Cardiac Remodeling in Elite Aquatic Sport Athletes

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ABSTRACT

Background: The “athlete’s heart” has been well characterized, and it is known that remodeling is dependent on the nature of the hemodynamic-stimuli. Aquatic-athletes are exposed to hydrostatic pressures, postural anomalies, and breath-holds that likely drive distinct cardiac adaptation; however, the aquatic-athlete’s heart has not been specifically interrogated. The aim of this investigation was to characterize and compare the sport-specific cardiac structure of elite aquatic-athletes. **Methods:** Ninety athletes at the 2019 FINA World Championships from swimming (SW:20M/17F), water-polo (WP:21M/9F), and artistic swimming (AS:23F) volunteered for echocardiographic assessment of cardiac structure. **Results:** Male SW displayed primarily eccentric volume-driven remodeling, while male WP had a greater incidence of pressure-driven concentric geometry (SW:5%, WP:25%) with elevated relative wall-thickness (RWT) (SW:0.35±0.04, WP:0.44±0.08, $P<0.001$). Female SW and WP hearts were similar with primarily eccentric-remodeling, but SW and WP had greater concentricity index than artistic swimmers (SW:6.74±1.45g/(ml)^{2/3}, WP:6.80±1.24g/(ml)^{2/3}, AS:5.52±1.08g/(ml)^{2/3}, $P=0.007$). AS had normal geometry, but with increased posterior-wall specific RWT (SW:0.32±0.05, AS:0.42±0.11, $P=0.004$) and greater left atrial area than SW (SW:9.7±0.9cm²/m², AS:11.0±1.1cm²/m², $P=0.003$). All females had greater incidence of wall-thickness ≥11mm than typically reported (SW:24%, WP:11%, AS:17%). **Conclusion:** Male athletes presented classic sport-specific differentiation, with SW demonstrating primarily volume-driven eccentric remodelling, and WP with greater concentric geometry indicative of pressure-driven remodeling. Female SW and WP did not display this divergence, likely due to sex-differences in adaptation. AS had unique LV-specific adaptations suggesting elevated pressure under low-volume conditions. The overall incidence of elevated wall-thickness in female athletes may point to an aquatic-specific pressure stress.

Keywords : swimming, water polo, synchronized swimming, cardiac morphology, artistic swimming, echocardiography

INTRODUCTION

The athlete's heart has been well investigated, and it is now understood that hemodynamic loading during exercise causes cardiac enlargement, with thickening of the ventricular walls that can be either proportional or disproportional to the cavity size.¹ The Morganroth hypothesis suggests that endurance (dynamic) exercise causes a "volume" stress through sustained elevations in stroke volume, which elicits eccentric hypertrophy characterized by an increase in left ventricular (LV) mass with minimal wall-thickening and proportionately dilated cavities.² In contrast, resistance (static) exercise is characterized as a "pressure" stress due to extreme elevations in blood pressure which may elicit disproportionate wall-thickening and unchanged internal diameters, termed concentric hypertrophy.² Recently, the Morganroth hypothesis has been contested as it pertains to concentric hypertrophy as six-months of strength training was not shown to elicit any morphological alterations.³ Further, cross-sectional analysis of Olympic athletes using 3D-echocardiography has demonstrated proportional eccentric remodeling regardless of sport-type,⁴ and LV wall stress may not be elevated during resistance exercise.⁵ As training for most sports represents a mixture of volume and pressure loading, it is likely that athletes fall across a spectrum of adaptation, with volume-based loading driving most of the changes in cavity dilation, and pressure driving increases in wall-thickness.⁶ It should, however, be recognized that there may be a human evolutionary predisposition towards volume-based adaptations.⁷

