, and 24 patients with LVH due to aortic valve stenosis were assessed. LV diastolic wall to volume ratio, which corresponds substantially to echocardiographic derived relative wall thicknesses, had the highest area under the curve (0.993) providing a sensitivity of 80% and a specificity of 99% to distinguish athlete’s heart (<0.15 mm × m^3/mL) from all forms of pathologic LVH. No false-positives and false-negatives were identified when differentiating athlete’s hearts from pathological LVH using a multivariate logistic regression model with multiple geometric measures. Single or combined geometric measures using CMR were not able to differentiate various other forms of pathological LVH such as HCM or that due to arterial hypertension. The potential advantage of CMR over echocardiography was also demonstrated. Compared to the reference CMR, echocardiography missed LVH in 6% of cases with suspected HCM and underestimated the maximal LV end-diastolic wall thickness by 20%; echocardiography also failed to document LV end-diastolic wall thickness ≥30 mm in 10% of cases. In subjects with abnormal ECGs but normal or borderline echocardiogram, CMR was able to identify patients with HCM and apical HCM (wall thickness >28 mm). LGE derived non-ischaemic pattern was described in multiple studies of HCM. Of interest, a small prevalence of LGE was demonstrated even in non-hypertrophied myocardial segments. Figure 4 shows a CMR image in an endurance athlete which facilitated a diagnosis of HCM, with LGE in the hypertrophied septum indicating regional fibrosis. This suggests that LGE increases the diagnostic accuracy over and above the geometric measures that one can provide and determine using CMR cines itself, but LGE absence cannot rule out HCM. On the other hand, LGE can be seen in athletes without evidence of HCM. T1 mapping might be of potential use to distinguish athlete’s heart from pathologic LVH but has never been systematically investigated for this differential diagnosis.

Figure 4: Diagnosis of HCM in a 41-year old male endurance athlete by CMR. (A) The left ventricle is enlarged (LV end-diastolic diameter = 58 mm), septal thickness is 15 mm. (B–D) LGE revealed myocardial fibrosis of anterior and inferior septum. Genetic analysis confirmed the diagnosis of HCM.
CMR can help to differentiate also athlete's heart from IDCM not only by providing high image quality and accurate measurements of volumes and EF of both ventricles, but also by using LGE which demonstrates mid-myocardial streaks in about one-third of subjects. However, the absence of LGE cannot rule out IDCM.

Expert consensus key points:

- CMR is superior to echocardiography in differentiating athlete’s heart from structural and functional changes which are related with HCM (80% sensitivity and 90% specificity of cine CMR derived LV diastolic wall to volume ratio < 0.15 mm x m²/mL in athlete's LVH).
- LGE may provide additional diagnostic information beyond geometric measures obtained by simple cine CMR in order to differentiate athlete's heart from HCM.
- CMR can be helpful to distinguish athlete's heart from IDCM not only because of more accurate measurements of volumes and EF compared with echocardiography, but also due to additional information provided by LGE.
- The absence of LGE does not rule out HCM or IDCM.

Left atrial size and sport practice: implications for normal ranges

Left atrial (LA) enlargement (Figure 5) is common in large cohorts of athletes, because of LA pressure increase during exercise. Whether increased LA size could be a potential determinant of atrial fibrillation in athletes remains controversial.

By using standardized methods, echocardiography allows identification of LA enlargement. The 2D LA volume method (area-length method or modified Simpson) is preferable to the linear LA antero-posterior diameter. LA size should be indexed for the body surface area (LA volume index = LAVi). Current ASE/EAE recommendations on LV diastolic function indicate a cut-off point of ≥ 34 mL/m² of 2D LAVi for establishing LA enlargement. Demographic and anthropometric factors (e.g., ethnicity) are recognized determinants of LAVi, whereas the role of ageing remains debated. Data from the large sample size (n = 734) of the NORRE study point out that age and gender do not influence 2D LAVi in normal subjects.

