CHAPTER 4

Echocardiogram in athlete’s heart

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1 Introduction

Echocardiography is one of the most used cardiovascular imaging method in the athletic population, due to its widespread availability, relatively low cost, and safety. Indeed, it has the unique ability to provide complementary information on cardiac morphology, function, and hemodynamics, playing a key role in the diagnosis and clinical management of a wide spectrum of cardiovascular diseases [1,2]. Its use in athletes is increasing, thanks to the fact that the low acoustic impedance of the chest of athletic population makes it possible to obtain high-quality images and assess all the cardiac structures and that scan can also be performed by noncardiologist physicians [3]. According to the current recommendation of the European Association of Preventive Cardiology (EAPC) and the European Association of Cardiovascular Imaging (EACVI), echocardiography is a valid second-line investigative tool in athletic populations. However [4,5], it has been proposed that echocardiography could be also be used as a first-line screening tool in the preparticipation cardiovascular evaluation of professional and amateur athletes, even in the setting of a normal clinical and electrocardiographic evaluation [3,6]. It has also been hypothesized [6] that focused echocardiography may become standard practice in larger screening practices (Table 1) (Figs. 1 and 2).

Over the decades, advances in ultrasound technology have resulted in the evolution of echocardiography from simple M-mode to two-dimensional imaging, Doppler assessments of flow and pressure, three-dimensional anatomical imaging, and dimensional analysis of myocardial deformation. At the same time, extensive data describing cardiovascular adaptation in response to

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Table 1 Proposed focused protocol of echocardiography in preparticipation screening of athletes.

Echo views	Structure	Measure
PLAX	LV	IVS
		End diastolic diameter
		Posterior wall
	Mitral valve	Leaflets
		Color
	Aortic valve	Valsalva sinus
		Color
	Ascending aorta	Size
PSAX-aortic valve	Aortic valve	Morphology
	OCA	
	RV	RVOT
	PDA	
A4C	LV	Trabeculations
		Wall motion
	VSD	
	ASD	
	Mitral valve	Color
		PW
	TV	Color
		CW
A5C	Aortic valve	Color
		CW
Subcostal	ASD	
	Inferior vena cava	Size
		Breath collapsibility
	Pericardium	Pericardial effusion
Suprasternal	Aortic arch	Size
	COA	

A2C, apical 2 chambers view; *A4C*, apical 4 chambers view; *A5C*, apical 5 chambers view; *ASD*, atria septum defect; *BSA*, body surface area; *COA*, aortic coarctation; *CW*, continuous Doppler wave; *EF*, ejection fraction; *FAC*, fractional area charge; *IVS*, interventricular septum; *LA*, left atrium; *LAVI*, left atrium ventricle index; *LV*, left ventricle; *OCA*, origin of coronary arteries; *PDA*, patent ductus arteriosus; *PLAX*, parasternal long-axis view; *PSAX*, parasternal short axis view; *PW*, power doppler wave; *RA*, right atrium; *RV*, right ventricle; *RVD*, right ventricle diameter; *RVOT*, right ventricle outflow tract; *STJ*, sinotubular junction; *TAPSE*, tricuspid annular plane excursion; *VSD*, ventricular septal defect.

Adapted from Palermi S, Serio A, Vecchiato M, Sirico F, Gambardella F, Ricci F, et al. Potential role of an athlete-focused echocardiogram in sports eligibility. World J Cardiol 2021;13(8):271–97.

exercise have been published, improving our understanding of the physiological and morphological adaptation of the heart of athletes [7,8].

Prolonged physical activity causes structural, functional, and electrical modification resulting in a physiological remodeling response termed "athlete's heart" [9,10]. While interest has largely focused on the left ventricle

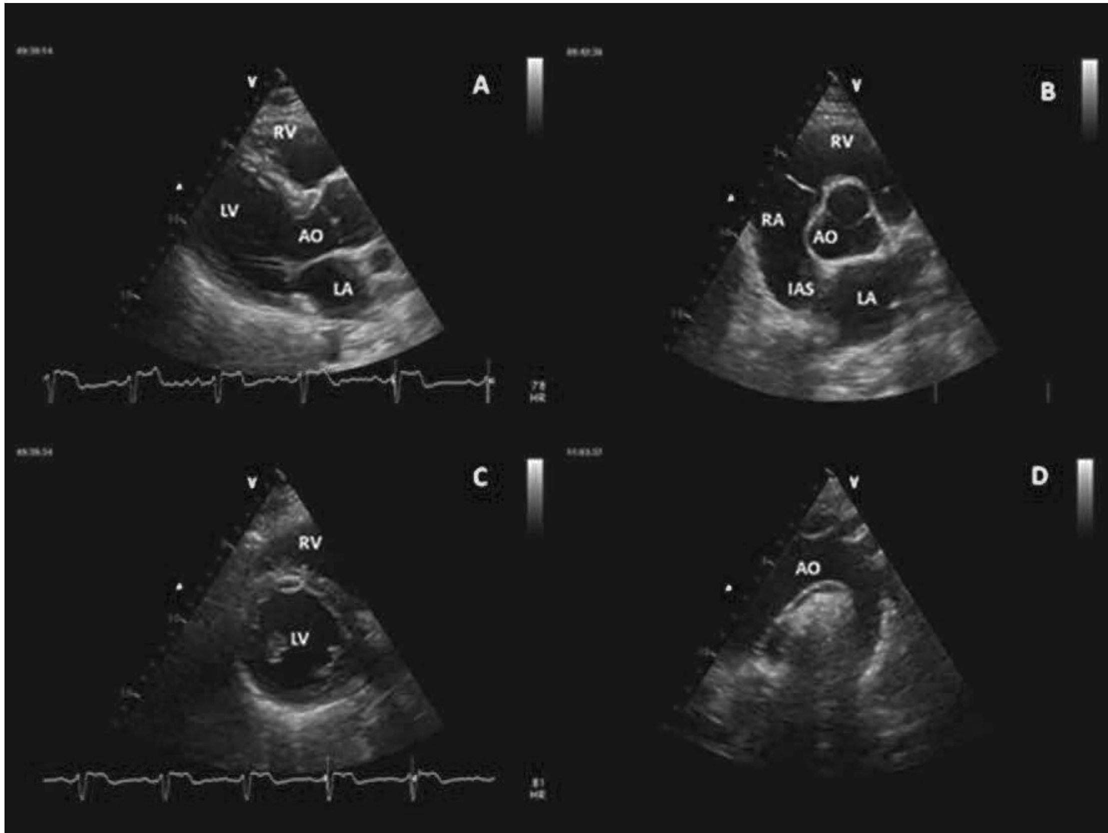

Fig. 1 Parasternal long-axis (A), short axis (B, C), and suprasternal windows (D) showing left and right chambers and aortic valve and arch. *LV*, left ventricle; *LA*, left atrium; *RV*, right ventricle; *RA*, right atrium; *AO*, aorta; *IAS*, interatrial septum.