In order to differentiate pathological from physiological remodelling, it is important to understand sport-specific athletic adaptation. Aquatic sport athletes are exposed to a unique training environment compared to land-based athletes, which may drive differential cardiovascular adaptation. Swimming is primarily an endurance sport with high-dynamic and moderate-static components⁸; however, unlike land-based sports, it is performed in horizontal body-positions which promote venous return.⁹ This may explain the reduced early diastolic function that has been demonstrated when comparing elite swimmers to equally-ranked elite runners.¹⁰ Water immersion itself also increases external pressure on capacitance vessels, which allows for increased volume-loading in both sides of the heart.⁹ Water-polo is a mixed static-dynamic sport, with both endurance and explosive-strength components¹¹; however, the water immersion promotes volume-loading¹² compared to land-based sports with similar demands. Finally, it is known that face-immersed breath-holds elicit the human dive-reflex, which is characterized by bradycardia and peripheral vasoconstriction -elevating arterial blood pressure and decreasing stroke volume.¹² Artistic swimmers (previously called synchronized swimmers) have moderate static-dynamic sporting demands,⁸ yet are repeatedly exposed to this dive-reflex stimulus as they perform explosive movements underwater under sustained breath-hold conditions.¹³ Altogether,

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the aquatic-specific hemodynamic stimuli, in combination with the well-established sporting demands, could elicit divergent cardiac remodeling in swimmers, water-polo players, and artistic swimmers, although this has yet to be investigated specifically.

The purpose of this investigation was to compare cardiac structure in elite aquatic sport athletes, with implications towards sport-specific environmental and training-driven cardiac adaptation. It was hypothesized that swimmers would have the most eccentric geometry as they undergo primarily volume-stress in training. Water-polo players were hypothesized to have a mixed eccentric-concentric geometry, as their sport involves sprinting and explosive strength components,¹¹ but the immersed body position would allow for increased volume loading. Finally, while artistic swimmers have rarely been examined to date, it was expected that they would present with the least eccentric geometry, and disproportionate wall-thickening, due to sustained elevations in pressure from underwater breath-hold stimuli.

METHODS

Elite athletes participating in swimming, water-polo, and artistic swimming events were recruited at the athlete's village during the 2019 FINA World Championships, and via formal invitations extended to national sporting bodies, coaches, and team physicians prior to the event. All athletes were asked to attend testing on rest days (outside of competition). Inclusion criteria stipulated that athletes be ≥ 18 years old, have no previous diagnosis of cardiovascular disease, and have sufficient English comprehension to provide written informed consent in accordance with the protocol approved by IRB, and the FINA sports medicine committee.

Athletes completed a medical and training history questionnaire which asked about years of competitive training in their sport, average weekly training hours, average weekly swimming distance, weekly land-based resistance training hours, and weekly land-based aerobic training hours. Measures of height at end-inspiration using a free-standing stadiometer (SECA; Hanover, MD, United States), and body mass with a calibrated electronic scale (Tanita TBF-300 WA; Arlington Heights, IL, United States) were collected with athletes wearing minimal clothing and no shoes. Seated blood pressure was assessed in triplicate with feet-uncrossed using an automated oscillometric device (BpTRU, Coquitlam, BC, Canada).

Echocardiography Assessment

In a private temperature controlled medical examination room, participants lay supine for ≥ 5 min of rest prior to vascular measurements, which are outlined in a related work.¹⁴ Echocardiographic images were collected in the left lateral decubitus position with

two-dimensional echocardiography and Doppler imaging using a Vivid IQ ultrasound (GE Healthcare, Horten, Norway) and GE M5Sc (1.5-4.6 MHz) probe. Images were analyzed offline using EchoPAC software (EchoPAC; GE Healthcare, Horten, Norway) according to task-force recommendations.¹⁵⁻¹⁷ Average values were determined from images of three cardiac cycles taken in the parasternal long and short-axis, and apical 4-chamber views. Body surface area (BSA) was calculated using the Du Bois and Du Bois formula,¹⁸ and morphological parameters were scaled allometrically to BSA as: linear dimensions scaled to $(BSA)^{0.5}$, areas to $(BSA)^1$, and volumes to $(BSA)^{1.5}$.^{19,20}

