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Aortic root/left ventricular diameters golden ratio in competitive athletes

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ABSTRACT

Background: The athlete's heart is a well-known phenomenon characterized by a harmonic remodelling that affects the cardiac chambers. However, whether mild-to-moderate aortic dilatation can be considered normal in athletes is debated. This study aimed to evaluate the ratio between left ventricular (LV) size and aortic dimensions, reporting the normal values of the ratio between the aortic root diameters at the level of the sinuses of Valsalva and LV diameters (AoD/LVEDD ratio) in a wide cohort of competitive athletes.

Materials and methods: Competitive athletes were compared with sedentary subjects and patients with aortic dilatation. 1901 subjects who underwent echocardiography from 2019 to 2022 were retrospectively enrolled: 993 athletes (74% males, mean age 26 ± 7 years), 410 sedentary (74.1% males, mean age 29 ± 11 years) and 498 patients with aortic dilatation (74.3% males, mean age 56 ± 7 years).

Results: Patients with aortic dilatation had both an absolute (39.2 ± 2.4 mm) and indexed (19.4 ± 2.2 mm/m2) aortic diameter larger than athletes (30.6 ± 3.2 mm; 16.1 ± 1.5 mm/m^2, $p < 0.05$) and sedentary subjects (30.5 ± 3.1 mm; 16.5 ± 1.6 mm/m^2, $p < 0.05$), with no differences between athletes and sedentary subjects. The AoD/LVEDD ratio was lower in athletes (0.59 ± 0.06) compared to controls (0.65 ± 0.05, $p < 0.05$) and patients with aortic dilatation (0.81 ± 0.06, $p < 0.05$). The patients with aortopathy had the lowest LVEDD/AoD ratio, while competitive athletes had the highest, with values of 1.71 ± 0.16 in the latter (overall p value<0.001).

Conclusions: In this study, we reported the AoD/LVEDD and LVEDD/AoD ratio values in a cohort of healthy athletes, additional parameters that could help confirm the harmonic remodelling in the athlete's heart.

1. Introduction

High-volume training, particularly endurance training, has a well-known effect on cardiac chamber size, left ventricular (LV) hypertrophy and LV mass, the so-called ‘athlete's heart’ [1–4]. The effect of endurance training is not confined to the myocardium but extends to the vascular system, particularly the aorta. Although moderate aortic dilatation is uncommon in competitive athletes, they tend to have a larger aortic root diameter and a larger ascending aorta than the general population [5–7], even though they rarely exceed the upper limits of normality [8,9]. The type of sport and gender have an influence, with males practising endurance sports, such as rowing and cycling, showing the highest degree of aortic remodelling [9,10].

Aortic dilatation is the principal risk factor for acute aortic syndrome [11] and the increase in systolic pressure during training and competition can accelerate the progression of the dilatation, also increasing the risk of aortic dissection [12,13]. Therefore, it is of paramount importance to understand whether intensive training is associated with aortic dilatation and which kind of relationship exists between LV size and aortic dimensions in healthy athletes practicing competitive sports.

The athlete's heart is typically characterized by harmonic remodelling, preserving the proportion among the cardiac chambers [2,4], even if the training-induced adaptation tends to have a more significant effect on LV diameters than on the aortic root [5]. We hypothesized that this different remodelling was reflected in the ratio between the aortic root diameter at the level of the sinuses of Valsalva (AoD) and the LV end-

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diastolic diameter (LVEDD), with athletes having a smaller ratio compared to healthy sedentary individuals and patients with pathological aortic dilatation, in which the constant harmonic ratio between LVEDD and the AoD, the so-called 'golden ratio', is lost.

Therefore, this study aimed to evaluate the ratio between aortic dimensions and LV size, reporting for the first time the normal values of the ratio between the aortic root diameter at the level of the sinuses of Valsalva and LV diameters (AoD/LVEDD ratio) in a wide cohort of competitive athletes, also comparing these results with those obtained in sedentary individuals, and patients with an aortopathy. The hypothesis was that this ratio is lower in athletes compared to the other groups as an effect of the training-induced remodelling that more markedly affects LV dimensions than aortic size.