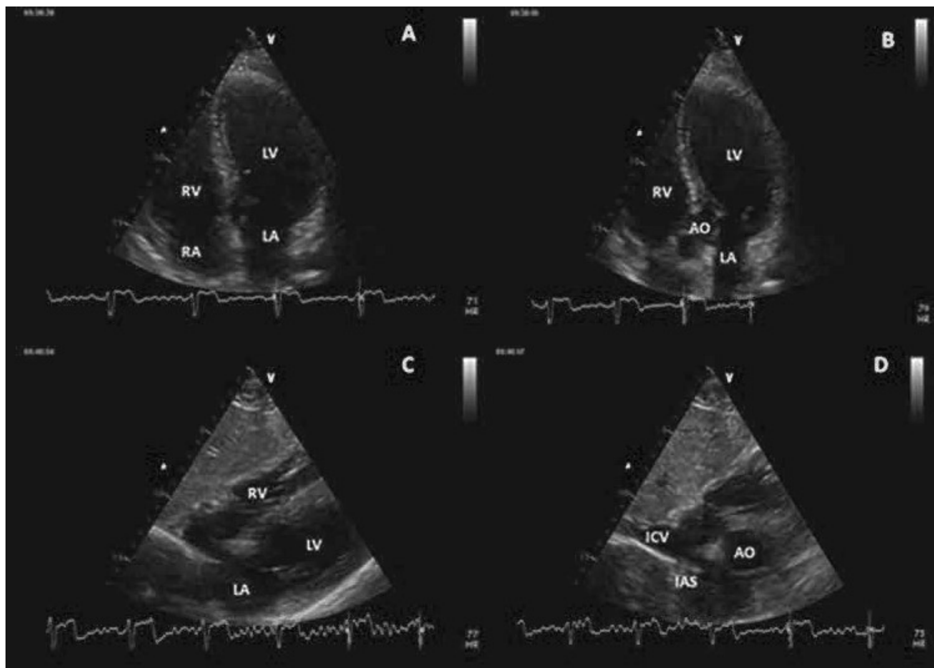

Fig. 2 Apical 4-chamber (A), 5-chamber (B), and subcostal windows (C, D) showing left and right chambers, inferior cavae vein, and pericardium. *LV*, left ventricle; *LA*, left atrium; *RV*, right ventricle; *RA*, right atrium; *AO*, aorta; *IAS*, interatrial septum; *ICV*, inferior cava vein.

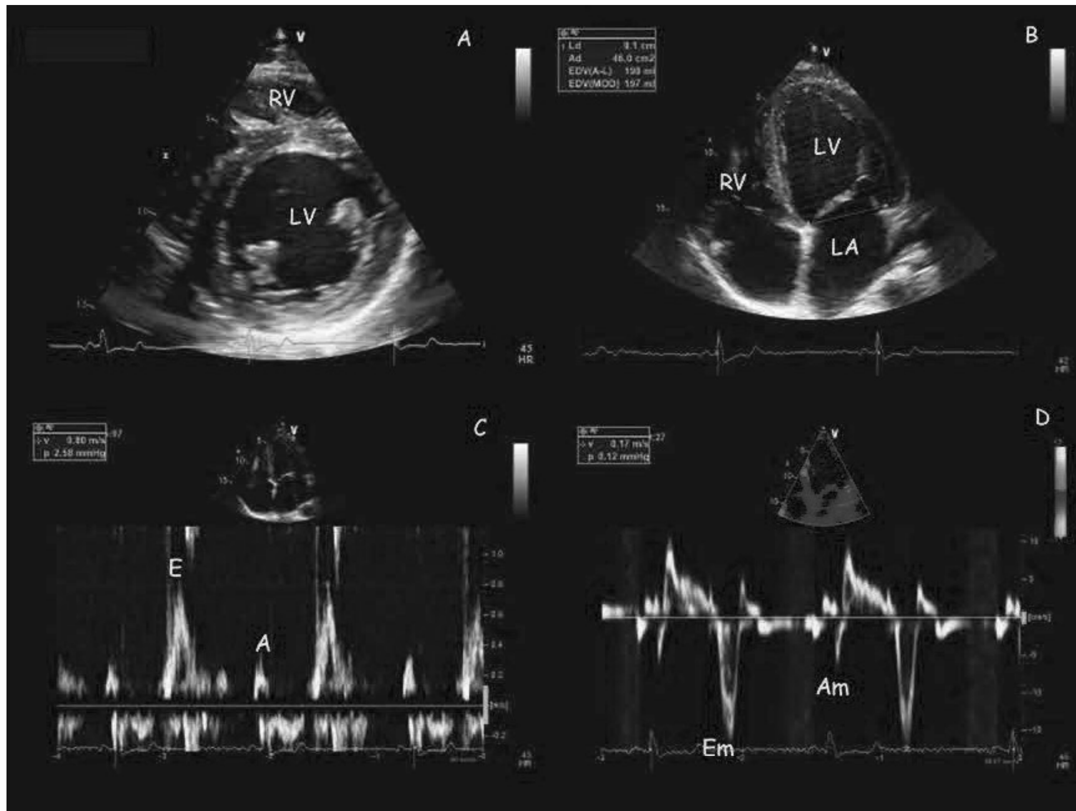

Fig. 3 Standard echocardiography and tissue Doppler of an endurance athlete. Note the symmetric increase in both LV and RV cavity diameters (A) and volumes (B) and also the LA consensual dilatation. LV diastolic function, despite the LV hypertrophy, is "supernormal," with main increase in the early-diastolic relaxation both at global (C) and regional (D) levels. *RV*, right ventricle; *LV*, left ventricle; *LA*, left atrium.