LV relative wall-thickness (RWT) was calculated as $(2 \times \text{diastolic posterior wall-thickness (LVPWd)}) / \text{LV diameter at end diastole (LVIDd)}$.¹⁶ LV maximal wall-thickness was measured in the parasternal long-axis view at the level of the mitral-valve leaflets, resulting in only interventricular wall-thickness during diastole (IVSd) and LVPWd being assessed. LV mass was estimated following the ASE-recommended formula for linear measurements.¹⁶ LV end-diastolic (LV EDV) and end-systolic volumes (LV ESV) were calculated using the modified Simpson's biplane method,¹⁶ with values used to compute ejection fraction (EF). LV concentricity was calculated as $\text{LV mass} / (\text{LV EDV})^{2/3}$.²¹ LV hypertrophy was categorized based on the four-tiered classification system as previously defined,²² using LVmass/BSA, LV EDV/BSA, and LV concentricity.^{21,22} Functional cardiac parameters were also assessed, but for clarity, this data is presented in a companion study.²³ We report an inter-rater ICC of 0.97 for LV EDV, and 0.92 for RV ESA.

Statistical Analysis

Statistical analysis was performed using SPSS software (Version 26, IBM Corporation, Armonk, NY) and GraphPad Prism (Version 8, GraphPad Software Inc., La Jolla, CA). All statistical analyses were performed within the same sex due to accepted morphological differences.²⁴ Univariate ANOVA was performed to assess between-group (sport) differences and when differences were found, Tukey HSD *post-hoc* tests were used to correct for multiple comparisons in female sports (as there were 3 groups). Pearson correlations were used to compare cardiac variables to self-reported training data including total training time, length-swimming distance, resistance training time, and land-based aerobic training time. Data is presented as mean $\pm$ standard deviation with significance set *a priori* at $P < 0.05$.

RESULTS

Participants

Four female athletes (1 artistic swimmer, 3 water-polo players) were excluded from the study due to previously diagnosed heart conditions, resulting in 37 swimmers (M:20, F:17), 30 water-polo players (M:21, F:9), and 23 artistic swimmers (all female) being included in the study. Self-reported race and ethnicity was mixed; however, most athletes identified as white (M:73%, F:55%), followed by mixed-race/other (M:17.5%, F:24%), asian (M:2.5%, F:18%), black (M:7%, F:2%). Self-reported training parameters from the questionnaire are presented in Table 1. Length-swimming distance per week was much greater in swimmers than water-polo players and artistic swimmers (all groups & sexes, $P<0.001$). In males, all other training characteristics including resistance training h/wk were similar (all $P>0.05$). Female water-polo players had been training competitively for more years ($P=0.01$), and completed more land-based aerobic training hours per week than swimmers ($P=0.004$), but this was not different from artistic swimmers (both $P>0.05$).

Table 1. Self-reported training parameters

	Males		Females		
	Swimming	Water Polo	Swimming	Water Polo	Artistic Swimming
Training					
Years in sport (yr)	9±3	10±3	8±3 ^w	13±2 ^s	10±4
Training volume (h/wk)	23±5	19±9	19±9	16±6	24±12
Swimming distance (km/wk)	48±22 ^w	13±7 ^s	42±17 ^{w,a}	10±5 ^s	8±7 ^s
Resistance (h/wk)	5±6	4±2	3±2	2±3	2±2
Land-based aerobic (h/wk)	1±1	1±2	1±2 ^w	4±3 ^s	3±2

^a $P<0.05$ from artistic swimming. ^w $P<0.05$ from water-polo of same sex. ^s $P<0.05$ from swimmers of same sex. Data as mean±SD.

