Original Article

Analysis of Diastolic Function and Atrial Function in High Performance Cyclists through Three-Dimensional Echocardiography

Wercules Oliveira, Ana Clara Tude Rodrigues, Luciana Janot, Adriana Cordovil, Claudia Gianini Monaco, Edgar Lira-Filho, Claudio Henrique Fischer, Samira Saady Morhy, Marcelo Luiz Campos Vieira
Hospital Israelita Albert Einstein, São Paulo, SP – Brazil

Abstract

Objectives: **To assess left ventricular diastolic and atrial function by means of Doppler and three-dimensional echocardiography of high-performance cyclists; To compare the variables studied for non-athlete controls.**

Methods: **The study included 18 professional cyclists (men, age 29, 5±4, 3 years) and 18 non-athlete control individuals (men, age 28, 8±5, 8 years). All individuals underwent two-dimensional and three-dimensional echocardiography including measures of diastolic function variables and atrial emptying, such as maximum, minimum and before contraction left atrial volume. Based on these fundamental volumes, active, passive and total emptying function, and atrial contraction strength were calculated.**

Results: **The individuals of both groups had similar anthropometric variables. The following was observed in the cyclist group as for the controls: lower A' wave velocity (5.9 cm/s ± 2.2 versus 7.6 ± 2.3 cm/s, with P = 0.03), smaller atrial contraction force (4.7 ± 1,4Kdyn vs. 6.2 ± 2.1Kdyn, P = 0.02) and greater passive emptying fraction (43.8% ± 12.8 versus 34.8 ± 10.4% with P = 0.03). A linear correlation was found between A' wave velocity and atrial contraction force in the cyclists group (r = 0.65, P <0.05), between atrial contraction force and passive emptying fraction (r = 0.80, P <0.05) and between atrial contraction and volume before contraction (r = 0.65, P < 0.05).**

Conclusion: **The cyclists group showed an increase in the passive component to the detriment of a reduction in the active component in total atrial emptying, which was showed to be correlated with supernormal diastolic activity in this group. (Arq Bras Cardiol: Imagem cardiovasc. 2014;27(4):235-242)**

Keywords: **Athletes; Bicycling; Motor Activity; Ventricular Dysfunction; Atrial Function; Echocardiography, Three Dimensional.**

Introduction

Intense and regular physical activity is physiologically related to structural and functional cardiac changes[1]. In response to high-performance training, there is often an increase in myocardial thickness, diameter of the heart chambers and myocardial mass, which determines the condition known as "athlete's heart"[2]. These cardiac physiological structural changes should be differentiated from pathological changes in the cardiac structure associated with non-compensated hemodynamic overload, which in turn are closely related to the increased frequency of cardiac arrhythmias and sudden death during exercise[3].

Pulsed Doppler and tissue Doppler have proven to be effective methods for differentiating physiological and pathological changes in athlete's heart. Some studies have used this technology for investigating the influence of sports activity on myocardial function[4]. In patients with pathological changes of the myocardial structure, there is an increased left ventricular relaxation time, reducing the rate of the initial ventricular filling and increasing the speed of delayed ventricular filling, reflecting a greater difficulty in passive ventricular filling because of reduced active relaxation of this chamber, which ultimately characterizes diastolic dysfunction[5].

Left atrial remodeling is also a component of the structural changes associated with exercise and is considered a physiological adaptation of this chamber to the new status of physical fitness. According to epidemiological studies, changes in left atrial volume and function are present in 20% of athletes who play competitive sports and are not associated with higher frequency of major cardiovascular events. Morphological changes in atrial remodeling are associated with increased venous return, cardiac ejection volume, increased left ventricle and depend mainly on the type and intensity of the exercise performed[6]. Left atrial function determined by three-dimensional echocardiographic analysis of its emptying phases is a set of variables that estimate the early onset of diastolic left ventricular dysfunction, because they directly depend on left ventricular filling pressures[7].

Corresponding author: Wercules Oliveira •
Serviço de Ecocardiografia
Av. Albert Einstein, 627/701, 05652-900, Jardim Leonor, São Paulo, SP- Brazil
E-mail: wercules.oliveira@gmail.com
Manuscript received on June 25, 2014; manuscript revised on July 17, 2014; accepted on August 26, 2014.

DOI: 10.5935/2318-8219.20140032

In three-dimensional echocardiography, there is a semiautomatic digital reconstruction of atrial content from the identification of specific anatomical points, making it more objective and less examiner-dependent compared to other techniques[8]. Studies on the use of three-dimensional reconstruction to calculate atrial volume show that two-dimensional echocardiography underestimates the quantification of three-dimensional methodology which in turn has lower values than the measurements by magnetic resonance imaging[9-11]. The discrepancy between methods can be explained not only by the limitation inherent in geometric inference, but also by the inaccuracy of atrial longitudinal or axial axis used in two-dimensional technology for volumetric estimation[12]. Studies that analyzed different techniques of left atrial volume assessment recommend the clinical application of three-dimensional echocardiography due to the shorter time spent on the acquisition and processing of images, lower interobserver variability than two-dimensional echocardiography and comparable values obtained by nuclear magnetic resonance imaging[10].