2. Methods

2.1. Study population

A retrospective analysis was conducted in a cohort of competitive athletes, sedentary subjects, and patients with known pathological aortic dilatation. All the subjects underwent two-dimensional (2D) echocardiography between January 2019 and May 2022 at the Department of Cardiology at the University Hospital in Siena.

Athletes were defined as subjects participating in sports activity, at a competitive level, for at least 6 h per week. All the subjects included in this group had an aortic root within the normal limits for competitive athletes, i.e. <40 mm for men and < 34 mm for women [9]. The subjects in this group have been further categorized into skill, mixed, power and endurance athletes based on each sport's static and dynamic components [14].

All the subjects included in the sedentary group had an absolute AoD within normal limits (<38 mm for men and < 34 mm for women), following the recommendation of the American Society of Echocardiography (ASE) and the European Association of Cardiovascular Imaging (EACVI) [15].

The group of patients with aortic dilatation included individuals with an AoD ≥38 mm in males and ≥ 34 mm in females. Patients with an aortic root >45 mm were excluded from this group, given that they had a well-recognized pathological aortic aneurysm.

The exclusion criteria applied to the study population were: age < 18 years or > 65 years, presence of risk factors for aortic aneurysm (bicuspid aortic valve, connective tissue diseases such as Marfan syndrome, Loeys-Dietz ed. Ehlers-Danlos syndromes positive family history for aortopathies), cardiomyopathy or presence of more-than-mild valvular stenosis or regurgitation.

Competitive athletes and sedentary individuals were consecutively enrolled while patients with aortic dilatation were retrospectively selected in our database.

2.2. Echocardiography

The echocardiographic examination was performed by expert cardiologists using a Vivid-Q, GE Healthcare, following the ASE and the EACVI recommendations for chamber quantification [15]. The aortic root size (AoD) was measured from the 2D parasternal long-axis view at the center of the Valsalva sinuses, perpendicularly to the axis of the aorta, with the "leading-edge to leading-edge" technique. The endocardial dimensions of the LV were measured in the 2D parasternal long-axis view at the tip of the mitral leaflet, perpendicular to the LV long axis, from the tissue-blood interface to the blood-tissue interface [15].

The value of the AoD was indexed for BSA and height (ratiometric and allometric scale). For the allometric rationalization, the ß exponent used was 1.025 (C value 0.05) [16].

The assessment of the other echocardiographic parameters, including LV mass (LVM), LV ejection fraction (EF) and diastolic function, was performed as recommended [15].

2.3. Statistical analysis

Continuous variables were reported as mean ± standard deviation (SD), and the qualitative variables were reported as absolute numbers or percentages. The normal distribution was evaluated with the Shapiro-Wilk test. The ANOVA or Friedman test was used to assess the statistical significance of the difference between two continuous variables among the different groups. The post hoc analysis of multiple variables was conducted using the Bonferroni or Dunn test appropriate for data distribution. The qualitative variables were studied using the Chi-squared test.

ROC curve analysis was conducted to evaluate the diagnostic performance of the variables of interest (i.e., AoD, AoD/BSA, AoD/height, AoD/height$^{1.025}$ e AoD/LVEDD) and to assess the sensitivity, specificity and the most appropriate cut-off value for the AoD/LVEDD ratio.

A p-value <0.05 was considered statistically significant for all the analyses. The analysis was conducted using the SPSS version 21.0 (Statistical Package for the Social Sciences Inc. Chicago, Illinois).

3. Results

3.1. Demographics

A total of 1901 subjects met the inclusion criteria. The general characteristics of the population are shown in Table 1. The first group included 993 competitive athletes, of which 735 were males (74%), and the mean age was 26 ± 7 years. The second group included 410 healthy sedentary subjects, of which 304 were male (74,1%), and the mean age was 29 ± 11 years. The third group included 498 patients with aortic root dilatation, of which 370 were male (74,3%), with a mean age was 56 ± 7 years. The BSA was significantly higher in the patient group than in any other group ($p < 0.05$). The systolic and diastolic blood pressure were higher in the patient group compared to any other group ($p < 0.05$) and were lower in athletes than in sedentary controls ($p < 0.05$).