in the past, attention has recently been directed to other structures such as the right ventricle, the atria, and the aorta [10–12]: adaptations to physical activity include balanced increases in the left and right cardiac cavity sizes, increased left ventricular wall thickness and supra-normal indices of systolic and diastolic function [13–16] (Fig. 3). Several reference values with regard to age, gender, ethnicity, and sport disciplines have been published in the literature by different study groups; however, we currently lack universally accepted cut-offs for basic echocardiographic measurements. These adaptations, strictly dependent upon on duration, type and intensity of training, are often benign and physiological but, sometimes, may predispose to pathological conditions [17,18]. Moreover, a key challenge in the assessments of an athlete's heart is the distinction between physiological adaptation and life-threatening cardiomyopathy [19–21], a differentiation that is often not clear, with athletes often categorized in to so-called "gray zones". In this scenario, echocardiography, both with its traditional and novel techniques [18], is the ideal tool for following up with athletes and

it allows dynamic evaluation of these morpho-functional training-related changes [3,18,19,22].

2 Left heart

Multiple studies have evaluated the long-term impact of activities in athletes on left heart size, structure, and function [8,11,23–38] (Table 2). According to the EACVI guidelines [39], LV wall thickness and internal diameter measures are performed at end-diastole in parasternal long-axis (PLAX) or in parasternal short-axis (PSAX) views, at the same level, perpendicular to the long-axis plane of the LV and immediately below the mitral valve leaflet tips. LV EF should be measured by Simpson's biplane method in apical 4 chambers (A4C) view; a visual estimate of LV EF should only be provided when suboptimal image quality precludes accurate measurement. The diastolic function should be assessed with power Doppler technique through the mitral valve, in A4C view. Measurement of the left atrium (LA) diameter should be perpendicular to the aortic root and at the level of the sinus of Valsalva: inner edge to inner edge method is used at end-systole. Biplane LA volume should be estimated using 2D imaging from the A4C and A2C views.

Athlete's left heart echo parameters with relative reference cutoff values are shown in Table 3.

In general, the increase in LV end-diastolic diameter (LVEDD) and wall thickness in athletes has a wide range, depending on multiple factors, such as body size, age, sex, race, and the type of sport: left ventricular size should therefore be considered in the context of exercise capacity, given also its robust association with VO_2 peak [40], and should always be indexed to BSA. In athletes, left ventricular cavity dilation is usually associated with increased wall thickness [30,41].

Table 2 Exercise-related left heart adaptations.

Chambers	Adaptations
LV	Dilation Increase of wall thickness Hypertrabeculation Normal systolic function Normal diastolic function
LA	Dilation

LA, left atrium; *LV*, left ventricle.

Table 3 Athlete's left heart echo parameters.

Parameter	Gender	Mean value	Cut-off for normal value
LVEDD (mm)	M	55	70
	F	49	66
	Adolescent	51	60
LV wall thickness (mm)	M	10	16
	Black	11.5	16
	F	9.5	13
	Adolescent	9.5	12
LV mass/BSA (g/mm^2)	M and F	103	146
LV EF (%)	M and F	64	55
E/A	M and F	1.93	1.3
E/e′ septal (cm/s)	M and F	6.4	8.5
TDI e′ septal (cm/s)	M and F	13.8	10.3
TDI s′ septal (cm/s)	M and F	24	10
TDI e′ lateral (cm/s)	M and F	16	11
TDI s′ lateral (cm/s)	M and F	15	9
LA antero-posterior diameter (mm)	M	37	50
	F	32	45
LAVI (mL/m^2)	M	28	36
	F	26.5	33

BSA, body surface area; *EF*, ejection fraction; *F*, female; *LA*, left atrium; *LAVI*, left atrial volume index; *LV*, left ventricle; *LVEDD*, left ventricular end-diastolic diameter; *M*, male; *TDI*, tissue Doppler index.
Adapted from Pelliccia A, Caselli S, Sharma S, Basso C, Bax JJ, Corrado D, et al. European Association of Preventive Cardiology (EAPC) and European Association of Cardiovascular Imaging (EACVI) joint position statement: recommendations for the indication and interpretation of cardiovascular imaging in the evaluation of the athlete's heart. Eur Heart J 2018;39(21):1949–69.

Pelliccia et al. [42] studied a cohort of young elite Italian athletes, participating in more than 30 different sports. LVEDD varied widely in the study participants, with a mean of 49 mm in women and 55 in men. In this study, a higher BSA and endurance type of sport were the main factors associated with an increase in LV dimensions. Other studies reported similar increases in LVEDD, which could reach a maximum of 70 mm in world-class professional cyclists [24]. LV dilation in athletes is frequently associated with a good systolic function (EF > 55%) and normal indices of diastolic function [43].

LV wall thickness also increases in response to the repetitive demand of high cardiac output in athletes. Mean LV wall thickness was studied in multiple studies: cutoff for normal range values in different kinds of populations oscillate between 8 and 12 [6], with a mean value of 11 mm. Additionally, LV wall thickness > 13 mm was noted in about 10% of professional cyclists up to a maximum thickness of 15 mm [24]. Pelliccia et al. studied more

than 900 elite athletes in different types of sports and noted that LV wall thickness was increased up to 16 mm in 7% of the 219 rowers, canoeists, and cyclists [8]. Endurance sports have a large physiologic impact on LV size and wall thickness [11,25]. Spirito et al. [8] showed that endurance cyclists, rowers, and swimmers had the largest LV diastolic cavity dimensions and wall thickness. In contrast, athletes training in sports such as track sprinting, field weight events, and diving were at the lower end of the spectrum of cardiac adaptations.

Several other structural changes can occur in the left heart of athletes. About 20% of athletes has LV hypertrabeculation, with about 10% meeting diagnostic criteria for left ventricle noncompaction (LVNC) [14,44]. This may be due to cardiac adaptation to load training and may be regarded as part of the spectrum of the athlete's heart [45], paying always attention to the gray zones' differential diagnosis process.