Despite having been employed in the analysis of atrial dynamics in populations with high prevalence of diastolic dysfunction, three-dimensional echocardiography has not been used in the study of atrial morphological changes physiologically associated with intense and regular physical activity in professional athletes.

Objectives

Assessing left diastolic and atrial function by means of Doppler and three-dimensional echocardiography of high-performance cyclists; Comparing the variables studied for non-athlete controls matched for age, gender and body surface.

Methods

Population

This study, carried out at Hospital Israelita Albert Einstein from 2010 to 2012, included 18 high performance cyclists (men, age 29.5 ± 4.3 years) from Brazilian professional cycling teams. The inclusion criterion for this group was the practice of competitive cycling, average workout duration of at least 10 hours/week, 10 months a year[13]. All these individuals were at the same stage of training and were examined at the same time of the day. The study also included 18 non-athlete controls (men, age 28.8 ± 5.8 years). The criterion for inclusion in this group were age and body surface area similar to the cyclists group. Exclusion criteria for both groups were current smoking, hypertension, any significant metabolic, pulmonary or cardiovascular disease. Those individuals with a limited echocardiographic acoustic window were also excluded from both groups. Individuals with a history of regular and intense or professional sports activity were excluded from the control group.

Echocardiography

Echocardiographic tests were performed according to the criteria established by the guidelines of the American Society of Echocardiography and the Brazilian Society of Cardiology[14,15]. Echocardiography tests were conducted using Toshiba system® Artida ultrasound (Toshiba Medical Systems, Tokyo, Japan) with digital storage application for offline analysis. Images in the parasternal longitudinal axis, transverse parasternal axis and apical four-and two-chamber views were obtained. Three-dimensional echocardiography was performed with transducers for full-volume data acquisition including four consecutive cardiac cycles during breath-hold. Total pyramidal volume (60° x 60°) resulted from the integration of four smaller volumes (15° x 15°). All digitally stored data were analyzed off-line by means of 4D Echo-View® 5.4 (TomTec Imaging Systems, Munich, Germany®).

Left atrial roof, as well as septal, lateral, anterior and posterior points were identified for the digital reconstruction. Atrial endocardial border in each frame throughout the cardiac cycle was set for semi-automatic processing and manually adjusted for left atrial appendage exclusion and pulmonary veins when necessary. The following were calculated throughout the cardiac cycle: maximum left atrial volume, minimum left atrial volume, and left atrial volume immediately before its contraction.

From the fundamental volumes found, the following measures and variables indexed to body surface area were calculated[16-18].

- Volume of total left atrial emptying = maximum left atrial volume — minimum left atrial volume;
- Fraction of total left atrial emptying = (volume of total left atrial emptying / maximum left atrial volume) x 100;
- Volume of active left atrial emptying = left atrial volume before contraction — minimum left atrial volume;
- Fraction of active left atrial emptying = (volume of active left atrial emptying / left atrial volume before contraction) x 100;
- Volume of passive left atrial emptying = maximum left atrial volume — left atrial volume before contraction;
- Fraction of passive left atrial emptying = (volume of passive left atrial emptying / maximum left atrial volume) x 100.

Also within the pyramid sample of three-dimensional echocardiography acquisition, end-systolic and end-diastolic left ventricular volumes were determined during the cardiac cycle to calculate ejection fraction. The endocardial border has been sequentially mapped by semiautomatic processing[19].

The strength of atrial contraction was calculated based on Newton's second law of motion using the following formula: strength of atrial contraction (Kdyn) = 0.5 x 1.06 x mitral valve area x (A wave velocity)^2 where 0.5 is A wave acceleration constant and 1.06 is the blood density (g/cm^3).

The mitral area was identified by apical slope of the three-dimensional volume pyramidal sample and manual planimetry of the inner edge of the mitral annulus[20,21] (Figure 1).

Diastolic function was assessed by pulsed Doppler in the mitral diastolic flow (maximum velocities of E and A waves; E/A ratio and E wave deceleration time). Tissue Doppler imaging was also used to determine the velocities of mitral annulus diastolic motion (E′ and A′ waves derived from the average values of septal and lateral points). These data were used to calculate the E/E' ratio[22].

Myocardial mass was determined by the Devereux formula with a cutoff of 134 g/m^2 [23].

