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REVIEW

CLINICAL CARDIOLOGY WILEY

The impact of demographic, anthropometric and athletic characteristics on left atrial size in athletes

Georgios A. Christou[1,2] | Jamie M. O'Driscoll[3,4]

[1]Laboratory of Sports Medicine, Sports Medicine Division, Aristotle University of Thessaloniki, Thessaloniki, Greece
[2]MSc Sports Cardiology, St George's University of London, London, UK
[3]School of Human and Life Sciences, Canterbury Christ Church University, Canterbury, UK
[4]Department of Cardiology, St George's Healthcare NHS Trust, London, UK

Correspondence
Georgios A. Christou, MD, PhD, Cardiologist, Laboratory of Sports Medicine, Sports Medicine Division, Aristotle University of Thessaloniki, Thessaloniki, Greece.
Email: georgios.christou@yahoo.gr

Abstract

The structural adaptations of the "athlete's heart" include left atrial (LA) enlargement. A literature search was performed based on PubMed listings up to November 2, 2019 using "athletes AND left atrium," "athletes AND LA," "sports AND left atrium," "sports AND LA," "exercise AND left atrium," and "exercise AND LA" as the search terms. Eligible studies included those reporting the influence of demographic, anthropometric and athletic characteristics on LA size in athletes. A total of 58 studies were included in this review article. Although LA volume has been reported to be greater in males compared to females when indexed for body surface area (BSA), there was no difference between sexes. The positive association between LA size and age in athletes may reflect the increase in body size with maturation in nonadult athletes and the training age of endurance athletic activity in adult athletes. Caucasian and black athletes have been demonstrated to exhibit similar LA enlargement. The positive association of LA size with lean body mass (LBM) possibly accounts for the relationship of LA size with BSA. LA enlargement has been reported only in endurance-trained, but not in strength-trained athletes. LA size appears to increase with an increase in both the volume and intensity of endurance training. LA size correlates independently with the training age of endurance athletes. The athlete's characteristics that independently determine LA size include LBM, endurance training, and training age.

KEYWORDS

age, body surface area, endurance sports, ethnicity, gender, lean body mass, left atrial diameter, left atrial volume, left atrium, training age

1 | INTRODUCTION

It has been well established that chronic exercise training results in specific cardiac adaptations, collectively known as the "athlete's heart."[1] These cardiac adaptations include electrical, structural and functional alterations that are generally considered benign.[2-4] With regard to structural adaptations, there is evidence of cardiac chamber enlargement, increased left ventricular (LV) wall thickness, and prominent LV trabeculations.[3,4] Notably, increased cavity size appears to involve both the left and right heart and it has been shown to affect not only the ventricles, but the atria as well.[3,4]

Growing concerns have arisen regarding the left atrial (LA) enlargement encountered in athletes, in the light of the potential adverse consequences attributed to increased LA size, including predisposition to atrial arrhythmias and especially atrial fibrillation.[5,6] Although LA enlargement in athletes can be reasonably considered

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benign in the absence of increased LV filling pressures and mitral valve dysfunction, the excessive LA enlargement in some athletes may challenge the notion of the benign nature of this process. In this respect, the characteristics of the athlete predisposing to LA enlargement are important to be elucidated, since this information will enable the clinician to judge whether the magnitude of LA enlargement in an athlete can be normally expected on the basis of the athlete's characteristics. Furthermore, the importance of the study of characteristics of the athletes with LA enlargement relies on the identification of possible modifiable predisposing characteristics leading to LA enlargement, such as training volume, that, if changed, could decrease the severity of LA enlargement in the case of athletes with atrial arrhythmias. Therefore, this review article discusses the demographic, anthropometric, and athletic characteristics associated with LA enlargement and attempts to elucidate the relative importance of them in determining LA size in athletes. No previous study has addressed these issues.