Prevalence of LA enlargement in competitive athletes were firstly reported by Pelliccia et al. who found a mild increase of LA antero-posterior diameter (≥ 40 mm) in 18% of athletes, a marked dilatation (≥ 45 mm) in 2%, and a close association between LA diameter and LV cavity dimension. LA enlargement appeared to be influenced by the type of sport (greatest impact of sports which combines endurance and strength training). Upper limits of LA diameters (45 mm in women, 50 mm in men) were defined in athletes. Figure 6 summarizes the data from two different studies that can be used to justify different normal ranges for LA size in athletes than in the normal population. The first study provided reference values and relative impact of different sport activities and found LA enlargement (LAVi ≥ 34 mL/m²) in 3.2% of the athletes. The key independent determinants of LAVi were training type and duration and LV end-diastolic volume. The second study compared prospectively LAVi determinants in healthy sedentary individuals and competitive athletes over a wide age range. LA volumes were marginally lower in athletes as abnormal.

STE-derived LA strain has been used to assess LA function, which is enhanced in athletes, and impaired in HCM patients. However, it would be premature to currently recommend its clinical use for the assessment of the athlete’s heart. Since echocardiography shows a trend to underestimate LA volumes, CMR can be an attractive alternative imaging modality. A very recent study demonstrated that both LA and right atrial (RA) volumes, despite being larger in athletes, did not differ from controls after normalization for total heart volume. Of interest, LA volumes were marginally lower in female athletes.

Expert consensus key points:

- Upper limits of LA antero-posterior diameter (45 mm in women, 50 mm in men) have been defined in athletes.
- Although LAVi is preferred over LA antero-posterior diameter as measure of LA size, currently normal ranges have not been defined for LAVi in athletes. The normal range for sedentary healthy controls (34 mL/m²) leads to frequent misclassification of dilated LA cavities in athletes.
- There is a need to develop normal ranges for LAVi in athletes and these should ideally be specific for gender and type of sport.
- Since echocardiography shows a trend to underestimate LA volumes, CMR can be an attractive alternative imaging modality and has confirmed less pronounced LA remodelling in female than in male athletes.

![Figure 5: Left atrial dilation in an endurance athlete (rower). The current ASE/EAE recommendations on LV diastolic function indicates a cut-off point ≥ 34 mL/m² to define LA enlargement (see Nagueh SF et al.83). Accordingly, LA volume index = 38.055 mL/m² of this rower is consistent with LA enlargement. However, the development of athlete-specific normalcy criteria, ideally partitioned according to gender and sport activity, could help avoid labelling such left atrial dilation as pathological. LALS A4C, LA longitudinal diameter in apical four-chamber view; LAAs A4c, LA area; LAESV A-L A4C, LA end-systolic volume; LA Vol IND, LA volume index.](https://academic.oup.com/ehjcimaging/article-abstract/16/4/353/2397505/Downloaded-from-https://academic.oup.com/ehjcimaging/article-abstract/16/4/353/2397505)
RV chambers and function

Training activity has a well-known impact on the right heart chambers, which react to increased blood volume with both RV and RA dilation (Figure 7). Mild functional tricuspid regurgitation and dilation of the inferior vena cava, but with preserved respiratory reactivity (Figure 7), are also common. Once more than mild tricuspid regurgitation is present, a structural heart disease should be sought for an athlete. While the potential for concentric RV remodelling in athletes is less clear, eccentric RV remodelling is common in athletes. The upper limits of RV and RA dimensions were derived from a cohort of 650 elite athletes using echocardiography. RV and RA dimensions appeared to be greater in elite endurance-trained athletes than in age- and sex-matched strength-trained athletes and sedentary controls. Another echocardiographic study demonstrated a trend towards thicker RV free walls and larger RV cavities in 127 male elite endurance athletes. Also, the inferior vena cava appeared to be dilated (average value = 26 mm, upper limit = 40 mm) in a study involving 58 endurance athletes. Other reports confirmed these observations using CMR and suggested a balanced RV and LV enlargement with a similar balanced increase in RV and LV mass. Controversial findings are available on the impact of strength training on the right ventricle. RV dilation coupled with enhanced systolic and diastolic function was observed in 40 endurance athletes but not in 24 strength-trained athletes, these results being possibly due to underpowered sample size of the second group of athletes. In a recent systematic meta-analysis study of training mode, RV dilatation was greater in the endurance group than in controls but regression models demonstrated positive and significant associations between body surface area and RV parameters. These results highlight the need of indexing RV parameters for the body surface area in athletes.