Statistical analysis

Continuous variables are presented as mean and standard deviation and categorical variables as absolute and relative frequencies. The difference between independent groups was determined by Student's t test and χ^2, for continuous and categorical variables, respectively. Pearson's correlation test was used to assess the linear relationship among continuous variables. A $p \leq 0.05$ was considered significant. The statistical analysis program used was Statistic 6.0.

Results

Population

No individual was excluded from the overall sample after application of the exclusion criteria. Individuals in the athletes' group presented a training time of 14.6 h/week ± 4.6, where they ran 702.8 ± 140.9 Km/week. The group of cyclists presented a lower body mass index compared to the non-athletes' control group (22.8 ± 1.3 kg/m^2 vs. 24.2 ± 1.8 kg/m^2, P = 0.02). There were no significant statistical differences between the groups for the other clinical data. The demographics of cyclists and non-athlete controls are shown in Table 1.

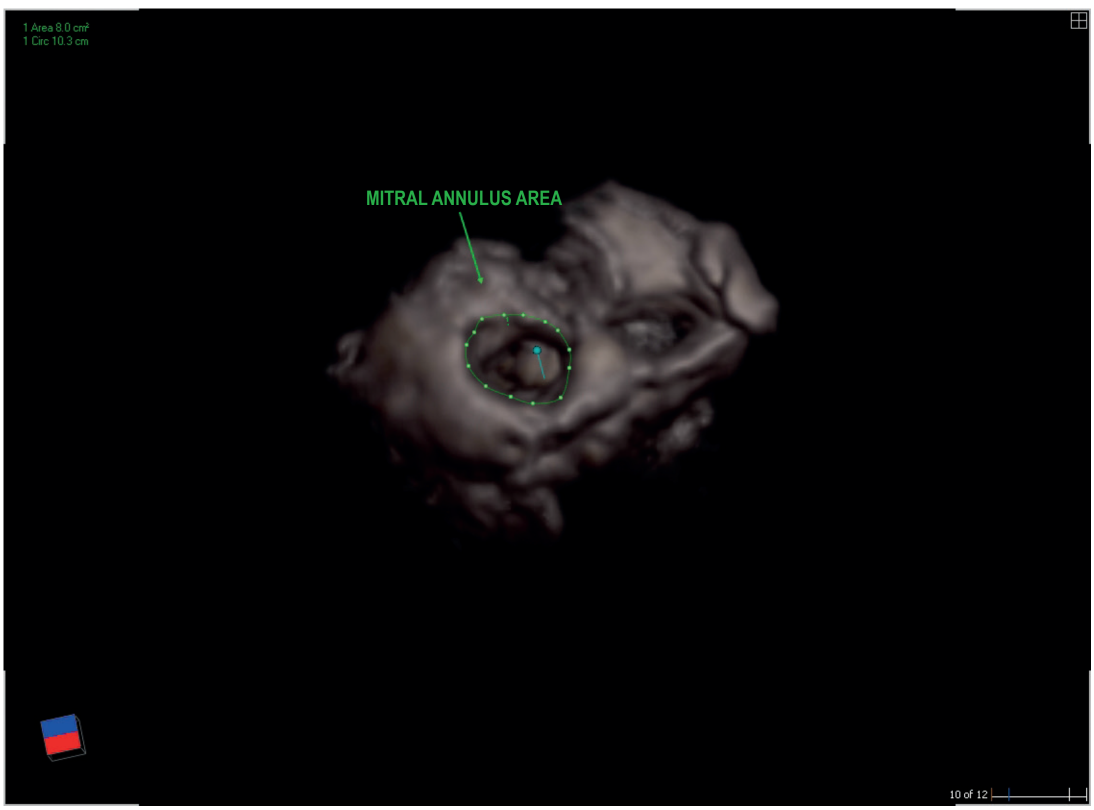

Figure 1 – *Acquisition of three-dimensional block and mitral annulus delineation.*

Table 1 – Results of anthropometric data

	Cyclists (n=18)	Controls (n=18)	p value
Weight (kg)	71.7 ± 6.2	75.4 ± 5.8	0.1
Height (cm)	177.1 ± 6.6	176.6 ± 5.0	0.8
Body mass index (kg/m^2)	22.8 ± 1.3	24.2 ± 1.8	0.02
Total body surface area (m^2)	1.9 ± 0.1	1.9 ± 0.1	0.3
Age (years)	29.5 ± 4.3	28.8 ± 5.8	0.7

Echocardiography

The following was observed in the cyclists' group: smaller A' wave velocity (5.9 ± 2.2 cm/s vs. 7.6 ± 2.3 cm/sec, P = 0.03); smaller atrial contraction strength (4.7 ± 1.4 Kdyn vs. 6.2 ± 2.1 Kdyn, P = 0.02) and higher passive ejection fraction (43.8 ± 12.8% vs. 34.8 ± 10.4%, P = 0.03); higher rate of left ventricular mass (157.1 ± 27.2 vs. 110.4 ± 8.9, P <0.01). The other echocardiographic variables showed no statistically significant difference between groups (Table 2).