3.2. Echocardiography

3.2.1. Cardiac chambers

Echocardiographic data obtained from the study population are reported in Table 2. The patients with aortic root dilation showed a greater LV thickness, LVM, and RWT than the other groups ($p < 0.05$). The athletes' group showed a significantly larger LV end-systolic (LVESD) and LVEDD diameter than the other two groups, even after indexing for BSA ($p < 0.05$). Athletes exhibited the greatest E/A ratio, while patients with aortic dilatation had the lowest (overall p-value <0.001). The LV EF was significantly lower in patients compared to the other groups ($p < 0.05$).

Table 1
Demographic characteristics of the study population ($n = 1901$).

	Athletes ($n = 993$)	Sedentary ($n = 410$)	Patients with aortic dilatation ($n = 498$)	P value
Age, years	26 ± 7	29 ± 11	56 ± 7*	<0.001
Male, n (%)	735 (74)	304 (74)	370 (74)	
Height, cm	178 ± 11*	175 ± 9	174 ± 9	<0.001
Weight, kg	74 ± 14^	71 ± 13	90 ± 15*	<0.001
BSA, m^2	1.9 ± 0.2	1.9 ± 0.2	2.0 ± 0.2*	<0.001
HR, bpm	60 ± 12*	71 ± 12	70 ± 12	<0.001
SBP, mmHg	114 ± 12^	119 ± 11	133 ± 16*	<0.001
DBP, mmHg	72 ± 8^	74 ± 8	83 ± 10*	<0.001

HR, heart rate; SBP systolic blood pressure; DBP, diastolic blood pressure.
* $p < 0.05$ vs. other groups.
^ $p < 0.05$ vs. sedentary individuals.

Table 2
Echocardiographic data collected in the study population.

	Athletes (n = 993)	Sedentary individuals (n = 410)	Patients with aortic dilatation (n = 498)	P value
Interventricular septum thickness, mm	9.5 ± 1.3	8.8 ± 1.2	11.5 ± 1.4*	<0.001
Posterior wall thickness, mm	9.2 ± 1.2	8.5 ± 1.1	10.7 ± 1.3*	<0.001
LV end-diastolic diameter, mm	51.9 ± 4.5*	47.1 ± 3.7	48.8 ± 4.0^	<0.001
LV end-systolic diameter, mm	32.1 ± 4.2*	28.3 ± 3.8	30.4 ± 4.9^	<0.001
LV end-diastolic diameter index, mm/m^2	27.3 ± 2.5*	25.5 ± 2.3	24.1 ± 2.5^	<0.001
LV end-systolic diameter index, mm/m^2	16.9 ± 2.1*	15.3 ± 2.1	15.0 ± 2.5	<0.001
LV mass, g	181.5 ± 50.7^	137.2 ± 34.9	204.0 ± 45.6*	<0.001
LV mass index, g/m^2	92.4 ± 21.1^	71.6 ± 13.9	95.0 ± 18.2*	<0.001
Relative wall thickness (RWT)	0.36 ± 0.04	0.36 ± 0.04	0.44 ± 0.06*	<0.001
LV ejection fraction, %	63.6 ± 4.7	61.3 ± 3.7	57.2 ± 3.8*	<0.001
Aortic root, mm	30.6 ± 3.2	30.5 ± 3.1	39.2 ± 2.4*	<0.001
Aortic root indexed (BSA), mm/m^2	16.1 ± 1.5	16.5 ± 1.6	19.4 ± 2.2*	<0.001
Aortic root indexed (height), mm/m	0.17 ± 0.01	0.17 ± 0.02	0.23 ± 0.01*	<0.001
Aortic root indexed (height$^{1.025}$), mm/m$^{1.025}$	0.15 ± 0.01	0.15 ± 0.01	0.20 ± 0.01*	<0.001
Aortic root/LV EDD ratio	0.59 ± 0.06^	0.65 ± 0.05	0.81 ± 0.06*	<0.001
LV EDD/Aortic root ratio	1.71 ± 0.16^	1.55 ± 0.12	1.25 ± 0.10*	<0.001
E wave, m/s	0.88 ± 0.16^	0.86 ± 0.15	0.65 ± 0.17*	<0.001
A wave, m/s	0.50 ± 0.11^	0.57 ± 0.13	0.77 ± 0.20*	<0.001
E/A ratio	1.87 ± 0.54^	1.56 ± 0.52	1.02 ± 0.27*	<0.001
PASP, mmHg	22.7 ± 4.0	22.2 ± 3.7	26.7 ± 4.4*	<0.001
TAPSE, mm	24.5 ± 3.2^	23.8 ± 2.6	22.6 ± 3.4*	<0.001
RV s' velocity, cm/s	14.6 ± 2.2^	14.0 ± 2.2	13.3 ± 2.7*	<0.001
Inferior vena cava, mm	20.8 ± 3.8*	16.5 ± 2.4	16.7 ± 2.6	<0.001