Males

Male swimmers and water-polo players demonstrated no between-sport differences in left atrial area, but swimmers did have greater right atrial area when indexed to BSA ($P=0.001$; see Table 2). Male water-polo athletes demonstrated greater LV concentric remodeling than swimmers ($P<0.001$), with a RWT of 0.44 ± 0.08 , and significantly greater LV concentricity index ($P=0.03$; see Table 2). Nine (43%) of the water-polo players had a maximal wall-thickness ≥ 13 mm, and two (10%) had a wall-thickness ≥ 14 mm (1 at 14.0mm, 1 at 15.0mm),²⁵ with non-dilated LV cavities <60 mm.²⁵ Using the 4-tiered classification system (Figure 1),²² concentric geometry was primarily seen in water-polo players, with 25% of water-polo players having concentric remodeling (including non-dilated and dilated LVH), and only 5% of swimmers demonstrated concentric remodeling. Reported weekly

swimming distance (which was highest in swimmers) was inversely related to RWT (see Figure 2), whereas hours of resistance training per week was positively related to LV EDV index ($r=0.32$, $P=0.045$). Right ventricular area was similar between sports.

Females

Female artistic swimmers had large left atria,²⁶ which were larger than swimmers ($P=0.003$) when indexed to BSA. Female swimmers and water-polo players presented with similar LV geometry, with no differences in RWT, LV mass index, or LV concentricity index (all $P>0.05$, see Table 2). Four swimmers (11, 11, 11.3, and 11.7mm), one water-polo player (12mm), and four artistic swimmers (11, 11.3, 12.3, and 14mm), had maximal wall-thicknesses ≥ 11 mm, and all presented with LVIDd <60 mm.²⁵ Swimmers and water-polo players had similar incidence of LVH, with 38% of swimmers and 26% of water-polo players displaying LVH (see Figure 1). Water-polo players had a marginally higher incidence of concentric geometry (including LVH) than swimmers at 24% vs 19%. None of the female athletes presented with concentric dilated LVH, and only 1 swimmer had eccentric dilated LVH. Artistic swimmers had lower LV concentricity index than both swimmers ($P=0.01$) and water-polo players ($P=0.045$), as well as lower LV mass index than swimmers ($P=0.03$), and the lowest incidence of LVH at 14%. Reported weekly swimming distance was inversely related to RWT (see Figure 2). Right heart area was similar between sports.

Figure 1. Distribution of left-ventricular geometry across a sample of elite male and female aquatic sport athletes. Artistic swimmers (AS), water-polo players (WP), and swimmers (SW). Created with BioRender.com.

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Table 2. Cardiac structural parameters in elite aquatic-sport athletes