A linear correlation between strength of atrial contraction and atrial volume before contraction (r = 0.65, P <0.05) and between the A' wave velocity and atrial contraction strength was observed in the cyclists' group (r = 0.80, P <0.05). A negative linear correlation between atrial contraction strength and passive emptying fraction was also observed (r = -0.88, p <0.05) (Figures 2, 3 and 4).

There was no linear correlation between volumetric variables of atrial contraction and Doppler variables in

Table 2 – Results of echocardiographic variables

	Cyclists (n = 18)	Controls (n = 18)	p value
Mitral E wave velocity (cm/s)	82.0 ± 3.1	81.9 ± 6.8	0.1
Mitral A wave velocity (cm/s)	39.5 ± 9.2	45.7 ± 11.3	0.09
E/A ratio	2.2 ± 0.5	1.9 ± 0.5	0.1
Mitral flow deceleration time (ms)	158.0 ± 13.6	161.9 ± 12.6	0.40
E' wave deceleration time (cm/s)	16.6 ± 2.1	15.6 ± 2.3	0.24
A' wave velocity (cm/s)	5.9 ± 2.2	7.6 ± 2.3	0.03
E/e' ratio	5.5 ± 0.6	5.3 ± 0.9	0.23
Left ventricular end-diastolic volume (mL)	142.7 ± 19.7	142.1 ± 20.8	0.94
Left ventricular end-systolic volume (mL)	57.4 ± 11.0	50.3 ± 9.7	0.06
Left ventricular mass index (mg/m^2)	157.1 ± 27.2	110.4 ± 8.9	<0.01
Maximum indexed left atrial volume (mL/m^2)	21.7 ± 4.1	19.7 ± 3.1	0.12
Minimum indexed left atrial volume (mL/m^2)	7.10 ± 3.1	7.6 ± 3.1	0.67
Indexed left atrial volume before contraction (mL/m^2)	11.8 ± 5.3	12.7 ± 1.8	0.2
Total left atrial ejection fraction (%)	66.0 ± 17.0	62.5 ± 13.1	0.50
Passive left atrial ejection fraction (%)	43.8 ± 12.8	34.8 ± 10.4	0.03
Active left atrial ejection fraction (%)	39.3 ± 12.8	40.6 ± 10.4	0.9
Left atrial contraction strength (Kdyn)	4.7 ± 1.4	6.2 ± 2.1	0.02
Mitral annulus area (cm^2)	5.9 ± 1.3	5.8 ± 1.7	0.8

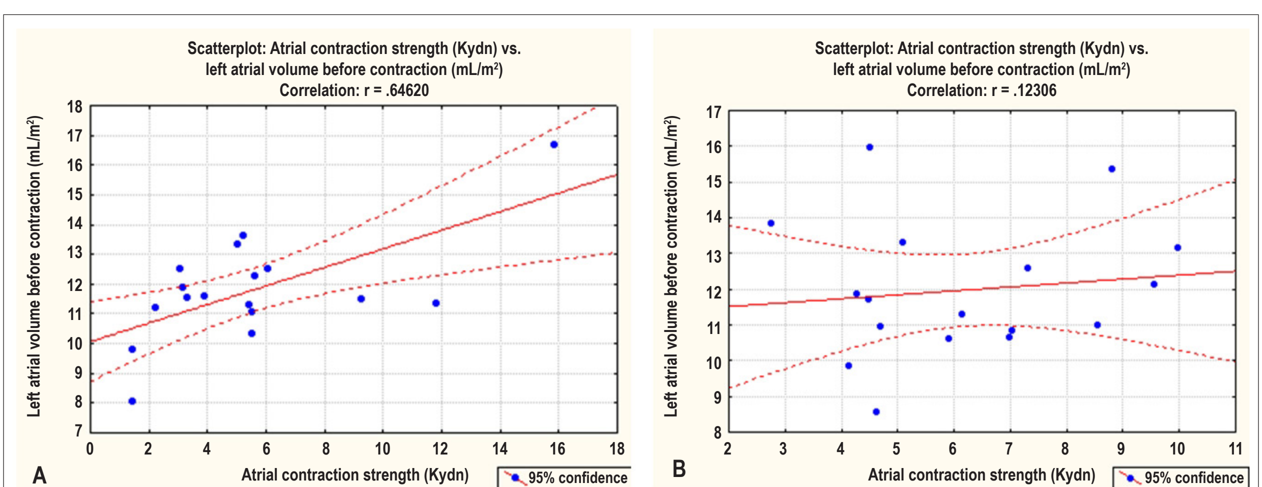

Figure 2 – *Correlation between left atrial contraction strength and volume before contraction (A) athletes and (B) controls.*