Many studies have investigated changes in LV systolic and diastolic function in response to exercise in elite athletes [46,47]. LV systolic function has been reported to be normal (EF ≥ 52%) or slightly reduced (EF ≤ 52%) [24] in several reports. A large meta-analysis showed preserved LV systolic and diastolic function in athletes similar to controls (mean EF 66% vs 67%, and mean E/A ratio 1.89 vs 1.84) [32]. Multiple studies revealed enhanced or normal LV diastolic function in athletes in response to extensive exercise [48–51]. Ahmad et al. compared the LV response to exercise in runners with healthy controls [35], demonstrating that the enhanced cardiac performance observed in runners was due to an early and sustained increase in LV diastolic volume without a significant increase in EF, suggesting the adaptation is dimensional rather than functional. These data support an important role of the Frank-Starling mechanism in rapid enhancement of LV response to exercise. A recent study by Boraita et al. investigated the mechanism of reduced EF in some athletes, a phenomenon explained previously by the need for a lower percentage of LV end-diastolic volume to meet resting stroke volume demands in this subset of athletes. All participants in the study had both normal QRS duration and diastolic function evidenced by their normal E, A, and E/A ratios. Analyses of mechanical interventricular and intraventricular desynchrony revealed that the time from QRS onset to different systolic waves was prolonged in the low EF group, even if normal diastolic parameters were still obtained. These findings suggest normal adaptive remodeling and might explain the slightly reduced EF in some athletes [52]. With regard to diastolic function, transmitral pulse wave Doppler inflow pattern demonstrates a normal pattern, with an increased

contribution of early filling velocity at rest (E/A ratio > 2) [43,53]. Pulsed tissue Doppler imaging (TDI) provides additional information showing normal s′ peak velocity at rest (>8 cm/s) and e′ peak velocity of the mitral annulus (>10 cm/s) [54–56], differently from individuals with mild morphological expression of hypertrophic cardiomyopathy (HCM) [57].

LA remodeling changes have been evaluated in conjunction with LV enlargement, and it is strictly related to dynamic types of sports [10]. Additionally, LA enlargement in athletes of different sports disciplines has been reported in multiple investigations in which a minority of athletes may reach extreme values >48 mL/m^2 or LA dimension >45 mm [16,58]. A large study by Engel et al. on 526 National Basketball Association professional athletes showed that LA diameter ranged from 26 to 49 mm, with a mean LA volume index (LAVI) of 30.9 mL/m^2 [27]. The authors concluded that LA enlargement should be regarded as a physiological adaptive change, and a cutoff value of >50 mm in men and >45 mm in women may be used to distinguish pathological changes [16]. Similar to prior investigations, D'Andrea et al. [58] studied more than 600 young athletes and found that the mean LA volume index was 28.2 ± 9.2 in men and 26.5 ± 7.2 in women. The LA size seems to be related mainly to LV end-diastolic volume and to the type and duration of the training, with larger LA volume in endurance-trained athletes. Moreover, findings from Gabrielli et al. indicated impairment in the reservoir and the contractile functions of the LA in patients with HCM and could be used to differentiate pathologic from physiologic LV hypertrophy [59]. Furthermore, LA remodeling is associated with a greater risk of atrial fibrillation development, especially in middle-aged male athletes with a history of intense endurance sports activity [60–63]. Despite this, the absolute risk of this arrhythmia in athletes remains low, given that physical activity, even if not intense, can reduce the incidence of AF, as well as minimizing all those cardiovascular risk factors that would make the heart predisposed to similar arrhythmogenic events [10].

3 Right heart

Concerning the right heart, the RV shows greater inflow and outflow dimensions in athletes compared with sedentary controls, with no significant differences observed in systolic function. Indeed, as the RV shares a similar hemodynamic load as the LV, RV response to intensive exercise is also similar, characterized by RV dilation and preserved systolic and diastolic function [15,40,64–67] (Table 4).

Table 4 Exercise-related right heart adaptations.

Chambers	Adaptations
RV	Increase of diameters Increase of outflow tract Normal TAPSE
RA	Dilation

RA, right atrium; *RV*, right ventricle; *TAPSE*, tricuspid annular plane systolic excursion.

According to the EACVI guidelines [39], all RV dimensions should be measured at end-diastole in the focused RV view. From the A4C view, three different measures can be obtained: RVD1 (basal RV diameter—measured at the maximal transverse diameter in the basal one-third of the RV); RVD2 (mid RV diameter—measured at the level of the LV papillary muscles); RVD3 (RV length—from the plane of the tricuspid annulus to the RV apex). Proximal and distal measurements of right ventricular outflow tract (RVOT) diameter are made in the PSAX plane at the level of the AV. Both measures are made at end-diastole by the inner-edge to the inner-edge method. Tricuspid annular plane systolic excursion (TAPSE) should be performed with the M-mode cursor aligned along the direction of the lateral tricuspid or mitral annulus to maximize longitudinal motion of the annulus, in A4C view. Right atrial dimensions and volume can be studied in A4C view.

Athlete's right heart echo parameters with relative reference cutoff values are shown in Table 5.

An initial cardiac MRI study by Scharhag et al. demonstrated an increase in RV mass, RV end-diastolic volume, and stroke volume in male athletes compared to controls. These changes were seen in conjunction with similar changes in LV dimensions and function [64]. Using electrocardiography and echocardiography, Zaidi et al. [15] evaluated RV remodeling changes in 300 black athletes, 375 white athletes, and 153 controls. The study showed that both black and white athletes exhibited greater RV dimensions than controls, and RV dimensions were marginally smaller in black athletes compared to the white athletes. Furthermore, both white and black athletes demonstrated RV enlargement with dimensions overlapping with arrhythmogenic right ventricular cardiomyopathy (ARVC). Forty percent of the white athletes and 28% of the black athletes had parasternal RVOT greater than 32 mm. In gender comparisons, male athletes had larger dimensions than female athletes. Bauce et al. [65] compared 40 athletes, 40 ARVC patients, and 40 controls and found that both athletes and ARVC patients had

Table 5 Athlete's right heart echo parameters.

