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Right Ventricular Structure and Function in Adolescent Athletes: A 3D Echocardiographic Study

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ABSTRACT

The aim of this study was to characterize the right ventricular (RV) contraction pattern and its associations with exercise capacity in a large cohort of adolescent athletes using resting three-dimensional echocardiography (3DE). We enrolled 215 adolescent athletes (16 ± 1 years, 169 males, 12 ± 6 hours of training/week) and compared them to 38 age and sex-matched healthy, sedentary adolescents. We measured the 3DE-derived biventricular ejection fractions (EF). We also determined the relative contributions of longitudinal EF (LEF/RVEF) and radial EF (REF/RVEF) to the RVEF. Same-day cardiopulmonary exercise testing was performed to calculate VO_2/kg. Both LV and RVEFs were significantly lower (athletes vs. controls; LVEF: 57 ± 4 vs 61 ± 3, RVEF: 55 ± 5 vs 60 ± 5 %, $p < 0.001$). Interestingly, while the relative contribution of radial shortening to the global RV EF was also reduced (REF/RVEF: 0.40 ± 0.10 vs 0.49 ± 0.06, $p < 0.001$), the contribution of the longitudinal contraction was significantly higher in athletes (LEF/RVEF: 0.45 ± 0.08 vs 0.40 ± 0.07, $p < 0.01$). The supernormal longitudinal shortening correlated weakly with a higher VO_2/kg ($r = 0.138$, $P = 0.044$). Similarly to the adult athlete's heart, the cardiac adaptation of adolescent athletes comprises higher biventricular volumes and lower resting functional measures with supernormal RV longitudinal shortening. Characteristic exercise-induced structural and functional cardiac changes are already present in adolescence.

Introduction

Regular, intense exercise training is associated with significant hemodynamic needs promoting subsequent structural and functional cardiac changes, commonly referred to as the athlete's heart.

In general, dilation of the chambers accompanied by increased myocardial mass is observed, and low-normal resting functional measures are also frequent findings in adult athletes [1, 2]. Pediatric athletes represent a unique population in which the interpretation of

different investigations is a clinical issue; yet there is a lack of data and evidence [3, 4].

The rationale behind pre-participation screening at an early age is justified by the fact that adolescent athletes often train and compete at the level of adults; thus, their developing circulatory system may face relatively even more significant demands [4, 5]. Importantly, a handful of clinically relevant cardiovascular conditions may already manifest in the first decades of life [6]. Therefore, such a screening should be performed in a way that it should be sensitive enough to capture congenital, acquired, or even exercise-induced pathologies but also specific to minimize the risk for prescribing additional costly investigations or even to disqualify a young individual due to overdiagnosis. Recent data show that cardiac remodeling appears early after the initiation of exercise training – irrespective of age and sex [7]. Thus, pre-participation screening should be conducted at even younger ages bearing its additional confounding factors like sexual maturation, growth, and the increasing insufficiency of investigational methods used in adult cardiology [4, 8].

Echocardiography is a good candidate to bridge this clinical gap. It is a non-invasive, relatively cost-effective and easy-to-use modality that can support clinical decision making by meaningful structural and functional parameters. Moreover, the application of emerging techniques, such as deformation imaging and three-dimensional (3D) echocardiography, may offer even more granular quantification during resting conditions and also enable a more detailed characterization of the right ventricle (RV) [9, 10]. Deformation along the long axis (by longitudinal strain) is a primetime measure of RV function in clinical adult cardiology; however, the non-longitudinal mechanical directions are also physiologically important components of RV systolic performance [11]. In response to hemodynamic stimuli, RV mechanics can change in a complex manner, carrying important diagnostic and prognostic information [12, 13]. As exercise capacity can only be as good as the performance of the worst ventricle, a better characterization of the exercise-induced RV changes and their associations with peak oxygen uptake can help to understand the physiological continuum between cardiac adaptations and sports performance [14].

Accordingly, the aim of this study was to investigate athlete's heart in adolescents using advanced 3D echocardiography to focus on the RV, and searching for associations between resting morphological and functional cardiac measures, as well as exercise capacity measured by same-day cardiopulmonary exercise testing (CPET).