2 | METHODS

2.1 | Search strategy

A literature search based on PubMed listings up to November 2, 2019 using "athletes AND left atrium," "athletes AND LA," "sports AND left atrium," "sports AND LA," "exercise AND left atrium," and "exercise AND LA" as the search terms identified 3387 articles (Figure 1). The reference lists of these articles were also interrogated and articles that were judged relevant were selected for inclusion in the review. In total, 58 studies were included in the text of this review article.

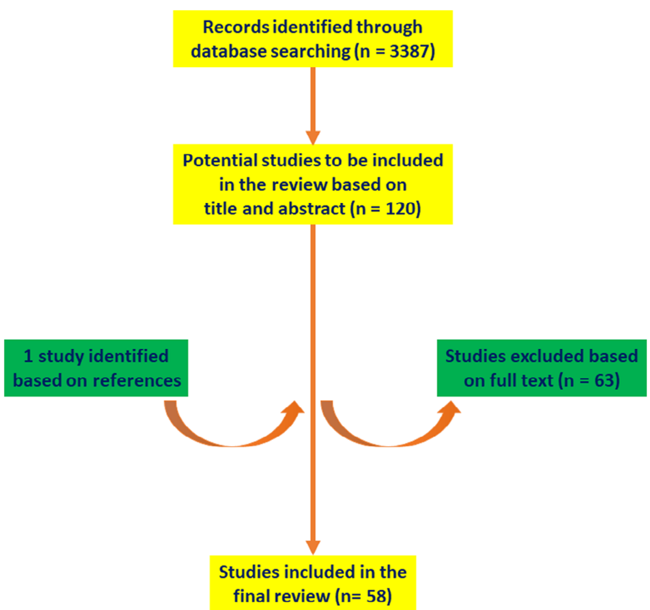

FIGURE 1 Schematic flowchart for the selection of studies to be included in the review

2.2 | Inclusion criteria

Studies fulfilling the following criteria were considered eligible for inclusion in the review:

1 Original research articles.
2 Studies investigating human individuals.
3 Studies mentioning the influence of demographic, anthropometric or athletic characteristics on LA size in athletes.
4 Full text written in English.

3 | THE INFLUENCE OF ATHLETE'S CHARACTERISTICS ON LA SIZE

Table 1 summarizes the characteristics and key findings of the main studies included in this review article. The main studies that were deemed eligible to be included in Table 1 were the ones fulfilling the following criteria: (a) at least one study investigating the effect of each individual athlete's characteristic on LA size, (b) studies with results that best reflect the effects of athlete's characteristics on LA size, (c) studies with novel results not investigated by other studies, and (d) among studies reporting similar information, we selected to include the study with the greatest number of participant.

3.1 | Gender

The majority of studies have shown that male athletes have greater LA volume compared to female athletes.[7-10] Moreover, George et al demonstrated that among nonadult athletes, LA diameter was increased in males compared to females.[11] Taking into account that LA enlargement usually occurs asymmetrically and LA diameter has been demonstrated to underestimate LA volume especially in females, the comparison of LA size between male and female athletes is more appropriately performed using LA volume rather than LA diameter.[12] However, the difference in LA volume between male and female athletes has been reported to disappear after indexing for body surface area (BSA) or lean body mass (LBM).[9,10,13,14] Considering that females are normally characterized by greater body fat percentage, the persistence in few studies of the difference in LA volume between male and female athletes after indexing for BSA may not represent a valid analysis.[7,15,16] In this case, indexing for the metabolically active LBM is possibly more appropriate. Therefore, the greater LBM of male athletes may account at least in part for their greater LA size.

Nevertheless, the presence of residual confounding cannot be totally excluded in the comparison of LA volume indexed for BSA between male and female athletes, since the training regimens of male athletes are usually characterized by greater volume and intensity, which may in turn affect LA size to a greater extent. Indeed, Mosen et al demonstrated that LA volume indexed for BSA differed only between male and female athletes, but not between male and female controls.[7] Moreover, Legaz Arrese et al reported that LA diameter of long- and middle-distance runners was increased compared to sprint runners; however, this was only

TABLE 1 The main studies evaluating the effects of demographic, anthropometric and athletic characteristics on left atrial size in athletes