Standard echocardiography is the initial imaging modality of choice for RV assessment in athletes. Normal values of RV wall thickness are <0.5 cm, as measured from the sub-costal or parasternal long-axis views. Using M-mode or 2D imaging, RV-free wall thickness should be measured at end-diastole at the level of the tricuspid valve chords. The combination of multiple views permits to obtain more information with an entire assessment of the areas of increased wall thickness. RV enlargement should be identified by measuring at least the RV basal diameter and RV base to apex diameter in the apical
Table 3 typically normal or even supranormal. By combining 3D echo and 2D STE of the right ventricle, it appears that RV preload exerts its maximal influence on the lateral longitudinal fibres (RV lateral longitudinal strain). This may contribute to RV supranormal function in the athlete’s heart, as the findings had been adjusted for potential confounders.

In subjects with suboptimal echocardiographic images, CMR is the reference standard for the assessment RV myocardial thickness and chamber volumes, and offers high spatial and temporal resolution. CMR is also able to identify RV myocardial muscle bands, such as the crista supraventricularis, which can be incorrectly included in the measurements of maximal LV wall thickness on echocardiographic assessment. If the diagnosis of AVRC is suspected in athletes, CMR should always be requested. Although the ARVC diagnostic criteria were not developed for the subgroup of athletes, they highlight the importance of RV wall motion abnormalities, RV size, and function. CMR evidence for fibro-fatty myocardial replacement in both RV and LV is not currently considered a diagnostic criterion for ARVC. It also needs to be considered that cardiac imaging, whether by echocardiography or CMR, cannot confirm or exclude a diagnosis of ARVC on its own and clinical features need to be considered. A possible effect of exercise in accelerating the development of ARVC in athletes who are genetically predisposed should also be taken into account.

EACVI expert consensus key points:
- Standard echocardiography is the first line cardiac imaging exam for differentiating RV remodelling in athlete’s heart from pathologic right ventricles.
- Eccentric RV remodelling is common in athletes while the occurrence of concentric RV remodelling is unclear.
- A differential diagnosis of ARVC in athletes should be investigated with echocardiography and CMR. Neither imaging modality may confirm or exclude the diagnosis of ARVC, which remains a clinical diagnosis. RV dilatation and reduction in RV systolic function in the absence of LV remodelling should raise suspicion that this cannot be solely due to exercise training.

The detection of myocardial ischaemia and delineation of coronary anatomy in athletes

Cardiovascular disease is reported as one of the main causes of SCD in athletes, due to CAD in older or congenital coronary artery anomalies in younger athletes. At present, there is a broad range of screening recommendations for the diagnosis of myocardial ischaemia in athletes with important variations between countries, type of sport and competition level. In 2011, the sections of Exercise Physiology and Sports Cardiology of the European Association of Cardiovascular Prevention and Rehabilitation stated that maximal exercise testing should be restricted to high-risk persons with at least moderate...
Cardiac nuclear imaging