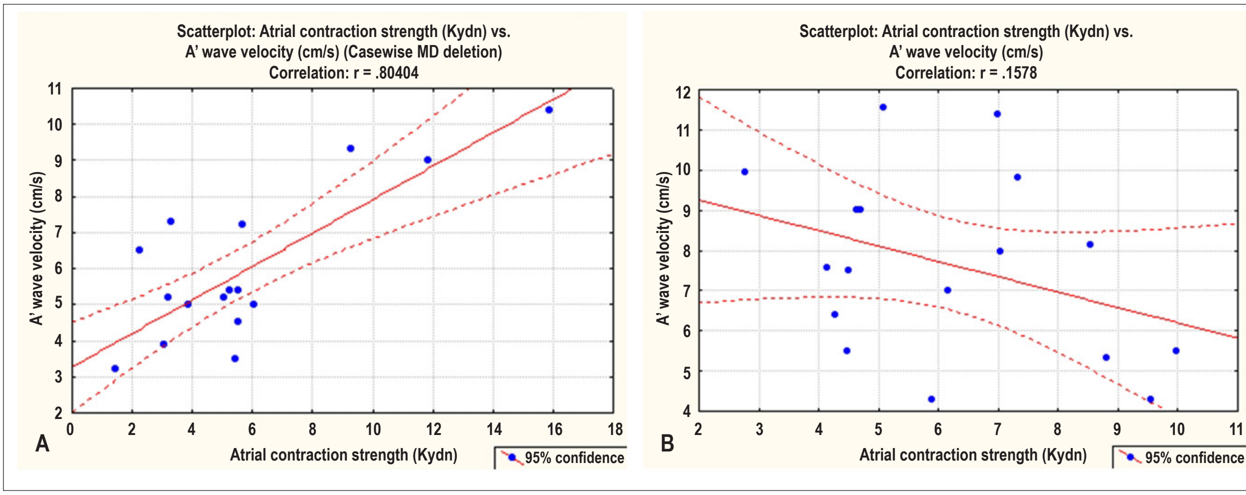

Figure 3 – *Correlation between atrial contraction strength and A' wave velocity (A) athletes and (B) controls.*

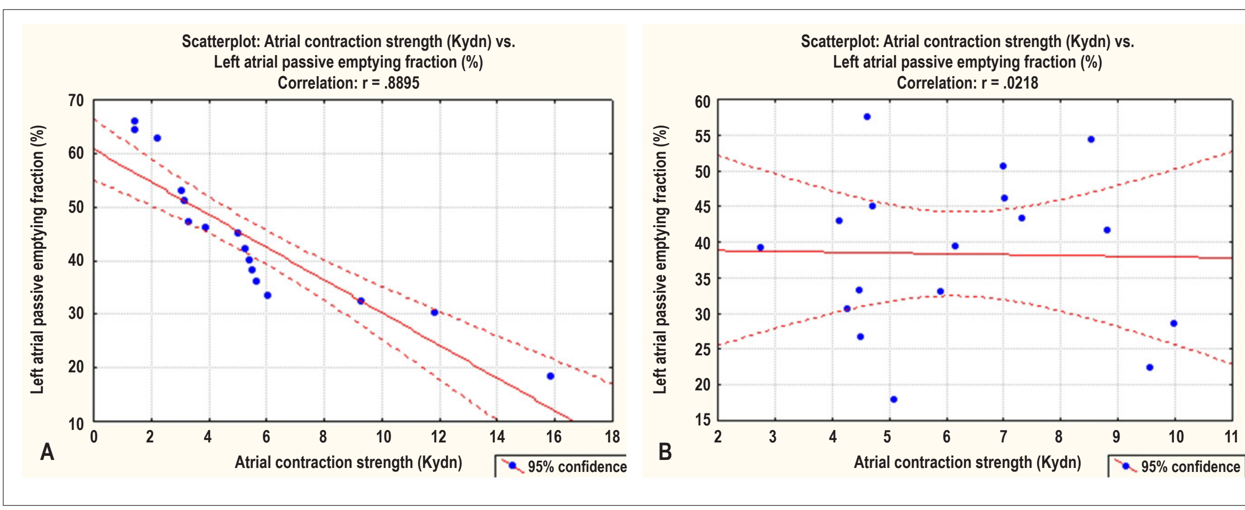

Figure 4 – *Correlation between atrial contraction strength and left atrial passive emptying fraction (A) athletes (B) controls.*

the control group (Figures 2, 3 and 4). There was also no correlation between the findings in the cyclists' group and the volume of exercise performed weekly or left ventricular mass index.