LV, left ventricular; EDD end-diastolic diameter; RV, right ventricular; TAPSE, tricuspid annular plane systolic excursion; PASP, pulmonary artery systolic pressure.
* p < 0.05 vs. other groups.
^ p < 0.05 vs. sedentary individuals.

3.2.2. *Aorta*

The AoD was greater in patients with known aortic dilatation, and this result was also confirmed after indexing for BSA or height ($p < 0.05$). No significant differences were found between athletes and controls in the absolute value of AoD.

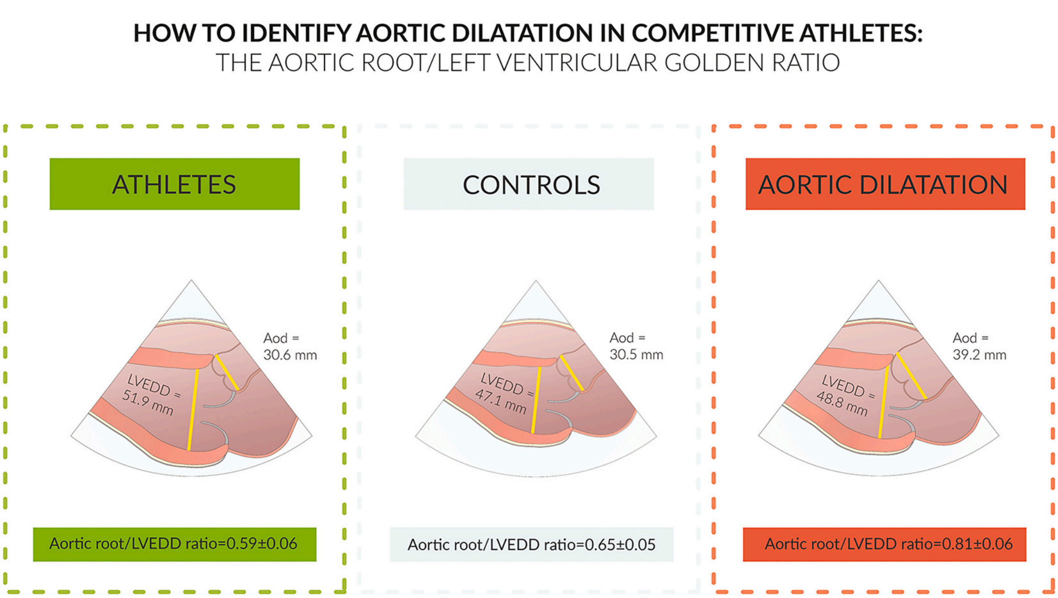
The AoD/LVEDD ratio was significantly higher ($p < 0.05$) in patients with known aortic dilatation (0.81 ± 0.06) than in sedentary subjects (0.65 ± 0.05) and athletes, which had the lowest value (0.59 ± 0.06), (overall p value<0.001). Similarly, the patients with aortopathy had the lowest LVEDD/AoD ratio and competitive athletes the highest (1.71 ± 0.16 in the latter overall p value<0.001).