Very limited data exist on the use of myocardial perfusion imaging (MPI) in asymptomatic athletes. Non-attenuation-corrected \(^{99m}\)Tc-sestamibi SPECT imaging was used to evaluate 18 young male elite athletes and myocardial perfusion defects were observed in areas with LVH, reducing the specificity of SPECT in the athlete’s setting. In another study, resting thallium-201 myocardial perfusion defects were common in young male endurance athletes but were not associated with echocardiographically detected LV wall motion abnormalities. Using positron emission tomography (PET) and measuring myocardial blood flow, oxygen consumption and free fatty acid uptake with \(^{15}\)O\(_2\), \(^{15}\)O\(_2\)O, and \(^{18}\)F\(_2\)FTHA during euglycaemic hyperinsulinaemia, myocardial oxygen consumption, and blood flow per unit mass of the myocardium were found to be reduced in endurance athletes compared with sedentary subjects. This can be explained by reduced energy requirements due to anatomical and physiological changes of the athlete’s heart as an adaptation to endurance training. Myocardial fatty acid uptake was not significantly changed during insulin stimulation. By assessing myocardial metabolism using \(^{18}\)F\(_2\)FDG PET, the rate of glucose uptake per unit mass of the myocardium was similarly decreased in endurance athletes and weightlifters with an increased LV mass compared with sedentary men (Figure 9). Prolonged exercise training may also alter the cardiac sympathetic function, which can be detected by MIBG imaging. One study examined the ratio of heart/mediastinum count (H/M) and the washout rates of \(^{123}\)I-MIBG in athletes and normal controls. There was a significant decrease in \(^{123}\)I-MIBG myocardial uptake in athletes, as well as an increased washout rate. Another study showed severely reduced myocardial MIBG uptake of the inferior region in athletes with sinus bradycardia, suggesting selective inferior myocardial wall sympathetic denervation, which may be related to increased vagal tone and athlete’s bradycardia. The magnitude to which this is a physiological or pathological change and whether it could have prognostic implications needs to be clarified. Taken together all these studies show that cardiac nuclear imaging in the athlete’s setting is more suitable for research purposes than for a clinical application and should not be recommended as a first line test in competitive athletes.

Coronary cardiac tomography

Although coronary anomalies as well as myocardial bridging are frequent findings in routine coronary cardiac tomography (CCT), the exact prevalence is unknown, ranging for myocardial bridging from 15 to 85% at autopsy and 0.5 to 16% at coronary angiography. CCT offers the opportunity to evaluate coronary arteries non-invasively (Figure 10) and, by using latest generations scanners, also with a very low radiation dose. Moreover, subclinical CAD can be detected also by calcium scanning. Owing to the high accuracy of CCT—especially in terms of ruling out significant CAD—it could provide valuable information also in the athletes setting. Considering that especially endurance athletes have favourable lipid values and a low-cardiovascular risk according to standard risk calculators, the ‘true’ cardiovascular risk might be underestimated. Moreover, the association between premature CAD and endurance training, e.g. marathon running, is discussed controversially. Möhlenkamp et al. reported higher calcium scores in athletes including 108 marathon runners compared with age- and risk-factor-matched athletes. It gives information about cardiac function, reserve, exercise capacity, and arrhythmias. CAD may be diagnosed by exercise stress echocardiography with moderate sensitivity and specificity (about 76 and 88%, respectively), comparing favourably with other stress-testing methods. However, in athletes with anomalous implantation of coronary artery, the exercise stress echo can be normal (absence of inducible ischaemia), but this does not change the risk of SCD in such patients. Exercise stress echo is also of particular interest in athletes with EF < 45–50% at rest to test if there is contractile reserve (=EF increase) during exercise. A considerable EF increase suggests low EF at rest to be related to low preload, and not to LV systolic dysfunction.