Studies	Athletic study population	Findings
Prakken et al[8]	120 endurance athletes • 60 regular athletes: training volume 9-18 h/wk • 60 elite athletes: training volume > 18 h/wk	Elite athletes vs regular athletes: ↑ LAV Multiple regression analysis. Independent predictors of LAV: BSA, training volume, gender
Giraldeau et al[9]	90 Caucasian college athletes (45 males, 45 females)	Males vs females: ↑ LAV, ↔ LAV/BSA, ↔ LAV/LBM$^{0.7}$
Wilhelm et al[10]	138 athletes (70 males, 68 females)	Males vs females: ↑ LAV, ↔ LAV/BSA
George et al[11]	464 junior athletes (14-18 y old)	Males vs females: ↑ LAD Athletes 17-18 y old vs athletes 14 y old: ↑ LAD Correlation with LAD: body weight (*b* exponent = 0.3 ± 0.1), BSA (*b* exponent = 0.5 ± 0.2)
Lakatos et al[13]	138 athletes (85 males, 53 females)	Males vs females: ↔ LAV/BSA (3D echocardiography)
Nistri et al[15]	157 athletes	Correlation with LAV/BSA: male gender, BMI (*r* > 0), age (*r* > 0)
D'Andrea et al[16]	615 athletes • 370 endurance-trained • 245 strength-trained	Endurance-trained athletes vs strength-trained athletes: ↑ LAD, ↑ LAV/BSA Correlation with LAV/BSA: age (*r* > 0), male gender, training age (*r* > o), endurance training Multiple regression analysis. Independent predictors of LAV/BSA: endurance training, training age
Legaz Arrese et al[17]	188 runners (134 males, 54 females) • 57 sprint-trained • 73 middle distance-trained • 58 long distance-trained	Long distance-trained vs middle distance-trained: ↔ LAD (males), ↔ LAD (females) Long distance-trained vs sprint-trained: ↑ LAD (males), ↔ LAD (females) Middle distance-trained vs sprint-trained: ↑ LAD (males), ↔ LAD (females)
Cavarretta et al[20]	2261 peri-pubertal athletes	Correlation with LAD: age (*r* > 0), BSA (*r* > 0) Multiple regression analysis. Independent predictor of LAD: BSA
Somauroo et al[21]	172 teenage soccer players	Correlation with LAD: BSA (*r* > 0), not with age (*P* = .100)
Elliott et al[25]	96 endurance athletes. Three groups according to lifetime training hours • L: (n = 30) < 3000 h • M: (n = 31) 3000-6000 h • H: (n = 35) > 6000 h	H vs L: ↑ LAV/BSA, ↔ LAD M vs L: ↑ LAV/BSA, ↔ LAD
Gjerdalen et al[29]	553 football players (504 Caucasian, 49 African)	Caucasian vs African: ↔ LAV, ↔ LAV/BSA, ↔ LAD
Riding et al[30]	1166 athletes (596 Arabic, 410 Black African, 160 Caucasian)	Caucasian vs Arabic: ↑ age, ↑ BSA, ↑ LAV, ↑ LAD Caucasian vs Black: ↑ age, ↑ BSA, ↔ LAV, ↔ LAD Black vs Arabic: ↑ age, ↑ BSA, ↑ LAV, ↑ LAD
McClean et al[37]	36 male athletes • 18 high dynamic-high static • 18 low dynamic-high static 20 male age-matched controls	High dynamic-high static vs Low dynamic-high static: ↑ LAV, ↑ LAD High dynamic-high static vs controls: ↑ LAV, ↑ LAD Low dynamic-high static vs controls: ↔ LAV, ↔ LAD
Kooreman et al[42]	72 female college athletes • (n = 37) higher intensity group • (n = 35) lower intensity group 31 female, age-matched controls	Higher intensity group vs controls: ↑ LAV/BSA Lower intensity group vs controls: ↔ LAV/BSA Higher intensity group vs Lower intensity group: ↑ LAV/BSA, ↑ LAV/LBM
D'Andrea et al[45]	650 athletes • (n = 395) endurance-trained • (n = 255) strength-trained 230 age-, gender-matched controls	Endurance-trained vs controls: ↑ LAV/BSA Strength-trained vs controls: ↔ LAV/BSA Endurance-trained vs strength-trained: ↑ LAV/BSA
Dores et al[54]	108 athletes • 60 high level (training volume ≥ 20 h/wk) • 48 low level (training volume < 10 h/wk)	High level athletes vs low level athletes: ↑ LAV/BSA
Mahjoub et al[57]	17 male endurance-trained athletes	High intensity interval training with cycle ergometer (3 sessions/wk) for 6 wk → ↑ LAV