No individual with diastolic dysfunction was found according to the patterns defined by the current guidelines[22,24].

Discussion

The main findings of this study show that, using three-dimensional echocardiography, it was possible to identify a smaller participation of active atrial emptying in left ventricular filling, to the detriment of a more efficient passive ventricular filling in professional cyclists compared with non-athlete controls. These data reinforce the finding of supernormal diastolic performance in this population, as observed by other technologies.

Several previous studies have shown that professional athletes present a better diastolic function compared to the non-athlete population[4,25,26]. In this context, supernormal diastolic function of athletes can be considered a phenomenon that involves not only increased ventricular compliance, but also the complex changes in atrioventricular electromechanical coupling occurring in situations of long duration physical training. D'Andrea et al[27] in a study with pulsed Doppler demonstrated a close connection between the velocities of mitral outflow and increased exercise-induced diastolic compliance[4]. However, the functional role of the left atrium in the dynamics of the athlete's heart is often neglected and conclusive data are not yet sufficiently determined[27].

This study showed that professional cyclists have a lower A' wave velocity speed than non-athlete controls, suggesting a supernormal ventricular diastole characteristic in this population. Hence, we infer that the reduced mitral annulus movement in the second half of diastole, as shown by the lower A' wave velocity, reflects a smaller residual volume before atrial contraction. According to the mechanism proposed by Frank-Starling, reducing atrial preload promotes a decrease in the contraction strength of that chamber, which becomes crucial for appropriate ventricular filling[28]. This physiological mechanism was corroborated in this study by the higher values of the variables related to passive atrial function and reduced atrial contraction strength in the cyclist group. Similarly, the absence of correlation between these variables in the control group reinforces the association between high-performance exercise training and changes in the physiology of cardiac diastole. However, there was no direct functional correlation between the amount of exercise practiced by the athletes and the findings mentioned above, which may be partially explained by the influence of other variables on the change in left atrial dynamics in this population, such as peripheral vascular resistance[29] and genetic polymorphism[30], which were not addressed in this study. These findings are consistent with those described by D'Ascenzi et al[13], who studied left atrial dynamics in soccer players through two-dimensional speckle tracking. According to these authors, the athletes showed an increase in the initial components of diastole in left ventricular filling[13].

The study of atrial emptying physiology in athletes has been shown to be a promising tool for measuring ventricular filling pressures in this group. The study of left atrial function by two-dimensional echocardiography has been described in previous studies and showed a high correlation with other variables of diastolic function. However, the two-dimensional technology presented limitations regarding reproducibility. Accordingly, the estimate of atrial contraction strength by three-dimensional echocardiography has been validated as a variable closely related to final ventricular filling, with a small interobserver variability and high accuracy[7,16]. The relationship of active left atrial emptying with ventricular resistance on mitral outflow was demonstrated in this study by the significant linear correlation between atrial contraction strength and the tissue A' wave velocity in the group of athletes. The smaller atrial contraction strength in this group would result from a relative predominance of initial atrial emptying in ventricular filling, which in turn was demonstrated by a negative linear correlation between left atrial contraction strength and left atrial passive emptying fraction. In addition, we also observed a high positive linear correlation between atrial contraction strength and left atrial volume before contraction. However, there was no significant difference between active emptying fractions between the groups. This can be partially explained by the difficulty of analyzing small volumetric variations of the left atrium, such as the difference between pre-atrial contraction volume and minimum atrial volume. Such limitation has been reported by Zhong et al[31], when they saw no correlation between emptying fraction and other diastolic variables[31].

This functional left atrial remodeling in athletes is probably a component of overall cardiac adaptation to increased preload associated with intense and frequent training[26]. This adaptation is not only linked to greater distensibility and increased left ventricular lusitropism, but also to an increase in the viscoelastic properties of the left atrium that are directly related to increased vagal tone in this population. Several studies have shown that the parasympathetic increment associated with intense and long-duration physical training causes a reduction in the time required for ventricular relaxation and filling, which would act as a compensatory mechanism to maintain cardiac output during episodes of high heart rate[32].

Previous investigations have suggested that trained athletes are predisposed to paroxysmal atrial fibrillation, possibly because of inappropriate cardiac remodeling associated with individual predisposition. It was also observed that many of these individuals who have arrhythmias of supraventricular origin have normal sized atria, which allows us to infer that the genesis of this condition is related not only morphological changes, but also to functional left atrial changes[6]. Because three-dimensional echocardiography uses the digital reconstruction of atrial content as well as their volumetric changes throughout the cardiac cycle, it has been proven a promising tool in the study of functional changes that precede the morphological changes of remodeling of that chamber. However, studies that include a larger population are needed to fully understand the relationship between the higher frequency of atrial arrhythmias and atrial remodeling observed in trained athletes.