Materials and Methods

Healthy, competitive, adolescent athletes were identified ($n = 215$) from our center's complex sports cardiology screening program to be included in a retrospective, cross-sectional study. We defined the adolescents as over the age of 10 and under the age of 18 years. As an inclusion criterion, all athletes should have 3D transthoracic echocardiographic images available. A detailed medical history and training regime were obtained along with a standard physical examination and a 12-lead electrocardiogram (ECG). Two-dimensional (2D) and 3D echocardiography and then cardiopulmonary exercise testing (CPET) were performed on all athletes on the same day

(time difference range between investigations: 0 to 3 hours). An age and sex-matched healthy, sedentary population ($n = 38$) (no previous participation in intensive training, < 3 h of exercise/week) served as the control group. These individuals also underwent the aforementioned screening protocol except for CPET. This control group was recruited from local schools on a voluntary basis; no individuals were identified subsequently with significant cardiac abnormalities revealed by echocardiography, ECG, blood pressure measurement, or review of medical history. All participants and/or their legal family representative provided written, informed consent to the study procedures. Body surface area (to index volumetric measures with) was calculated using the Mosteller formula [15]. This study is in accordance with the Declaration of Helsinki and approved by the local ethics committee. Our methodical pipeline is summarized in ▶ Fig. 1.

Two and three-dimensional echocardiography

Transthoracic echocardiographic examinations were performed on commercially available ultrasound systems (E95, 4Vc-D probe, GE Vingmed Ultrasound, Horten, Norway and EPIQ 7, X5-1 probe, Philips Medical Systems, Best, The Netherlands) by cardiologists throughout the working day. A standard acquisition protocol consisting of 2D loops from parasternal, apical, and subxiphoid views was applied. Left ventricular (LV) internal diameters, wall thicknesses, and relative wall thickness; left atrial 2D end-systolic volume index (LAVi); mitral inflow velocities such as early (E) and late diastolic (A) peak velocities, their ratio, and E-wave deceleration time; systolic (s'), early diastolic (e'), and atrial (a') velocities of the mitral lateral and septal annulus; average E/e'; RV basal short-axis diameter, tricuspid annular plane systolic excursion (TAPSE), fractional area change (FAC), right ventricular systolic pressure (RVSP), and right atrial 2D end-systolic volume index (RAVi) were measured according to current guidelines [16, 17].

Beyond conventional echocardiographic examination, ECG-gated full-volume 3D datasets reconstructed from four cardiac cycles optimized for the left or right heart were obtained for further analysis on a separate workstation. Three-dimensional datasets focused on the left heart were processed using semi-automated, commercially available software (4D LV-Analysis 3, TomTec Imaging, Unterschleissheim, Germany). We determined LV end-diastolic volume index (EDVi), end-systolic volume index (ESVi), stroke volume index (SVi), and LV mass index (LV Mi). To assess global LV function, ejection fraction (EF) was calculated. Concerning the right heart, we quantified 3D RV EDVi, ESVi, and SVi, EF, and septal and free wall 2D longitudinal strain (RV SLS and RV FWLS) as well (4D RV-Function 2, TomTec Imaging).