(Continues)

TABLE 1 (Continued)

Studies	Athletic study population	Findings
Król et al[58]	114 rowers (61 males, 53 females)	Correlation with LAV: VO_{2max} (r > 0)
D'Ascenzi et al[62]	21 adolescent soccer players after 2 mo of detraining	After 4 mo of exercise training vs baseline: ↑ LAV/BSA After 8 mo of exercise training vs baseline: ↑ LAV/BSA
Pedlar et al[66]	21 runners having participated in Boston Marathon	After 8 wk of detraining vs peak prerace performance: ↔ LAV
Hasdemir et al[72]	23 retired football players (>50 y old) 18 controls (>50 y old). Never regular exercise in their life	Retired athletes vs controls: ↑ LAD

Note: Symbols "↑" and "↔" represent increase and no difference, respectively.
Abbreviations: BSA, body surface area; LAD, left atrial diameter; LAV, left atrial volume; LBM, lean body mass; VO_{2max}, maximal oxygen uptake.

true in male athletes.[17] The comparison of LA size between male and female athletes needs further investigation, and importantly, comparisons need to be made between genders matched for sporting discipline and training volume and intensity, and indexing LA volume to LBM, producing body size independent measures.

3.2 | Age

With regard to the relationship between LA size and age in athletes, LA enlargement has been shown to be more pronounced in adult athletes compared to teenage athletes of the same sport.[18,19] In addition, LA size in athletes has been found to increase with increasing age from childhood to early adulthood.[11,20] However, the relationship between LA size and age from childhood to early adulthood appears to result from the accompanied increase in body size with maturation, rather than from an independent effect of chronological age per se, since the relationship between LA size and age has been found to disappear after adjustment for body size.[19,20] Even more, Somauroo et al showed that among teenage soccer players LA diameter correlated only with BSA and not with age.[21]

In the majority of studies, a positive association between LA size and age has been found in adult athletes.[13,15,22-24] Taking into account that this relationship has been shown to be attenuated after adjustment for training age, this association in athletes possibly occurs at least in part through the effect of training age on LA size.[16,25] Indeed, the LA has been reported to progressively enlarge over the years of active athletic life in endurance-trained athletes.[24,26] In other words, the greater number of lifetime endurance training hours of older athletes may determine their greater LA size. Consistently, LA size in healthy nonathletes has been reported to be determined mostly by body size rather than age and thus an increase in LA size is possibly an expression of pathology and it cannot be attributed to normal aging.[27,28]

3.3 | Ethnicity

The overwhelming majority of studies evaluating LA size in athletes is in Caucasian athletic populations. Few studies have investigated whether LA size in athletes is influenced by ethnicity.[29-31] Specifically, Caucasian and black athletes have been demonstrated to exhibit similar LA enlargement, while Caucasian athletes were characterized by greater LV size and decreased relative wall thickness compared to black athletes.[29-31] Thus, black athletes may have disproportionately greater LA size compared to LV enlargement. A possible explanation for these findings may be the equally thin atrial wall of both Caucasian and black athletes permitting similar LA enlargement, as opposed to the greater LV wall thickness of black athletes limiting the magnitude of LV dilatation compared to Caucasian athletes.