Using adenosine stress echocardiography in endurance athletes, a supernormal coronary flow reserve (5.9 ± 1.0 vs. 3.7 ± 0.7 in controls, \(P < 0.01\)) in the distal left anterior descending coronary artery was observed. The hyperaemic flow velocities were higher, whereas resting flow velocities were lower than in controls.
controls. This observation is of major importance as coronary calcification is an independent risk factor for all-cause mortality and cardiovascular events in the general population. Whether these observations can be generalized to athletes remains open to speculation. However, at present CCT should not be recommended as a first line imaging test in competitive athletes.132

Perfusion CMR imaging
Stress perfusion CMR imaging can help in the diagnosis of CAD in athletes as in the general population. Stress CMR has become a routine clinical test in many institutions, although it remains less available than stress echocardiography and cardiac nuclear imaging.133 Current ESC guidelines recommend stress CMR alongside other tests as a gate keeper to invasive angiography in patients with suspected CAD and intermediate pre-test probability.134 However, only very few studies were performed using stress perfusion CMR in athletes or in patients with HCM. In one of these, which compared 35 patients with HCM and 14 healthy controls, vasodilator stress myocardial perfusion was significantly reduced and correlated with the degree of hypertrophy (as an expression of coronary microvascular dysfunction) in HCM patients.135 In cohorts of patients with overt HCM, HCM mutation carriers, athlete’s heart with physiological LVH and normal controls, myocardial perfusion reserve by CMR was impaired only in overt HCM, but normal in athletes with LVH.136 Thus, if diagnostic uncertainty prevails in an athlete with LVH, perfusion CMR could provide additional information to facilitate the differential diagnosis. CMR may also play an important role in depicting proximal coronary artery anomalies in athletes using coronary magnetic resonance angiography (MRA). Three-hundred-sixty healthy men and women (207 athletes and 153 non-athletes) were assessed with the standard CMR and an additional coronary MRA within a maximum of 10 min scan time: among 335 individuals with technically adequate CMR studies, four showed a malignant variant of the right coronary artery. The authors concluded that a 10 min coronary MRA is able to depict coronary origins and their proximal course. Therefore, this technique may be used as a non-invasive tool to exclude coronary artery anomalies in asymptomatic athletes under 35 years of age, as they have low risk of CAD.137
### Table 4

*Average and upper limits of the main echocardiographic LV parameters in elite athletes (*sample sizes ≥ 400)*

<table>
<thead>
<tr>
<th>Athlete’s left heart morphologic and functional parameters</th>
<th>Upper limit</th>
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<tbody>
<tr>
<td>Authors</td>
<td>Journal</td>
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<tr>
<td>Pelliccia et al.</td>
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Intense exercise: good or dangerous?

The positive effect of training exercise on LV contractile reserve is recognized, with increased endurance exercise while altered heart rate and blood pressure are induced during exercise. Exercise-induced symptoms and/or ischaemic-like ECG signs may be suspected, it is reasonable to consider CCT and/or CMR as well as attenuation-corrected SPECT MPI and PET MPI. Intense exercise: good or dangerous?

Table 5  *Average and upper limits of the main echocardiographic RV parameters in elite athletes (*sample sizes ≥ 400)

<table>
<thead>
<tr>
<th>Athlete's right heart morphologic and functional parameters</th>
<th>Upper limit</th>
<th>Athlete's right heart morphologic and functional parameters</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authors Journal</td>
<td>Number of athletes</td>
<td>Type of sport</td>
<td>Parameter</td>
</tr>
<tr>
<td>D’Andrea et al.</td>
<td>650</td>
<td>Endurance/power</td>
<td>RV end-diastolic diameter (basal) (RVD1) (mm) (male)</td>
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<tr>
<td>Int J Cardiol 2013;164:48–57</td>
<td></td>
<td></td>
<td>(female)</td>
</tr>
<tr>
<td>Zaidi et al. 173</td>
<td>675</td>
<td></td>
<td>RV end-diastolic diameter (basal) (RVD1) (mm) (female)</td>
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<tr>
<td>Circulation 2013;127:1783–92</td>
<td></td>
<td></td>
<td>(male)</td>
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<tr>
<td></td>
<td>675</td>
<td></td>
<td>RV end-diastolic diameter (middle ventricle) (RVD2) (mm) (male)</td>
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<tr>
<td>Zaidi et al. 173</td>
<td></td>
<td></td>
<td>(female)</td>
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<tr>
<td>Circulation 2013;127:1783–92</td>
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<td>RV end-diastolic diameter (base-to-apex) (RVD3) (mm) (male)</td>
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<tr>
<td></td>
<td>650</td>
<td>Pulmonary artery systolic pressure (mmHg)</td>
<td>24</td>
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<tr>
<td>Currin et al. 169</td>
<td></td>
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<td>RA area (cm²/m²) (male)</td>
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<tr>
<td>Int J Cardiol 2013;164:48–57</td>
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<td>RA area (cm²/m²) (female)</td>
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<td>Pulmonary artery systolic pressure (mmHg)</td>
</tr>
<tr>
<td>Zaidi et al. 173</td>
<td></td>
<td></td>
<td>TAPSE (cm)</td>
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<tr>
<td>Circulation 2013;127:1783–92</td>
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<td>RV area change (%)</td>
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</table>
flow reserve following a marathon run. However, LGE was observed by CMR in 12% of marathon runners and its presence was correlated with the number of marathons previously performed, suggesting that intense sport activity could induce myocardial scarring.