Limitations

A potential limitation was the inherent difficulty of matching the control group as for body mass index. However, we believe that there was no loss in the final analysis because the body surface was similar between groups. According to the guidelines of the American Society of Echocardiography and the Brazilian Society of Echocardiography[14,15], body surface area should be used as a variable for indexing echocardiographic measurements.

Another possible limitation was the lack of women and elders in the groups studied, which did not allow us to determine whether the information found could extend to females and to a population with a broader age group.

Conclusion

By means of the three-dimensional echocardiography, our study demonstrated an increase in the passive emptying component against a reduction in the ventricular filling active component in professional athletes compared to non-athlete controls. These results not only reaffirm the finding of supernormal diastolic function in high-performance professional athletes, but also reveal a functional left atrial remodeling in this population.

Authors' contribution

Research creation and design: Oliveira W, Rodrigues ACT, Cordovil A, Monaco CG, Lira-Filho E, Fischer CH, Morhy SS, Vieira MLC; Data acquisition: Oliveira W, Janot L; Data analysis and interpretation: Oliveira W; Statistical analysis: Oliveira W;

Manuscript drafting: Oliveira W; Critical revision of the manuscript as for important intellectual content: Oliveira W.

Potential Conflicts of Interest

No relevant potential conflicts of interest.

Sources of Funding

This study had no external funding sources.

Academic Association

This study is not associated with any graduate programs.