With regard to Arabic athletes, Riding et al showed that these athletes had decreased LA size compared to both Caucasian and black athletes.[30] However, in this study, Arabic athletes were younger and had a lower BSA compared to Caucasian and black athletes and the authors used measures of LA size without adjustment for body size.[30] Thus, the reported differences in LA size may have been confounded by the different ages and BSA between the athletes.[30] Further studies are needed to elucidate whether LA size differs between athletes of different ethnicity, who are matched for gender, age, body size, and sport discipline.

3.4 | Anthropometric characteristics

LA size, expressed as either LA anteroposterior diameter or LA volume, has been demonstrated to correlate positively with BSA.[7,8,20,22,32] Taking into account that BSA represents an estimate of the total tissue mass perfused and hence of cardiac output, this association of LA size with BSA possibly reflects the impact of cardiac volume overload on LA remodeling.[33] Consistently, both LA and LV enlargement in athletes have been found to be balanced with a strong independent correlation between them, mirroring the same magnitude of loading conditions.[15] According to the law of Laplace (ie, wall tension = intracavitary pressure × cavity radius/[2 × wall thickness]), the thinner LA wall is associated with higher wall tension predisposing the LA to dilatation, while the LA enlargement in athletes without concomitant increases in LA wall thickness further increases LA wall tension promoting additional LA enlargement.

Scaling of LA size should be ideally performed for LBM, which is the metabolically active tissue mass in human body.[34] Scaling for body weight, as a proxy measure of LBM, can be precise to the extent that the body fat percentage remains similar across the study population, which is not always the case among athletes of different sports.

Importantly, a common pitfall in allometric scaling of cardiovascular parameters is the inappropriate power to which is raised the allometric parameter used for the scaling of cardiovascular parameters.[34] The ideal scaling procedure should result in body size independent variables.[34] Even more, based on the theory of geometric similarity the one-dimensional LA diameter should be appropriately indexed for $LBM^{0.3}$ and $BSA^{0.5}$, while the three-dimensional LA volume for LBM and $BSA^{1.5}$.[11,34,35] Consistently, LA volume indexed for BSA may not be body size independent, as indicated by the reported association between this variable and body mass index in both athletes and nonathletes.[15] Appropriately powered prospective studies are needed to investigate this issue further, such as ascertaining any changes in LA size following weight loss interventions in athletes and nonathletes. With regard to nonadult athletes, the relationship between LA size and BSA appears to underly the increase in LA size with aging during maturation.[11,20,21,36]

3.5 | Sport discipline

The degree of LA enlargement in athletes has been found to depend on sport discipline. Specifically, only endurance-trained athletes have been reported to have increased LA size compared to nonathletes, while the LA size of strength-trained athletes has been shown to be similar to age- and gender-matched controls.[16,37-46] Of particular interest, there appears to be a more pronounced LA enlargement reported in endurance cyclists.[37,38,40,47] In addition, among athletes performing the same mode of exercise, LA size appears to increase as the endurance component of the sport increases.[17,48] Indeed, LA size was found to be greater in both long- and middle-distance runners compared to sprint runners.[17] Similarly, LA size of baseline tennis players was shown to be increased compared to offensive tennis players, who are known to be characterized by lower energy demands during training and competition compared to the former.[48,49]

The effect of endurance training on LA size is possibly mediated through the volume overload of this type of training, resulting in a balanced enlargement of all cardiac cavities.[15,16,42,50-52] Indeed, the ratio of LA volume to LV end-diastolic volume has been shown not to differ among endurance-trained athletes, strength-trained athletes and controls.[42]

With regard to sports in which a high body weight confers an advantage to the athlete, such as the position of lineman in American Football, athletes often seek advice for weight gain with the goal of becoming larger than their opponents. These athletes are characterized by greater LA size compared to other type of athletes, while this difference has been found to disappear after indexing for BSA, implying that this difference can be attributed to the greater body size of the former.[53]

3.6 | Training regimen

Both training volume and intensity appear to determine the effect of endurance exercise training on LA enlargement. The impact of training volume on LA size has been more adequately studied compared to the effect of training intensity. Specifically, among endurance-trained athletes, higher training volumes have been associated with greater LA size.[8,54,55] This pattern was demonstrated to exist even in junior athletes.[56] Regarding the effect of training intensity on LA size, Mahjoub et al demonstrated that LA volume in endurance athletes increased following 6 weeks of high intensity interval training with cycle ergometer.[57]