The AoD/LVEDD ratio values were not significant different in the comparison between males and females in the group of athletes (0.60 ± 0.05 vs 0.58 ± 0.05 respectively), in sedentary controls (0.65 ± 0.05 vs 0.64 ± 0.05, respectively), and in the patients with aortic dilatation (0.81 ± 0.06 vs 0.80 ± 0.06, respectively).

The ROC curve analysis (Fig. 1) highlighted that the AoD/LVEDD ratio has a greater power in differentiating between pathological and physiological remodelling than the other AoD indexed parameters (AoD, AoD/BSA, AoD/height, AoD/height$^{1.025}$). A cut-off of 0.71 for the AoD/LVEDD ratio had a 96% sensitivity and 99% specificity in detecting pathological remodelling.

3.2.3. *Sport disciplines*

The group of competitive athletes was further categorized, based on the sports practised, into 100 skill athletes (10.1%), 454 mixed athletes (45.7%), 227 power athletes (22.9%) and 212 endurance athletes (21.3%). The echocardiographic results are shown in Table 3.



Summary of the main findings of the study.

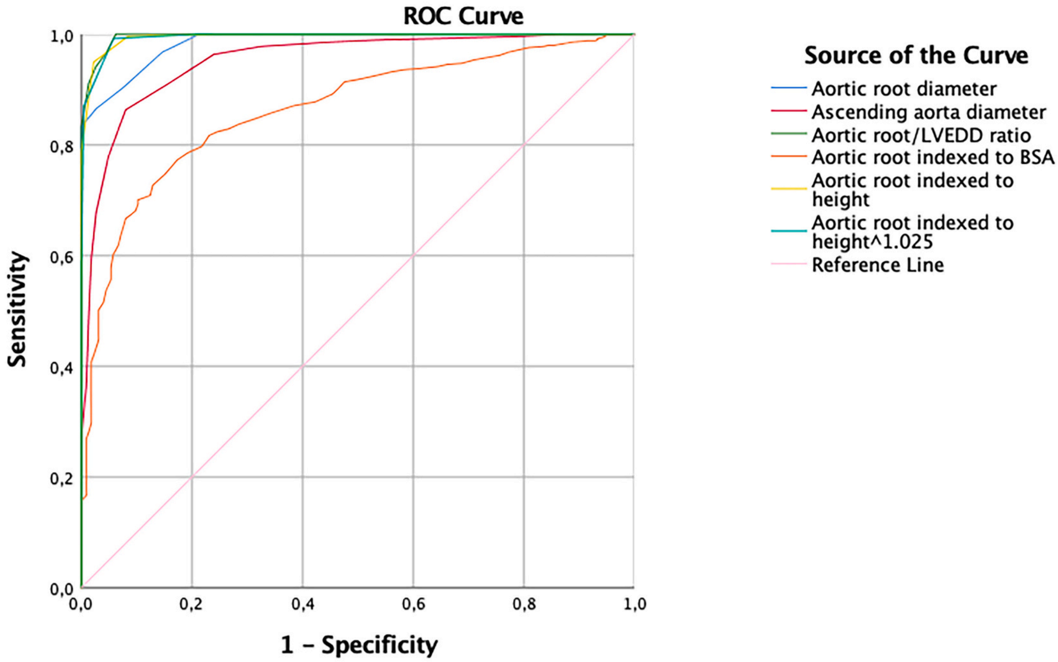


Fig. 1. ROC curve analysis describing the sensitivity and specificity of echocardiographic parameters, including the AoD/LVEDD ratio, to distinguish between pathological and physiological remodelling of the aorta.

Endurance athletes showed the greatest degree of LV remodelling, and LV dimensions were greater than the other groups ($p < 0.05$). The aortic root diameter was greater in endurance athletes than in the other groups ($p < 0.05$), and this result was confirmed after indexing for BSA or height. The endurance athletes had the lowest AoD/LVEDD ratio and the highest LVEDD/AoD ratio, significantly different from power athletes ($p < 0.05$).