Parameter	Gender	Mean value	Cutoff for normal value
RV diameter basal (mm)	M	43.5	55
	F	39	49
RV diameter middle-ventricle (mm)	M	34	47
	F	32	43
RV longitudinal diameter (mm)	M	89	109
	F	82	100
RVOT proximal index (mm/m^2)	M	26.1	32
	F	14.4	18
RVOT distal index (mm/m^2)	M	27.3	34
	F	15	19
PASP (mmHg)	M and F	24	40
TAPSE (mm)	M and F	24	19
RV FAC (%)	M	52	39
	F	53.4	38
RV TDI e′ (cm/s)	M and F	10	6
RV TDI s′ (cm/s)	M and F	11	8
RA area (cm^2)	M	18.9	25
	F	14.8	20

F, female; *FAC*, fractional area change; *M*, male; *PASP*, pulmonary artery systolic pressure; *RA*, right atrium; *RV*, right ventricle; *RVOT*, right ventricular outflow tract; *TAPSE*, tricuspid anulus peak systolic excursion; *TDI*, tissue Doppler imaging.

Adapted from Pelliccia A, Caselli S, Sharma S, Basso C, Bax JJ, Corrado D, et al. European Association of Preventive Cardiology (EAPC) and European Association of Cardiovascular Imaging (EACVI) joint position statement: recommendations for the indication and interpretation of cardiovascular imaging in the evaluation of the athlete's heart. Eur Heart J 2018;39(21):1949–69.

RV enlargement when compared with the controls. However, RV fractional shortening and RV EF were significantly lower in ARVC patients when compared to athletes and controls. D'Andrea et al. [66] studied more than 600 elite athletes to evaluate the impact of the type of sport on RV parameters and showed that RV and RA measurements were significantly higher in endurance-trained athletes. RV systolic function was similar when compared to the strength-trained athletes but diastolic RV function was supranormal.

4 Vessels

Echocardiographic evaluation of aortic root dimensions is an important part of the comprehensive screening of athletes, especially in those with clinical features that raise diagnostic suspicion of Marfan's syndrome. Practically, aortic root diameter measurements should be performed from the PLAX

view using the leading edge-to-leading edge convention (except for the measurement of the annulus, in which inner edge-to-inner edge measurements are recommended) and preferring 2D measurements [68,69]. The aortic annulus shall be measured by inner edge-to-inner edge diameter in mid-systole, while all other measurements shall be taken using the leading edge-to-leading edge convention at end-diastole [39]. The exception is in children and subjects ≤25 years, where aortic root dimensions should be made using the inner-wall-to-inner-wall technique during systole [70]. Measurements should embrace the aortic valve annulus, the sinuses of Valsalva, the sinotubular junction, and the proximal ascending aorta.

The athlete's aortic echo parameters are shown in Table 6.

Engel et al. [27] studied NBA players with BSA of 2.38 m^2. Aortic root dimensions ranged from 25 to 42 mm, and only 4.6% of athletes had a diameter ≥ 40 mm. The aortic root diameter had a nonlinear relationship with athlete's height and BSA, with the aortic root dimensions increasing with BSA or height until a plateau was reached with no further increase above 42 mm. These findings were consistent with other studies investigating aortic root dimensions in athletes [71–75]. Boraita et al. [52] studied a large sample of healthy athletes and found that age, LV mass, and BSA were the main predictors of aortic size. Dimensions corrected for BSA were higher in male athletes than females at the aortic annulus, without significant differences at the sinus of Valsalva, but were smaller in men at the sinotubular junction and the proximal ascending aorta. The aortic root dimensions in athletes were within the established limits for the general population, and therefore, the American Heart Association/American College of Cardiology Task Force recommended surveillance and serial imaging for tall athletes with aortic root diameters >41 mm [76]. Clinicians evaluating athletes should therefore know that marked aortic root dilatation represents a pathological process and not a physiological adaptation to exercise [72,75].

Table 6 Athlete's aortic parameters.

Parameter	Gender	Mean value	Cut-off value
Aortic root diameter (mm)	M	32	41
	F	28	34
Proximal ascending aorta (mm)	M and F	28	34

F, female; *M*, male

Adapted from Pelliccia A, Caselli S, Sharma S, Basso C, Bax JJ, Corrado D, et al. European Association of Preventive Cardiology (EAPC) and European Association of Cardiovascular Imaging (EACVI) joint position statement: recommendations for the indication and interpretation of cardiovascular imaging in the evaluation of the athlete's heart. Eur Heart J 2018;39(21):1949–69.

If dilated aortic root dimensions are found, it is recommended to exclude the presence of associated conditions such as Marfan syndrome or bicuspid aortic valve (BAV) [77,78].

5 New echocardiographic techniques

The development and rapid dissemination of 2D echocardiography led to a comprehensive understanding of cardiac adaptation to exercise conditioning. However, advanced echocardiographic techniques have recently begun to clarify significant functional adaptations of the myocardium that accompany previously reported morphological features of the athlete's heart. In particular, speckle-tracking echocardiography (STE) and 3D echocardiography have recently provided further insights into the characterization of the myocardial properties of athletes (Table 7). These very advanced echocardiographic techniques are not part of the routine evaluation of the athlete but may become useful in specific circumstances to clarify the nature of cardiovascular adaptations [19].

Speckle tracking echocardiography (STE) is a relatively recent noninvasive echocardiographic technique of deformation imaging that has provided new insights into the characterization of the athletes' heart [79]. It is able to detect subclinical ventricular systolic function in an early-stage cardiac disease when LV EF is still normal. It is largely independent of the angle that allows an objective and quantitative evaluation of global and regional myocardial function. Myocardial strain is a not dimension-related parameter

Table 7 Usefulness of speckle-tracking and/or 3D echocardiography when evaluating the athlete's heart.