	Males		Females		
	Swimming	Water Polo	Swimming	Water Polo	Artistic Swimming
<i>Subjects (n)</i>	20	21	17	9	23
Height (cm)	184±7 ^w	190±6 ^s	174±8 ^a	173±4 ^a	165±5 ^{w,s}
Body Mass (kg)	81.3±8.6 ^w	94.9±8.0 ^s	68.4±8.5 ^a	67.2±4.3 ^a	59.0±6.9 ^{w,s}
Body mass index (kg/m ²)	24.1±1.6 ^w	26.3±2.3 ^s	22.6±1.8	22.4±1.3	21.7±2.1
Body surface area (m ²)	2.04±0.14 ^w	2.23±0.11 ^s	1.82±0.15 ^a	1.80±0.07 ^a	1.64±0.10 ^{w,s}
Seated SBP (mmHg)	118±10	121±9	110±8	110±9	111±10
Seated DBP (mmHg)	78±8	75±10	72±6	70±12	72±8
Left Heart					
<i>Minimal subjects (n)</i>	20	21	16	8	22
LA area (cm ²)	18.0±3.3	19.5±3.5	17.6±2.1	17.6±1.6	17.9±1.7
LA area index (cm ² /m ²)	8.8±1.4	8.7±1.4	9.7±0.9 ^a	9.9±1.0	11.0±1.1 ^s
IVSd (mm)	10.0±1.1 ^w	11.2±1.6 ^s	9.7±1.5 ^a	9.2±1.1 ^a	7.9±1.2 ^{w,s}
LVIDd (mm)	54.6±3.7	53.5±3.9	50.7±3.6 ^a	47.4±2.6	44.0±4.0 ^s
LVPWd (mm)	9.4±1.1 ^w	11.6±1.8 ^s	8.4±1.0	9.4±1.4	9.1±2.0
RWT	0.35±0.04 ^w	0.44±0.08 ^s	0.32±0.05 ^a	0.40±0.07	0.42±0.11 ^s
Mass (g)	204±39 ^w	244±44 ^s	160±41 ^a	155±22 ^a	119±26 ^{w,s}
Mass index (g/(m ²))	100±16	109±19	88±21 ^a	85±12	73±15 ^s
LVEDV (mL)	143±23 ^w	161±23 ^s	115±18 ^a	109±10	101±15 ^s
LVEDV index (mL/(m ²) ^{1.5})	49±7	48±6	47±5	45±4	48±6
LVESV (mL)	59±9 ^w	72±18 ^s	45±7	43±5	42±10
LVESV index (mL/(m ²) ^{1.5})	20±3	22±5	18±2	18±2	20±5
Ejection Fraction (%)	59±3 ^w	55±7 ^s	61±4	61±3	58±8
Concentricity (g/(ml) ^{2/3})	7.44±0.95 ^w	8.28±1.32 ^s	6.74±1.45 ^a	6.80±1.24 ^a	5.52±1.08 ^{w,s}
Right Heart					
<i>Minimal subjects (n)</i>	18	17	13	4	22
RA area (cm ²)	18.4±3.6	16.6±2.8	15.5±2.5	15.6±2.5	14.1±2.1
RA area index (cm ² /m ²)	9.0±1.6 ^w	7.4±1.1 ^s	8.6±1.3	8.8±1.4	8.6±1.3
RVEDA (cm ²)	22.3±3.3	23.8±4.5	18.8±1.9	18.5±3.6	15.6±2.7
RVEDA index (cm ² /m ²)	11.0±1.6	10.6±1.7	10.4±0.8	10.5±2.2	9.5±1.6
RVESA (cm ²)	14.1±2.8	14.5±2.8	11.0±0.8 ^a	10.6±3.0	9.2±1.5 ^s
RVESA index (cm ² /m ²)	6.9±1.4	6.5±1.1	6.1±0.5	6.1±1.8	5.6±1.0
RVFAC (%)	37±10	39±5	41±3	43±7	41±7
TAPSE (cm)	2.9±1.1	2.9±0.5	2.6±0.3	2.4±0.4	2.4±0.4

Minimal subjects, smallest amount of subjects used per category. SBP, systolic blood pressure. DBP, diastolic blood pressure. LA, left atria IVSd, interventricular wall-thickness during diastole. LVIDs, left ventricular internal diameter during diastole. LVPWd, left ventricular posterior free wall thickness during diastole. RWT, relative wall-thickness. LV, left ventricle. EDV, end-diastolic volume. ESV, end-systolic volume. RA, right atria, RVEDA, right ventricular end diastolic area. RVESA, right ventricular end systolic area. RVFAC, right ventricular fractional area change. TAPSE, tricuspid annular plane systolic excursion. ^aP<0.05 from artistic swimming. ^wP<0.05 from water-polo of same sex. ^sP<0.05 from swimmers of same sex. BP, blood pressure. Data as mean±SD.

Figure 2. Relative wall-thickness (RWT) in relation to self-reported weekly swimming distance among elite aquatic sport male (solid line) and female (dashed line) athletes. Artistic swimmers (AS), water-polo players (WP), and swimmers (SW).