The main results of the study are reported in the Central Illustration.

4. Discussion

The athlete's heart is a well-known phenomenon of cardiac remodelling subsequent to the haemodynamic changes induced by intensive training. This is particularly evident in the cardiac chambers, where it leads to an increase in ventricular or atrial size and wall thickness [17,18]. This adaptation extends to the vascular system, including the inferior vena cava which is usually dilated, while aortic dilatation is rare in athletes [5,8,9]. Our study demonstrates that: i) intensive and regular training can induce a remodelling of the cardiac chambers, particularly for endurance disciplines; however, this adaptation is not accompanied by a significant remodelling of the aorta, as demonstrated by similar values of aortic size between competitive athletes and sedentary individuals; ii) a simple 'golden' ratio between the AoD and LVEDD can help to evaluate a physiological exercise-induced remodelling and demonstrates significant differences among competitive athletes, sedentary individuals, with athletes exhibiting a harmonic remodelling of the heart; iii) a peculiar training-induced remodelling of the aorta exists according to the type of sports disciplines practised, with endurance athletes exhibiting the greatest AoD.

Our study showed that intense training is associated with an enlargement of the LV cavity size. Indeed, competitive athletes show larger LV dimensions and greater LV mass compared to sedentary individuals. Notably, despite the LV remodelling, aortic diameters were not significantly different between competitive athletes and sedentary controls, suggesting that the effects of intensive training on the aorta are minimal. These findings confirmed that, in the presence of a dilatation of the aorta, it is important to avoid attributing the enlarged aorta to BSA or a physiological response to exercise and further investigations are needed to determine whether an underlying aortopathy is present. These findings agree with Sotiriou et al. [19] demonstrating no significant differences in the aortic root diameter between athletes and controls. In a meta-analysis by Iskandar et al. (23 studies and 5580 athletes were included) [5], athletes were found to have significantly greater aortic diameters than controls (the aortic diameter at the sinus of Valsalva was 3.2 mm greater in athletes, $p = 0.02$). Nevertheless, the difference was small, and the authors concluded that the effect of training is minimal, in line with similar conclusions obtained in a study conducted on elite athletes by Pelliccia and colleagues [9].

Cardiac dimensions are strictly related to anthropometric features; for this reason, the absolute values of LV and aortic root diameters are usually indexed for BSA or height. This method assumes a linear correlation between the values and the anthropometric characteristics. This linear correlation has been demonstrated between the LVEDD and BSA and height in a cohort of American basketball players [20]. However, although increasing BSA is associated with larger aortic diameters, there is a non-linear relationship between the aortic size and BSA, with a plateau in tall individuals, for BSA >2.3 m^2 and also height $>$ 189 cm in men and $>$ 175 cm in women. Therefore, even if the z score is recommended [21,22], a universal and recommended cut-off for defining aortic dilatation in competitive athletes does not exist. However, when evaluating the heart from the parasternal long-axis view, the expert physicians suspected a pathological aortic dilatation with an instinctive eye-balling analysis, irrespective of absolute or indexed values, relating the aortic diameter with the LV cavity size.

In this study, we determine for the first time the normal values of the AoD/LVEDD ratio and LVEDD/AoD ratio in a large cohort of competitive athletes. The AoD/LVEDD ratio was significantly lower in athletes than in sedentary controls (0.59 ± 0.06 vs 0.65 ± 0.05, $p < 0.05$), while patients with aortic dilatation showed the highest value (0.81 ± 0.06). The LVEDD/AoD ratio was significantly higher in athletes than sedentary controls and patients with aortic dilatation showing mean values significantly different in the three groups (1.71 ± 0.16 vs 1.55 ± 0.12 vs 1.25 ± 0.10, $p < 0.05$). These results corroborate the hypothesis that training-induced hemodynamic overload in competitive athletes has a

Table 3
Echocardiographic data collected in the athletic population and analyzed according to the type of sports discipline practiced.