Technique	Proprieties
STE	Identification of regional wall motion abnormalities Preclinical impairment of LV function in individuals with early DCM Preclinical anomalies useful for differentiating between athlete's heart and early HCM Improved ability to recognize RV functional abnormalities suggestive for ARVC
3D echocardiography	Assessment of LV volume and function Assessment of LV cavity size and geometry Improvement of the characterization of LV hypertrabeculation

ARVC, arrhythmogenic right ventricle cardiomyopathy; *DCM*, dilated cardiomyopathy; *HCM*, hypertrophic cardiomyopathy; *LV*, left ventricle; *STE*, speckle-tracking echocardiography.

expressed as the percentage of myocardial deformation; negative values indicate shortening or compression; and positive values indicate lengthening or stretching. Depending on the spatial resolution, selective analysis of epicardial, mid-wall, and endocardial function may be possible, allowing the analysis of longitudinal, radial, and circumferential strain [80,81]. In addition, STE permits the evaluation of the occurrence, velocity, and direction of LV rotation [82]. STE can be applied to both ventricles and atria. However, while all LV segments can be analyzed successfully in most patients, signal quality may be suboptimal for the atria and the right ventricle because of their thin walls [83]. It should be noted that, although feasibility is generally good for longitudinal and circumferential strain, it is more challenging for radial strain. The main limitation of STE is that it relies on good imaging quality, and there are still differences among manufacturers because STE analysis is performed on data stored in a proprietary scan line format which cannot be analyzed by software from another manufacturer. This lack of standardization of different speckle-tracking algorithms makes it difficult to establish normal values and compare data generated in different centers.

LV global longitudinal strain (GLS) obtained by STE is the most used strain parameter in clinical practice, and it is not significantly different between athletes and healthy controls. The current normal range for GLS in the general population is −16% to −22% [84,85] (Table 8). Despite heterogeneity in the literature reports, probably linked to study designs, types of sports included, and the inconsistent approach in scaling tissue velocity, similar values have been found in athletes, suggesting that a measure <15% should raise the suspicion of an underlying myocardial disease, particularly in cases of other concomitant subclinical anomalies [86–88], such as doubtful LV hypertrophy or dilatation [84–91]. Measurements of strain are especially helpful in extreme cases of exercise-induced cardiac remodeling that may overlap with cardiology pathology [19,92–96], such as HCM [93], dilated

Table 8 Athlete's global longitudinal strain parameters.

Parameter	Mean value
LV GLS	−18.1 ± 2.2%
RV GLS	−27 ± 6%

GLS, global longitudinal strain; *LV*, left ventricle; *RV*, right ventricle.
Adapted from Pelliccia A, Caselli S, Sharma S, Basso C, Bax JJ, Corrado D, et al. European Association of Preventive Cardiology (EAPC) and European Association of Cardiovascular Imaging (EACVI) joint position statement: recommendations for the indication and interpretation of cardiovascular imaging in the evaluation of the athlete's heart. Eur Heart J 2018;39(21):1949–69.

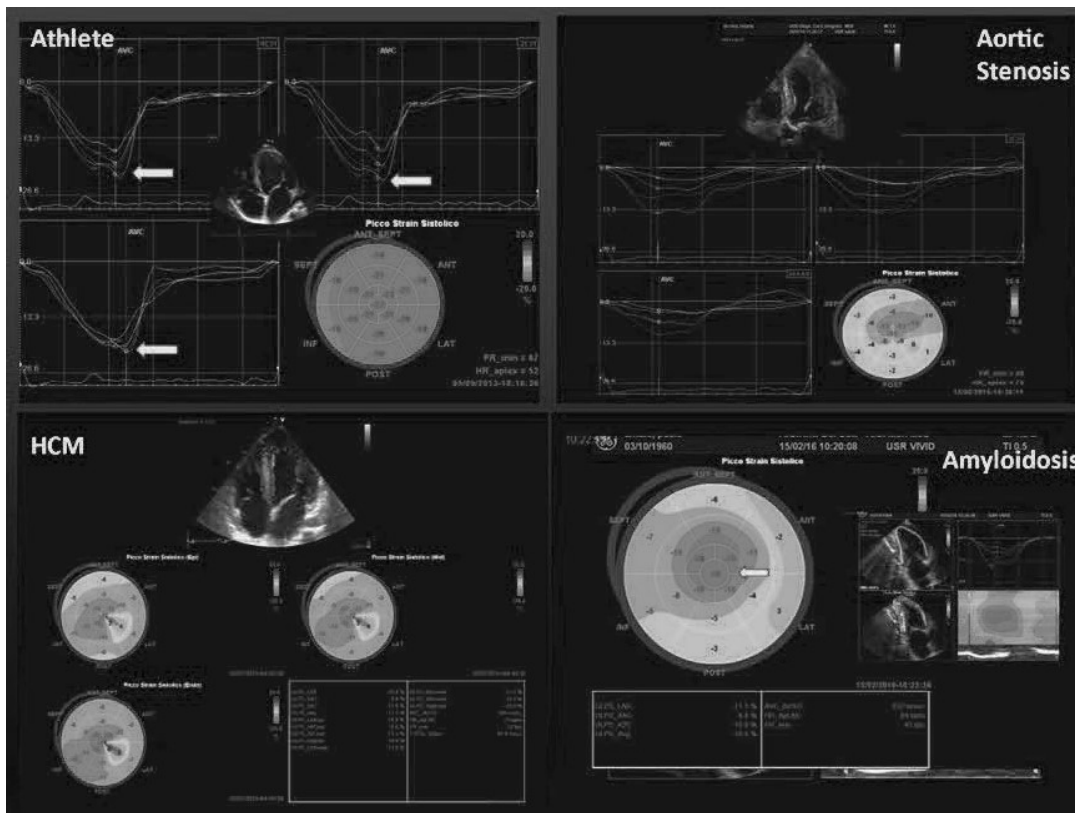

Fig. 4 Bull's eye speckle tracking analysis, in different models of LV hypertrophy. Strain evaluation shows normal values of myocardial deformation in athlete, diffusely reduced deformation in aortic stenosis, main involvement of IVS in HCM, and apical sparing in amyloidosis. *HCM*, hypertrophic cardiomyopathy; *LV*, left ventricle; *IVS*, interventricular septum.

cardiomyopathy (DCM) [94] or other pathological conditions, helping in differentiating subclinical pathologic patterns before a significant decline in cardiac function (Fig. 4).