DISCUSSION

This investigation sought to assess differences in cardiac structure between elite swimmers, water-polo players, and artistic swimmers, with implications towards environmental and training-driven hemodynamic stimuli. It was found that male swimmers and water-polo players had divergent cardiac morphology, with swimmers displaying primarily volume-based adaptations, while male water-polo players demonstrated higher incidence of pressure-based concentric geometry as indicated by elevated wall-thickness and concentricity index. In females, swimmers and water-polo players had similar cardiac morphology, with both following a typical pattern of volume-based adaptation. Finally, artistic swimmers demonstrated unique cardiac morphology with relatively normal LV geometry, but with dilated left atria and thickened LV posterior walls. These findings are important to help inform clinical decisions that must differentiate between physiological and pathological remodeling.

Male Athletes

In male athletes from both sports, mean LV dimensions, mass, and volumes were in the upper-end of normal ranges.²⁶ In accordance with our hypothesis, we demonstrate many between-sport differences in cardiac structure including elevated RWT, LV concentricity, and greater incidence of concentric hypertrophy in water-polo players

compared to swimmers. Water-polo players had elevated LV wall-thickness, with 43% of the athletes tested having a wall-thickness ≥ 13 mm (with 2 athletes ≥ 14 mm), consistent with the “grey-zone” of hypertrophic cardiomyopathy.²⁷ In support of this finding, Pelliccia et al. report only 1.7% of highly trained male Italian athletes present with a maximal wall-thickness ≥ 13 mm, and this was restricted to rowers, canoeists, and cyclists who undergo mixed high-static and high-dynamic loads during competition.²⁷ More recently, Whyte et al. reported 11 of 442 (2.5%) of British athletes of various sporting backgrounds had a wall-thickness ≥ 13 mm, and suggested an upper physiological limit of 14mm for elite athletes.²⁵ As such, the very high incidence of elevated wall-thickness in this population of male water-polo players is noteworthy. However, Pavlik et al. demonstrated very similar results to our own in Olympic champion water-polo players,²⁸ with no indication of reduced function indicative of pathology. We did not perform 12-lead ECG which would have helped determine whether athletes had any pathologies including hypertrophic cardiomyopathy; however, none of the athletes in this study met the full criteria for pathological LV adaptation in athletes.^{23,29,30} The very large body size of water-polo players, combined with elevated pressure-stress exposure during resistance training and in-game grappling under breath-hold conditions²⁸ likely explain the differences between male water-polo and swimmer heart morphology.

Female Athletes

In contrast with our hypothesis and to the male athletes, female water-polo players and swimmers had similar cardiac structure to each other. While mean group data suggests both swimmers and water-polo players had primarily volume-based adaptations characterized by greater cardiac mass with minimal wall-thickening and large EDVs in the upper-end of normal ranges,²⁶ there was a noticeably higher incidence of female concentric remodeling than in previous reports.³⁰⁻³² Water-polo players had a higher incidence of concentric remodeling than swimmers; however, both sports had much higher incidence of concentric remodeling (including LVH) than the ~0-4% previously reported in female elite athletes.^{31,32} Four swimmers had elevated wall-thickness (≥ 11 mm), with only one water-polo player having elevated wall-thickness. This was remarkable, as previous reports on elite athletes have reported 0-1% of female athletes to have elevated maximal wall-thickness.^{25,33} Black athletes are reported to have greater incidence of elevated wall-thickness than white athletes,²⁹ yet none of the athletes with elevated wall-thickness self-identified as black. While it is unclear why the incidence of elevated wall-thickness and concentric remodeling was greater in this investigation, it is possible that the specific focus on elite aquatic sport athletes might demonstrate an independent effect of water-immersion sports precipitating greater LV thickness. This could be due to hydrostatic

pressure, breath-holds, or the dive-reflex eliciting greater pressure-based stimuli¹² during training, but at present this remains speculative. The 4-tiered classification system has been demonstrated to better discriminate between eccentric and concentric LVH in male runners,²¹ but has not been specifically used with female athletes, and may have increased resolution for concentric classification.²² As with the men, none of the females displayed signs of pathologic adaptation,^{23,29,30} but it must be recognized that a selection factor may exist among elite athletes who undergo regular screening.