	SKILL ($n = 100$)	POWER ($n = 227$)	MIXED ($n = 454$)	ENDURANCE ($n = 212$)	P value
LV end-diastolic diameter, mm	50.0 ± 4.0[^]	51.2 ± 4.4	51.9 ± 4.4	53.6 ± 4.5[*]	<0.001
LV end-systolic diameter, mm	30.8 ± 3.8[^]	31.6 ± 4.0	32.19 ± 4.3	33.0 ± 4.2[$]	<0.001
LV end-diastolic diameter index, mm/m^2	27.1 ± 1.9	27.1 ± 1.9[^]	26.5 ± 2.3	29.2 ± 2.6[*]	<0.001
LV end-systolic diameter index, mm/m^2	16.8 ± 1.8	16.7 ± 1.8	16.4 ± 2.0	18.1 ± 2.3[*]	<0.001
LV mass	157.9 ± 42	174.8 ± 48.6[£]	177.9 ± 47.4[£]	207.6 ± 53.8[*]	<0.001
LV mass index, g/m^2	82.8 ± 17	89.1 ± 18.1[£]	88.4 ± 18.4	109 ± 22.7[*]	<0.001
LV ejection fraction (LVEF), %	63.8 ± 4.9	64.3 ± 4.8[^]	62.8 ± 4.6	64.2 ± 4.6[^]	<0.001
Aortic root, mm	29.3 ± 3.1	30.1 ± 3.3	30.1 ± 3.3	31.0 ± 3.4[*]	<0.001
Aortic root indexed (BSA), mm/m^2	15.9 ± 1.6	15.9 ± 1.5	15.9 ± 1.5	16.8 ± 1.5[*]	<0.001
Aortic root indexed (height), mm/m	0.17 ± 0.02	0.17 ± 0.02	0.17 ± 0.01	0.18 ± 0.02[*]	<0.001
Aortic root indexed (height$^{1.025}$), mm/m$^{1.025}$	0.15 ± 0.01	0.15 ± 0.01	0.15 ± 0.01	0.15 ± 0.01	0.06
Aortic root/LV EDD ratio	0.59 ± 0.05	0.60 ± 0.05	0.59 ± 0.05	0.58 ± 0.06[a]	<0.001
LVEDD/Aortic root ratio	1.72 ± 0.15	1.68 ± 0.15	1.71 ± 0.15	1.75 ± 0.17[a]	<0.001
RV end-diastolic mid-cavity diameter, mm	24.5 ± 4.4	26.5 ± 4.6[£]	27.8 ± 4.8[$]	27.4 ± 4.9[£]	<0.001
TAPSE, mm	23.9 ± 3	24.3 ± 3.3	24.4 ± 3.2	25 ± 3.3[£]	<0.031
RV s' velocity, cm/s	14.7 ± 2	14.4 ± 2.3	14.6 ± 2.2	14.7 ± 2.1	<0.001
Inferior vena cava, mm	19.9 ± 3.2	20.3 ± 3.4	20.4 ± 3.9	22.6 ± 4[*]	<0.001
PASP, mmHg	21.4 ± 3.9	22.4 ± 4.1	22.6 ± 4.1[£]	23.5 ± 3.9[*]	<0.001

LV, left ventricular; EDD end-diastolic diameter; RV, right ventricular; TAPSE, tricuspid annular plane systolic excursion; PASP, pulmonary artery systolic pressure.
[*] $p < 0.05$ vs. other groups.
[^] $p < 0.05$ vs mixed (C).
[$] $p < 0.05$ vs. power and skill (BD).
[£] $p < 0.05$ vs skill (D),
[a] $P < 0.05$ vs. power.

more pronounced effect on intracavity diameters than on aortic diameters, contrary to what occurs in patients with pathological aortic dilatation, in which the alteration of the structure or function of the connective tissue within the vascular wall leads to a disproportionate increase in aortic diameters compared to LV diameters, typically seen by echocardiography from the parasternal long-axis view.