Data regarding the interpretation of RV STE-derived parameters in athletes are still controversial [40,65,97–100] (Table 8). Strenuous and chronic exercise training seems to have a detrimental effect on RV function, with reductions of RV strain observed immediately after endurance races, followed by complete recovery [101] (Fig. 5). Finally, RV strain imaging can be useful to distinguish between physiology and pathology, given its ability in identifying regional wall motion abnormalities in patients with arrhythmogenic cardiomyopathy [40] (Fig. 6). However, studies investigating RV function in athletes by STE remain limited, and we lack universally accepted cutoff values [19].

During the past decades, STE has also been applied to the evaluation of left and right atrial function [59,102,103]. In both athlete's heart and cardiomyopathy, atrial enlargement can be found, but atrial deformation indices are reduced only in the latter. Strain imaging is able to identify specific

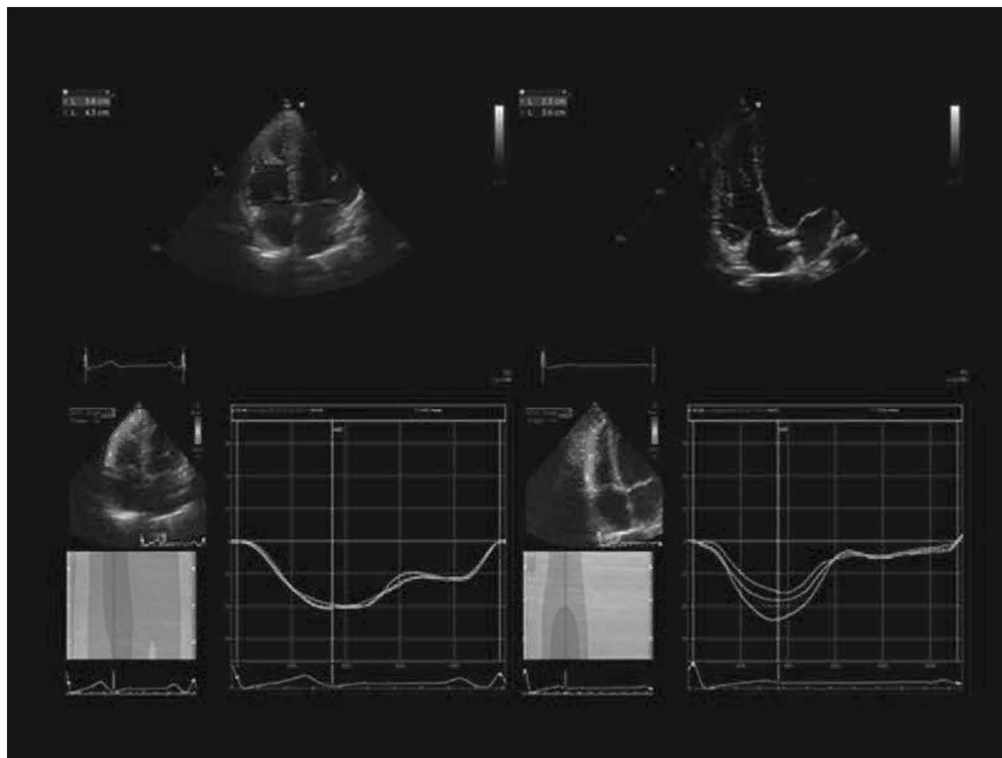

Fig. 5 Comparison of an endurance athlete (on the left) with a power athlete (on the right). While endurance training induces a marked increase in RV cavity size compared to power training, both types of training are associated with preserved function as shown by normal or even supranormal value of RVFW strain curves. *RV*, right ventricle; *RVFW*, right ventricle free wall.

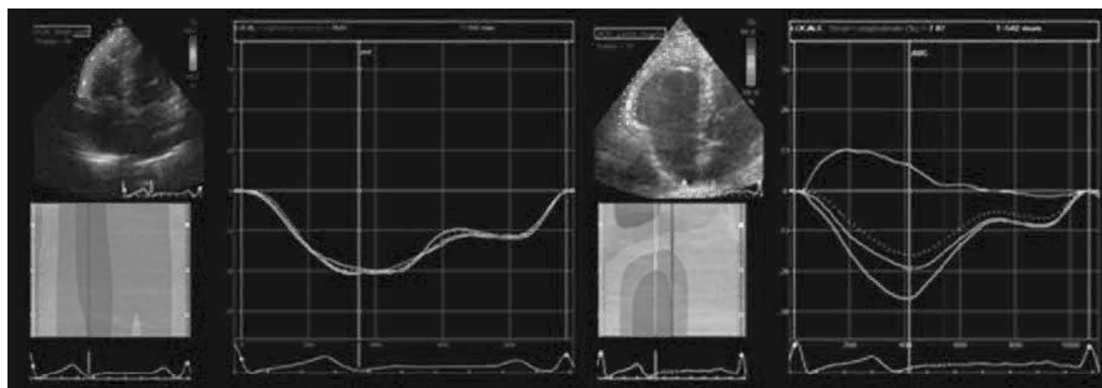

Fig. 6 2D longitudinal strain by speckle tracking echocardiography demonstrating RV strain in athlete's heart (on the left) and abnormal RV strain in ARVC in which RVFW strain curves are reduced and show the dispersion of RV contraction. *RV*, right ventricle; *ARVC*, arrhythmogenic right ventricle cardiomyopathy; *RVFW*, right ventricle free wall.

adaptations of biatrial myocardial deformation to exercise conditioning in competitive athletes [99,104–106]. This functional remodeling, in both male and female athletes, is dynamic in nature and is accompanied by normal, or even reduced, atrial stiffness and, despite a marked dilatation, does not have a significant impact on biatrial function [107,108]. The application

of STE to the atria of competitive athletes has demonstrated a functional adaptation that goes beyond mere cavity enlargement, suggesting a possible future use of this technique as a new parameter for distinguishing between the athlete's heart and cardiomyopathies. However, again, we currently lack clear thresholds to differentiate these two states.

The development of speckle tracking has made studying LV mechanics more feasible, and many other parameters have been studied.