The right ventricle appears to be particularly vulnerable to the effects of intense endurance exercise. RV dilation following an ultra-endurance triathlon without changes of LV dimensions was observed by M-mode, 2D echo and STE (reduction of longitudinal strain \( \approx \) 15% relative to baseline values). The upper physiological limit of pulmonary arterial systolic pressure in endurance athletes may reach 40 mmHg at rest, in line with the greater increase in SV and pulmonary arterial pressure increase during exercise is more pronounced in athletes than in non-athletes. Obviously, pulmonary arterial pressure can increase during effort. Repeated observations of RV dysfunction following prolonged intense exercise would suggest that there is some point in time in which the physiological demands of exercise can no longer be sustained by RV metabolic reserves. It remains to be determined whether recovery from repeated bouts of exercise-induced RV dysfunction is complete in all athletes.

EACVI expert consensus key points:

- Transient ‘cardiac fatigue’ can occur during prolonged exercise.
- Marginal decreases of global and regional LV systolic function (decrease of EF), alterations of LV diastolic function, and appearance of regional wall motion abnormalities have been documented in endurance athletes.
- RV dilation following an ultra-endurance triathlon without changes of LV dimensions has been observed and pulmonary arterial pressure is more pronounced during intensive exercise in athletes.

A proposal for multimodality imaging for distinguishing athlete’s heart from cardiac disease

Considerations regarding pre-participation screening for the prevention of SCD in athletes

Strategies for the prevention of SCD are endorsed by sport governing bodies but mandatory pre-participation screening remains rare. The goal of pre-participation screening of competitive athletes is the early identification of those with potentially fatal cardiovascular abnormalities, thus reducing the individual risk of SCD during sport activity. Comprehensive pre-participation screening protocol in competitive athletes was established in Italy, in which family history, physical examination, and 12-lead ECG at rest—very effective for detection of electrical abnormalities and also HCM

![Figure 11](image-url)
and ARVC in athletes—\textsuperscript{159–161}—are combined. With this protocol, near 90\% reduction in the incidence rates of SCD from 3.6/100,000 per person-years to 0.4/100,000 per person-years was demonstrated in a secular trend study.\textsuperscript{162} This is reflected in the ESC guidelines, which recommend the inclusion of a ECG at rest in pre-screening programmes.\textsuperscript{155} In the same guidelines, conditions predisposing to SCD incorporate cardiac imaging (mainly echocardiography) in athletes with suspected or ascertained congenital and acquired heart diseases.\textsuperscript{115} Conversely, the American Heart Association does not consider cardiac imaging and does not support the routine use of the ECG in the athlete’s setting.\textsuperscript{116} Primary arguments against ECG use include the possibility of false-positive results, high-incremental cost-effectiveness ratio, and psychological implications for athletes and their families. Moreover, the interpretation of the athlete’s ECG and recognition of normal variants according to age, ethnicity, gender, sports modality, or competitive level is often difficult and requires specific expertise. Furthermore, a recent study from Israel reported no change in SCD incidence rates in athletes following the implementation of screening programmes.\textsuperscript{163} The role of pre-participation screening may even be controversial. To date, the current evidence is not sufficient to justify the use of cardiac imaging as primary screening modality in the guidelines on athletes, but these concerns shall not be confused with the very useful application of imaging for the assessment of athletes with symptoms, abnormal ECG or positive family history.\textsuperscript{164}