Furthermore, our results corroborate the theory that physiological remodelling follows the golden ratio between the LVEDD and the AoD while pathological remodelling does not. The golden ratio has been first described by Pitagora: it is an irrational constant of approximately 1.618 and is present through nature. For this reason, it has been hypothesized that it should be conserved in physiological cardiac remodelling. Indeed, an LVEDD/AoD ratio of 1.62 was observed in healthy young individuals. It was demonstrated that the golden ratio did not differ according to age or ethnicity in healthy populations, contrary to what occurs in heart failure patients [23,24]. Notably, in our study, sedentary subjects and athletes had a LVEDD/AoD ratio closer to the golden number 1.618. At the same time, patients with the pathological remodelling of the aorta showed a significantly lower LVEDD/AoD ratio ratio, suggesting an alteration of the cardiac harmony.

Therefore, the finding in athletes of an AoD/DTD index greater than those described (or a LVEDD/AoD ratio lower) could suggest that the aortic diameter should not be considered a physiological adaptation to physical exercise but can be the expression of a pathological condition, probably exacerbated by intensive training, requiring a close follow-up and eventually further investigations.

The type of sport typically influences the degree of cardiac remodeling [25,26] in athletes, with endurance sports having the greatest impact. In this study, the sub-group analysis according to the sport's category confirmed that endurance training correlates with the highest degree of cardiac remodelling, especially on cardiac chamber dimensions and wall thickness. Indeed, the endurance-trained group had the highest LVEDD, LVESD and LVM than any other group. Notably, also the AoD was higher in endurance athletes, even after indexing for BSA or height, with comparable measures among the other sports disciplines. Therefore, our study demonstrated in a large cohort that a specific subgroup of endurance athletes might exhibit a greater diameter of the aorta due to the sport practised. These findings agree with other studies on AoD in different sports disciplines, demonstrating that endurance athletes had higher values [8,9,16].

When we applied the AoD/LVEDD ratio and the LVEDD/AoD ratio, we found that endurance athletes had the lowest and the highest value, respectively. Indeed, this group is exposed to the highest hemodynamic overload, and contemporary has the larger LVEDD and AoD. These results confirm the hypothesis that cardiac adaptation to physical activity is harmonic. On the other hand, it is possible that a greater LVEDD might lead to an underestimate of the AoD/LVEDD ratio, thus normalizing aortic size by definition. Nevertheless, it should be noted that none of the subjects in the competitive athletes' group had an aortic dilatation. Further prospective studies are needed to evaluate the clinical significance of this parameter.

4.1. Limitations

The main limitation of this study is that we did not enroll a population of athletes with a known aortic dilatation. Although the main aim of the study was to evaluate this ratio in a population of athletes and patients with aortic dilatation, the inclusion of a population of athletes with aortic dilatation would have been helpful to discriminate between athletes with normal aorta and athletes with a pathological aortic dilatation. Future research is needed to validate this ratio in the population of athletes with mild-to-moderate aortic dilatation that continue to practice sport and to understand if it is applicable in any type of sport. Another limitation is that the group of athletes was composed of competitive, well-trained athletes who were not elite. However, our findings are in line with the studies conducted on top-level Olympic athletes [3], demonstrating a relevant remodelling of the LV in the absence of an important effect of training on the aorta.

Finally, the participants in this study were Caucasian athletes. However, even if these findings cannot be extensively applied to other ethnicities, the current evidence does not suggest a different aortic remodelling according to ethnicity.

5. Conclusion

Intensive and regular training can induce a remodelling of the cardiac chambers without a significant remodelling of the aorta. In this study, we reported for the first time the values of the AoD/LVEDD ratio and LVEDD/AoD ratio in a cohort of healthy athletes, additional parameters that could help confirm the harmonic remodelling that exists in the athlete's heart. A peculiar training-induced remodelling of the aorta exists according to the type of sports disciplines practised, with endurance athletes exhibiting the greatest AoD.

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Author note

Any author take responsibility for all aspects of the reliability and freedom from bias of the data presented and their discussed interpretation.

Declaration of Competing Interest

None declared.

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