The reported positive association between LA size and maximal oxygen uptake in athletes can be possibly explained by the fact that higher aerobic capacity may reflect a higher level of endurance training, which in turn can contribute to LA enlargement.[7,40,58-61] With regard to the association between LA size and maximal oxygen uptake, when the latter is indexed for body weight, this relationship possibly reflects only the level of endurance training, but when the latter is expressed in absolute terms (ie, L/min) this association may incorporate information about both endurance training and body size.

Importantly, LA size has been shown to increase progressively during the process of a training macrocycle from preseason to end season.[62-65] However, LA volume in marathon runners has been found not to change following 2 months of detraining from peak prerace performance.[66] Therefore, the evaluation of LA size in athletes should consider the current training status of the athletes with regard to not only the current training regimen, but also the exact phase in the temporal sequence of training periodization.

The increase in LA size during the process of a training macrocycle appears to be associated with a decline in peak reservoir and contraction LA strains after at least 4 months of intensification of exercise training.[32,57,62] The clinical significance of this exercise training-associated decline in LA strain remains to be elucidated.

3.7 | Training age

Among endurance-trained athletes, training age, as estimated by lifetime training hours, lifetime years of training or total number of previous competitions, has been demonstrated to correlate positively with LA size.[16,25,50,67] Consistently, the LA size of endurance athletes has been shown to progressively increase over the years of their athletic career.[26] However, Brugger et al reported that peak reservoir, conduit and contraction LA strains (LA mechanics) did not differ among three groups of amateur male runners stratified according to low, moderate and high lifetime training hours.[67]

Considering that former endurance athletes have been reported to have greater LA size compared to age- and gender-matched nonathletes, the adaptation of LA size to endurance training appears to be long lasting with residual LA enlargement many years after the end of the athletic career.[68-72] Notably, this residual training effect on LA size appears to be at odds with the reversible changes in LV wall thickness and LV end-diastolic volume following a long-term deconditioning period.[70,72,73]

Thus, LA size in endurance athletes is possibly determined by the lifetime exposure to volume overload in the context of endurance exercise training with the additive effect of current endurance training to further enhance the exercise-induced adaptations of LA size.

4 | KNOWLEDGE GAPS AND FUTURE AVENUES FOR RESEARCH

The comparison of LA size between male and female athletes needs to be investigated between participants matched for sport discipline and training volume and intensity, as well as indexing LA volume to LBM. Further studies are needed to elucidate whether LA size differs between athletes of different ethnicity, who are matched for gender, age, body size and sport discipline. In addition, the impact of exercise intensity on LA size should be further investigated by altering training frequency and/or training intensity of the workouts of interval training.

The overwhelming majority of studies, which have evaluated the impact of athlete's characteristics on LA size used 2D echocardiography. Cardiac magnetic resonance (CMR) imaging represents a more accurate and reproducible method for the evaluation of cardiac volumes.[8] Specifically, measurement of LA volume with 2D echocardiography is limited by foreshortened views and geometric modeling resulting in decreased LA volumes compared to CMR imaging.[74,75] Therefore, further studies are needed using CMR imaging in the evaluation of LA volumes, especially to confirm whether an athlete's characteristic so far considered to have a neutral effect on LA size, such as ethnicity, has indeed no effect.