**The potential role of multimodality imaging**

The multi-modality imaging approach of the athlete’s heart has an important potential in order to differentiate it from serious cardiac diseases, which may mimic physiologic changes due to intensive training.\textsuperscript{165} Before cardiac imaging can be utilized in pre-participation screening, specific reference values of the various cardiac structural and functional parameters in athletes are needed. Table 4\textsuperscript{1,6,28,52,76,77,166–172} and Table 5\textsuperscript{93,155,173} show average values and upper limits of the main echocardiographic LV and RV parameters, respectively, established in studies with large sample size in competitive (endurance and strength-trained) athletes. Efforts should be made to collect normal values of some missing parameters and also presenting them according to race, gender, and different sport disciplines. LV wall thickness is a key parameter since it can contribute to the distinction between athlete’s LVH and HCM. LV end-diastolic diameter is another hinge parameter.

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**Figure 12:** Proposed EACVI algorithm for differential diagnosis between athlete’s heart and ARVC and diagnosis of CAD in athletes.
In athletes with suspected CAD, cardiac imaging provocative tests should be performed when the results of exercise ECG appear uncertain. Among provocative tests, physical exercise echocardiography may be the first choice. The use of CCT and nuclear cardiology techniques should be restricted to athletes with unclear stress echocardiography.

**EACVI expert consensus key points:**

- The goal of pre-participation screening of competitive athletes is to identify those who have cardiovascular abnormalities, thus reducing the risk of SCD during sport activity.
- ESC guidelines recommend pre-screening including ECG at rest, but the American Heart Association does not recommend this.
- ESC guidelines propose echocardiography and, possibly, other non-invasive cardiac imaging, in athletes with suspected or ascertainable congenital heart disease, heart valve disease, cardiomyopathies, and myocarditis.
- Normal ranges for all relevant cardiac parameters and for each imaging technique are needed, by categorizing the majority of parameters by gender and type of sport.
- CMR may help to differentiate athlete’s heart from other forms of LVH and LV dilatation through demonstration of non-ischaemic patterns of LGE, which would not be seen in exercise-related remodelling.
- In athletes with suspected CAD, cardiac imaging provocative tests should be performed when the results of exercise ECG appear uncertain. Among provocative tests, physical exercise echocardiography may be the first choice. The use of CCT and nuclear cardiology techniques should be restricted to athletes with unclear stress echocardiography.

**Future perspective**

Cardiac imaging is important in identifying cardiovascular disease in athletes, but the final diagnosis has to be based on multiple factors including medical history, sports history, training load, symptoms, age, gender, ECG (resting and exercise), or genetic analysis. The controversy of using echocardiography in the pre-participation screening of competitive athletes is likely to remain as it is mainly around the high-incremental cost-effectiveness ratio and the impact of false-positive results on athletes and family. Although studies are still limited, cardiac ultrasound using pocket size imaging devices might offer a cheap but valid possibility of first-line imaging assessment also in athletes. Whenever needed, more advanced cardiac imaging techniques, such as CCT, CMR, and nuclear imaging may add incremental diagnostic and prognostic information, CMR LGE, CMR T1 mapping, low-dose CCT, and new PET tracers offer the greatest potential.

**Conflict of interest:** none declared.

**References**


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Multi-modality imaging and athlete’s heart