The phenomenon of LV systolic twisting (LVT) and subsequent early diastolic untwisting has been evaluated in the context of exercise [88,109]. Weiner et al. [88] have demonstrated the impact of endurance exercise on increasing peak apical systolic rotation, peak systolic LV twisting (LVT), and early diastolic untwisting rate (UTR) in male rowers after 90 days of training. A possible partial explanation for this finding may be related to enhanced exercise-induced volume expansion, which increases LV twisting and untwisting rates. The enhanced LVT and UTR in athletes at rest and in response to exercise could represent target parameters to differentiate physiological from pathological remodeling given that both parameters are reduced in dilated cardiomyopathy and postmyocardial infarction [110,111] and elevated at rest but not in response to exercise in HCM patients [109].

Myocardial work (MW) is a novel, less load-dependent ultrasonographic index of LV contractile function, which corrects STE-derived parameters for afterload, by using systolic blood pressure [112]. In different physiologic and pathologic conditions, an increased afterload may lead to strain impairment, with preserved or increased MW indices. This may be important for athletes with variable blood pressure and loading conditions from exam to exam and in different phases of the training program.

Color Doppler flow mapping is an advanced echocardiographic tool that evaluates LV function through the analysis of intracardiac flows [113]. LV vortex flow study may provide new insights into the characterization of athlete's heart properties and their differences with normal subjects and patients with cardiomyopathies.

Three-dimensional echocardiography has added quantitative information to the assessment of the athlete's heart; indeed, cardiac volumes and mass can be estimated more precisely than with 2D echo and without the use of geometric assumptions [85,114,115]. Three-dimensional derived measurements of LV geometry are very similar to those obtained by CMR, while 2D echocardiography routinely underestimates these measurements [116]. 3D echocardiography also allows accurate quantification of LV volume and mass, providing detailed data on LV remodeling and function

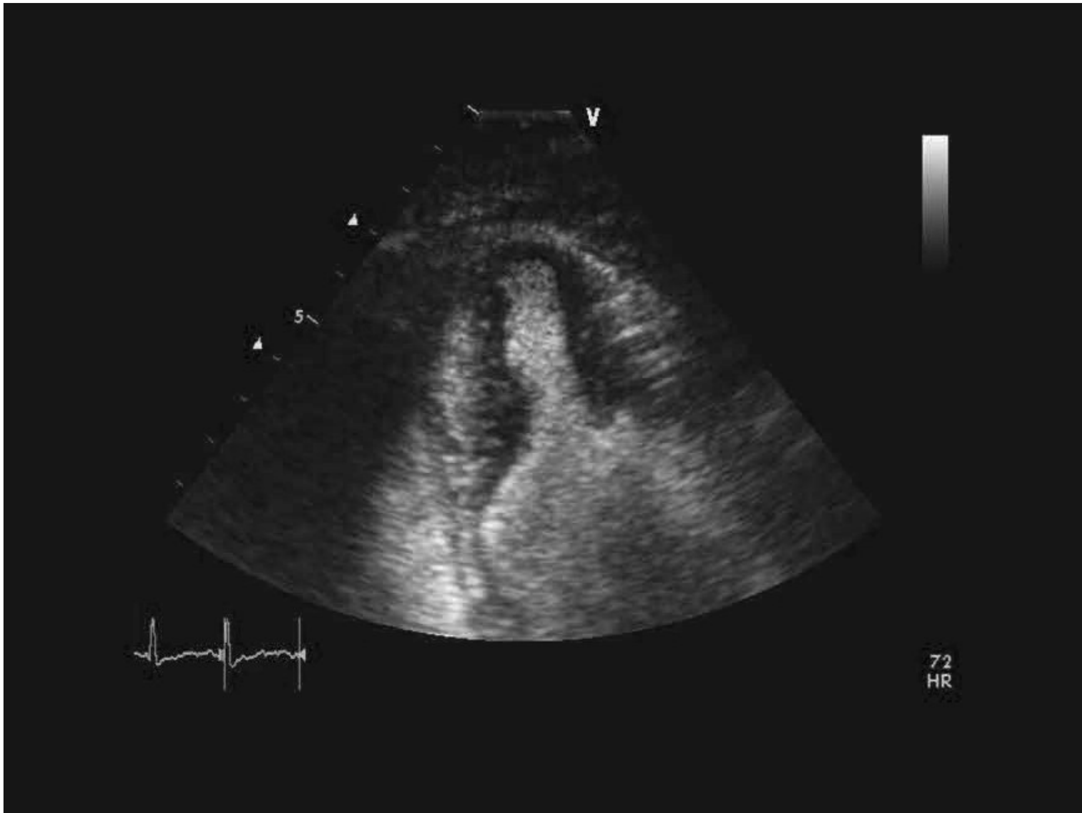

Fig. 7 Contrast echocardiography showing the presence of apical hypertrophic cardiomyopathy in a power athlete with repolarization abnormalities by ECG. Note the "spade-like" configuration of LV cavity. *LV*, left ventricle.

[117]. The geometric pattern of LV adaptation to different training protocols has been investigated with 3D echocardiography. In athletes, regardless to the sports discipline, a balanced ratio between LV mass and end-diastolic volume has been described by 3D echocardiography as opposed to what typically occurs in cardiomyopathies [118]. Evaluating the RV using 2D echocardiography depends on geometric assumptions that do not reflect the complex irregular structure of the RV accurately [119]. However, 3D echocardiography enables more accurate measurements of RV volumes and EF that are comparable to the measurements obtained by CMR [120–122].

Finally, also contrast echocardiography has shown good diagnostic sensitivity in evaluating athlete's heart modifications (Fig. 7).

6 Conclusion

Echocardiography is a valuable tool helping in detecting several hidden cardiovascular conditions afflicting athletes. This technique, with the aid of its advanced functions, could also help to distinguish between physiological

and pathological adaptation to physical activity, assisting in sport eligibility process. Scientific literature offers echocardiographic cutoff measures that could be very helpful in assessing exercise-induced morphologic evaluation of heart chambers and vessels, even if these have to be used carefully and always related to the clinical context of the patient.

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