References

1. Pluim BM, Zwinderman AH, van der Laarse A, van der Wall EE. The athlete's heart: a meta-analysis of cardiac structure and function. Circulation. 2000;101(3):336-44.
2. Fagard R. Athlete's heart. Heart. 2003;89(12):1455-61.
3. Maron BJ, Pelliccia A, Spirito P. Cardiac disease in young trained athletes: Insights into methods for distinguishing athlete's heart from structural heart disease, with particular emphasis on hypertrophic cardiomyopathy. Circulation. 1995;91(5):1596-601.
4. D'Andrea A, D'Andrea L, Caso P, Scherillo M, Zeppilli P, Calabro R. The usefulness of Doppler myocardial imaging in the study of the athlete's heart and in the differential diagnosis between physiological and pathological ventricular hypertrophy. Echocardiography. 2006;23(2):149-57.
5. Maron BJ, Spirito P, Green KJ, Wesley YE, Bonow RO, Arce J. Noninvasive assessment of left ventricular diastolic function by pulsed Doppler echocardiography in patients with hypertrophic cardiomyopathy. J Am Coll Cardiol. 1987;10(4):733-42.
6. Pelliccia A, Maron BJ, Di Paolo FM, Biffi A, Quattrini FM, Pisicchio C, et al. Prevalence and clinical significance of left atrial remodeling in competitive athletes. J Am Coll Cardiol. 2005;46(4):690-6.
7. Oliveira W, Campos O, Cintra F, Matos L, Vieira ML, Rollim B, et al. Impact of continuous positive airway pressure treatment on left atrial volume and function in patients with obstructive sleep apnoea assessed by real-time three-dimensional echocardiography. Heart. 2009;95(22):1872-8.
8. Jenkins C, Bricknell K, Marwick TH. Use of real-time three-dimensional echocardiography to measure left atrial volume: comparison with other echocardiographic techniques. J Am Soc Echocardiogr. 2005;18(9):991-7.
9. Maddukuri PV, Vieira ML, DeCastro S, Maron MS, Kuvin JT, Patel AR, et al. What is the best approach for the assessment of left atrial size? Comparison of various unidimensional and two-dimensional parameters with three-dimensional echocardiographically determined left atrial volume. J Am Soc Echocardiogr. 2006;19(8):1026-32.
10. Khankirawatana B, Khankirawatana S, Lof J, Porter TR. Left atrial volume determination by three-dimensional echocardiography reconstruction: validation and application of a simplified technique. J Am Soc Echocardiogr. 2002;15(10 Pt 1):1051-6.
11. Khankirawatana B, Khankirawatana S, Porter T. How should left atrial size be reported? Comparative assessment with use of multiple echocardiographic methods. Am Heart J. 2004;147(2):369-74.
12. Lester SJ, Ryan EW, Schiller NB, Foster E. Best method in clinical practice and in research studies to determine left atrial size. Am J Cardiol. 1999;84(7):829-32.
13. D'Ascenzi F, Cameli M, Zaca V, Lisi M, Santoro A, Causarano A, et al. Supernormal diastolic function and role of left atrial myocardial deformation analysis by 2D speckle tracking echocardiography in elite soccer players. Echocardiography. 2011;28(3):320-6.
14. Lang RM, Bierig M, Devereux RB, Flachskampf FA, Foster E, Pellikka PA, et al. Recommendations for chamber quantification: a report from the American Society of Echocardiography's Guidelines and Standards Committee and the Chamber Quantification Writing Group, developed in conjunction with the European Association of Echocardiography, a branch of the European Society of Cardiology. J Am Soc Echocardiogr. 2005;18(12):1440-63.
15. Campos Filho O, Zielinsky P, Ortiz J, Maciel BC, Andrade JL, Mathias Jr. W, et al. Diretriz para Indicações e Utilização da Ecocardiografia na Prática Clínica. Arq Bras Cardiol. 2004;82(Suppl 2):11-34.
16. Anwar AM, Soliman OI, Geleijnse ML, Nemes A, Vletter WB, ten Cate FJ. Assessment of left atrial volume and function by real-time three-dimensional echocardiography. Int J Cardiol. 2008;123(2):155-61.
17. Blondheim DS, Osipov A, Meisel SR, Frimerman A, Shochat M, Shotan A. Relation of left atrial size to function as determined by transesophageal echocardiography. Am J Cardiol. 2005;96(3):457-63.
18. Poutanen T, Jokinen E, Sairanen H, Tikanoja T. Left atrial and left ventricular function in healthy children and young adults assessed by three dimensional echocardiography. Heart. 2003;89(5):544-9.
19. Hung J, Lang R, Flachskampf F, Shernan SK, McCulloch ML, Adams DB, et al. 3D echocardiography: a review of the current status and future directions. J Am Soc Echocardiogr. 2007;20(3):213-33.
20. Anwar AM, Soliman OI, Geleijnse ML, Michels M, Vletter WB, Nemes A, et al. Assessment of left atrial ejection force in hypertrophic cardiomyopathy using real-time three-dimensional echocardiography. J Am Soc Echocardiogr. 2007;20(6):744-8.
21. Manning WJ, Silverman DI, Katz SE, Douglas PS. Atrial ejection force: a noninvasive assessment of atrial systolic function. J Am Coll Cardiol. 1993;22(1):221-5.
22. Paulus WJ, Tschope C, Sanderson JE, Rusconi C, Flachskampf FA, Rademakers FE, et al. How to diagnose diastolic heart failure: a consensus statement on the diagnosis of heart failure with normal left ventricular ejection fraction by the Heart Failure and Echocardiography Associations of the European Society of Cardiology. Eur Heart J. 2007;28(20):2539-50.
23. Devereux RB, Reichek N. Echocardiographic determination of left ventricular mass in man. Anatomic validation of the method. Circulation. 1977;55(4):613-8.
24. Nagueh SF, Appleton CP, Gillebert TC, Marino PN, Oh JK, Smiseth OA, et al. Recommendations for the evaluation of left ventricular diastolic function by echocardiography. Eur J Echocardiogr. 2009;10(2):165-93.
25. Claessens PJ, Claessens CW, Claessens MM, Claessens MC, Claessens JE. Supernormal left ventricular diastolic function in triathletes. Tex Heart Inst J.2001;28(2):102-10.
26. Pelliccia A, Culasso F, Di Paolo FM, Maron BJ. Physiologic left ventricular cavity dilatation in elite athletes. Ann Intern Med. 1999;130(1):23-31.
27. D'Andrea A, Caso P, Galderisi M, Di Maggio D, Cicala S, D'Andrea L, et al. Assessment of myocardial response to physical exercise in endurance competitive athletes by pulsed doppler tissue imaging. Am J Cardiol. 2001;87(10):1226-30.
28. Anwar AM, Geleijnse ML, Soliman OI, Nemes A, ten Cate FJ. Left atrial Frank-Starling law assessed by real-time, three-dimensional echocardiographic left atrial volume changes. Heart. 2007;93(11):1393-7.

29. Petersen SE, Wiesmann F, Hudsmith LE, Robson MD, Francis JM, Selvanayagam JB, et al. Functional and structural vascular remodeling in elite rowers assessed by cardiovascular magnetic resonance. J Am Coll Cardiol. 2006;48(4):790-7.

30. Kasikcioglu E, Kayserilioglu A, Ciloglu F, Akhan H, Oflaz H, Yildiz S, et al. Angiotensin-converting enzyme gene polymorphism, left ventricular remodeling, and exercise capacity in strength-trained athletes. Heart Vessels. 2004;19(6):287-93.

31. Zhong L, Tan LK, Finn CJ. Effects of age and gender on left atrial ejection force and volume from real-time three-dimensional echocardiography. Ann Acad Med Singapore. 2012; 41(4):161-9.

32. Baggish AL, Wood MJ. Athlete's heart and cardiovascular care of the athlete: scientific and clinical update. Circulation. 2011;123(23):2723-35.