Finally, the incorporation of myocardial mechanical analysis using LA strain can aid in the detection of abnormal LA function even in athletes with normal LA size.[76,77] Importantly, impaired LA strain has been demonstrated to predict not only the development of atrial fibrillation, but atrial fibrillation-related stroke as well, over and above clinical and standard echocardiographic parameters.[78,79] The predictive value of LA strain for the development of atrial fibrillation has also been reported to exist in male endurance veteran athletes.[80] Interestingly, in patients with a normal LA size, LA strain was more predictive of atrial fibrillation, whereas in patients with abnormal LA volumes, LV strain was more predictive of atrial fibrillation.[78] Therefore, it is conceivable that both LA and LV strain (global atrioventricular strain) and associated interrogation of the LA-LV coupling, which provides a comprehensive assessment of left heart mechanics, may contribute to the identification of benign or adverse remodeling that may predispose to the development of atrial fibrillation. In this respect, future studies investigating the impact of athlete's characteristics on LA size should use strain analysis of both LA and LV, in order to elucidate whether the effect of each characteristic on LA size in athletes has any prognostic relevance in terms of predisposition to atrial fibrillation.

5 | CONCLUSIONS

LA enlargement appears to be a well-established component of the "athlete's heart." The athlete's characteristics that independently determine LA size include LBM, endurance training and training age

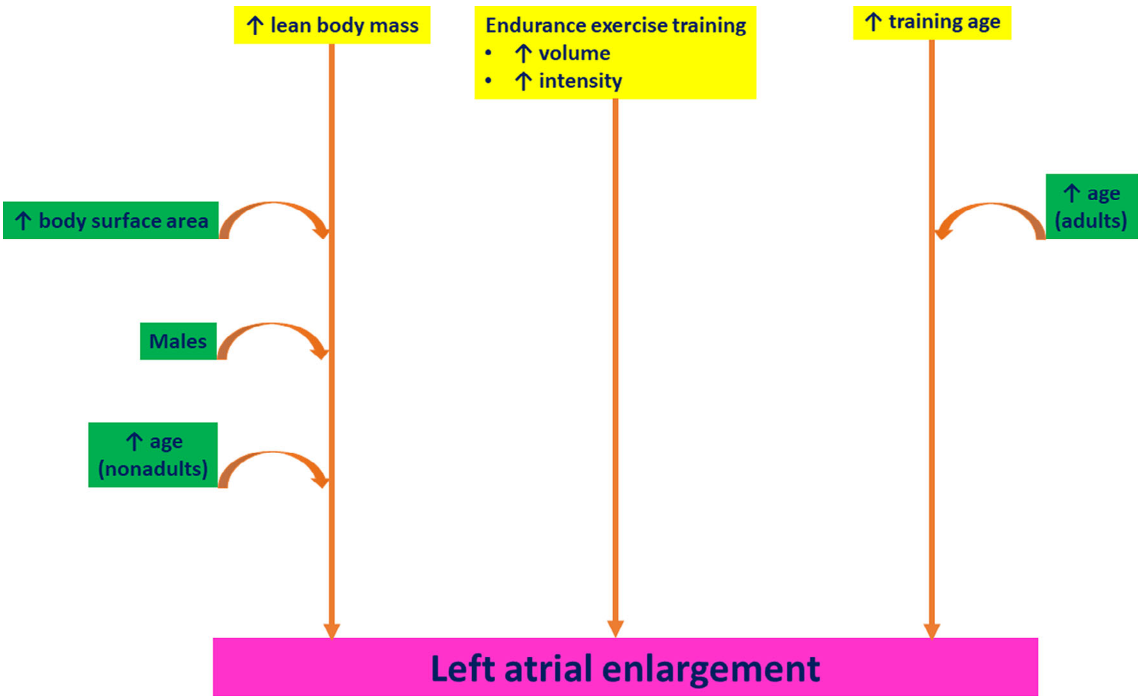

FIGURE 2 The direct and indirect effects of demographic, anthropometric and athletic characteristics on left atrial size in athletes. The straight arrows indicate direct effects, while the curved arrows suggest indirect associations

(Figure 2). The effects of gender, age, and ethnicity on LA size in athletes may be mediated through the above-mentioned characteristics. The accurate interpretation of these variables, which impact LA size in athletes, is of significant clinical importance, in order to ascertain if the LA enlargement detected in an athlete is physiological or represents an underlying cardiac disease.

CONFLICT OF INTEREST

The authors declare no potential conflict of interests.

ORCID

Georgios A. Christou https://orcid.org/0000-0002-7004-8718

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