The lack of resting structural differences demonstrated between female water-polo players and swimmers is important. It has been previously reported that cardiac changes occur to a greater degree in male athletes compared to female athletes²⁹; however, when indexed to body surface area these differences are mitigated and female hearts may actually have greater plasticity in response to volume stimuli than men.³¹ Further, the Morganroth hypothesis has been contested as it pertains to concentric remodeling,^{3,34} and accordingly, Kooreman et al. demonstrated no differences in scaled cardiac geometry in female college athletes when separated into high and low static-component sports.³⁴ Herein, we demonstrate a higher incidence of female concentric remodeling than previously reported, yet without the between-sport (swimming vs water-polo) differences observed in males. As such, the lack of differences between female water-polo players and swimmers could be due to training or competition factors such as less resistance training or high-pressure stimuli (in-game grappling) in female players compared to males; or this could reflect anabolic sex-differences³³ in response to high pressure stimuli that have not been fully established to date.^{32,35}

To our knowledge, artistic swimmer's hearts have not been thoroughly investigated, despite the unique training and environmental stressors imposed on these athletes. It is known that artistic swimmers must undergo prolonged underwater breath-holds, and artistic swimmers have been shown to have a heightened dive-reflex response.¹³ This response acts to reduce filling, and elevates arterial and intrathoracic pressure¹³ and afterload, which might be hypothesized to drive concentric remodeling. However, female artistic swimmers in this investigation had mostly normal geometry, with reduced septal thickness, LV mass, and concentricity index compared to water-polo players and swimmers, likely due to less volume-driven stimuli in training. The artistic swimming group did have 4 cases of elevated wall-thickness - all in the posterior wall - and a group mean RWT of 0.42, which is the cut-off for concentric remodeling.¹⁶ The disproportionate left-wall thickening was accompanied by large left atria, and could represent an adaptation to the reduction in filling seen in underwater diving.¹² In fact, Marabotti et al. describe elevated early-transmitral filling velocities and deceleration times, coupled with decreased or unchanged left ventricular volumes during breath-hold diving at 3m depth using underwater

echocardiography.¹² The authors noted that this presentation resembled that of restrictive/constrictive cardiac disease,¹² and the pressure-overload during artistic swimming could drive left atrial enlargement as is seen clinically in cases of hypertrophic cardiomyopathy.³⁶ It is important to note that despite artistic swimmers having greater left atrial areas than female water-polo players and swimmers, they were within the normal range,¹⁶ and did not present with any indication of adverse remodeling. We did not measure left atrial volume, which has more prognostic value than atrial area²⁶ and is an area for future follow-up.

Limitations

As with any cross-sectional investigation, we cannot infer causation from either sporting demands or aquatic environment on cardiac adaptations. However, a strength of the design is the caliber of athletes studied and the lifetime exposure in their sports, up to and including the highest level of competition. We had only 9 female water-polo players in this investigation, which may have limited our findings and comparisons in their sport. The *a priori* aim of this investigation was to focus on LV morphology; therefore, further analysis of atria and the right ventricle in elite aquatic athletes is warranted. When examining maximal wall-thickness, we used only parasternal long-axis images, which precluded assessment of regional differences from short-axis views. Finally, there is also the potential of over-estimating LV wall-thickness using echocardiography when compared to cardiac magnetic resonance techniques,³⁷ which was not available in this setting.

Conclusions

Elite swimmers and water-polo players demonstrate increased LV mass and volume, indicative of classic athlete's heart, with male water-polo players displaying greater LV wall-thickness and concentric remodeling than swimmers. In contrast, female swimmers and water-polo players have similar cardiac morphology, with primarily eccentric volume-based adaptations; however, they both have greater incidence of wall-thickening and concentric remodeling than previously reported, which could be an adaptation inherent to water sports, and is an important consideration for athlete screening. Finally, artistic swimmers have normal geometry with reduced LV mass and volumes compared to the other athletes, but a specific increase in LV posterior wall-thickness and atria area, which could be an adaptation to under-water breath hold stimuli.

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