Advanced three-dimensional echocardiographic analysis of the right ventricle

In order to quantify the three major functional components contributing to the global RV performance, we used the ReVISION software (Argus Cognitive, Inc, Lebanon, NH, USA). First, the 3D mesh model exported from the 4D RV-Function software package was re-oriented by a standard, automated method to identify the longitudinal (from the tricuspid annulus to the apex), radial (perpendicular to the interventricular septum), and anteroposterior (parallel to the interventricular septum) axes. Next, motion decompo-
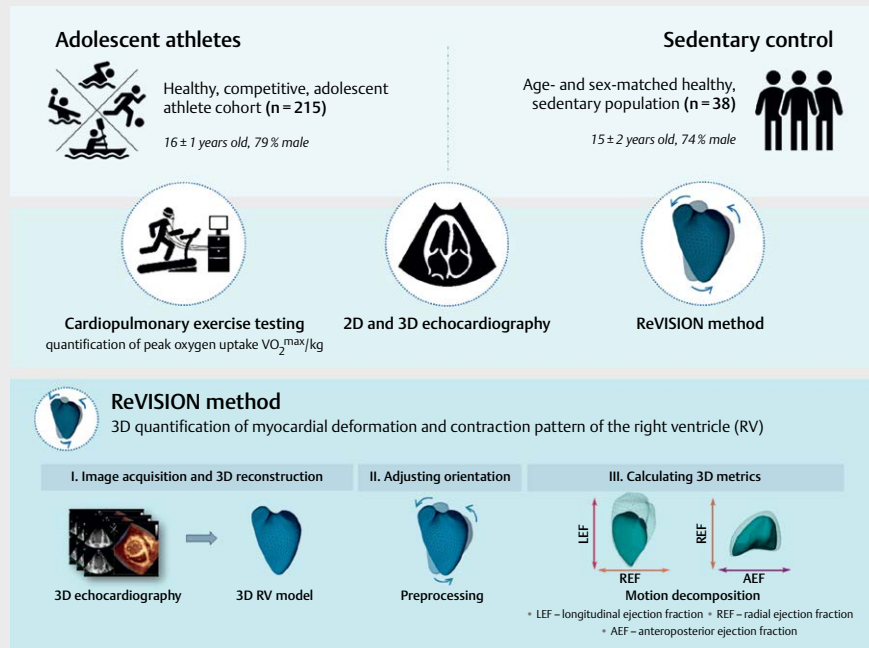
▶ **Fig. 1** The methodical pipeline of the study. A total of 215 adolescent athletes were enrolled and compared to 38 age and sex-matched healthy, sedentary children. 3D echocardiographic datasets were obtained to evaluate the contributions of longitudinal EF (LEF/RVEF), anteroposterior EF (AEF/RVEF), and radial EF (REF/RVEF) to the right ventricular ejection fraction (RVEF) using the ReVISION method. Additionally, cardiopulmonary exercise testing was performed to calculate VO_2/kg.

sition was performed along these directions in a vertex-based manner to quantify component values generated by each motion component [i.e. longitudinal EF (LEF), radial EF (REF), and anteroposterior EF (AEF)], as previously described [18]. The relative contribution of each component to the total RV pump function was expressed as the ratio between LEF, REF, and AEF and total RVEF (LEF/RVEF, REF/RVEF, and AEF/RVEF, respectively). Notably, the absolute volume change of the RV is generated by the aggregated contribution of the three motion components. This composition is not additive, rather multiplicative, and therefore, the sum of the decomposed volume changes is not equal to the global volume change. Thus, the relative contribution of the motion components (i.e. LEF/RVEF, REF/RVEF, AEF/RVEF) do not add up to 100%. To facilitate a better explainability, we also expressed the relative contributions as a signed parameter (i.e. LEF', REF', AEF'), where, for example, LEF' = LEF*[RVEF/(LEF + REF + AEF)], etc. With this method, the sum of the signed values adds up to the global RVEF (LEF' + REF' + AEF' = RVEF). Good reproducibility was previously reported by our laboratory concerning these metrics [18, 19].

Cardiopulmonary exercise testing

Cardiopulmonary exercise testing for peak oxygen uptake (VO_2 and VO_2/kg) quantification was performed on a treadmill on institutional, sport-specific, incremental protocols (starting with a 1-min sitting resting phase, followed by 1–2 min flat walk of 6 km/h as warm-up, then by continuous 8–10 km/h uphill running with an increasing slope of 1.0 to 1.5% every minute until exhaustion) [20]. The volume and composition of the expired gases were analyzed breath by breath using an automated cardiopulmonary exercise system (Respiratory Ergostik, Geratherm, Bad Kissingen, Germany). Participants were encouraged to achieve maximal effort. Maximal intensity was considered to be achieved, if the athlete reported maximal subjective exhaustion and either the respiratory exchange ratio (RER) was over 1.1, and/or flattening could be seen in the oxygen uptake and the heart rate curves.

Power and statistical analysis

Using a previous study of similar methodology with smaller but more balanced sample sizes (60 athletes vs. 40 controls) [21], we determined the effect-sizes (Cohen's d) of representative parameters that describe left and right ventricular morphology and function (LV EDVi, LV EF, RV EDVi, RV EF, LEF/RVEF). After calculating Cohen's d, all of these parameters were considered to have a relatively large/medium effect size (Cohen's d values respectively: 2.616, 1.527, 2.418, 1.193, 1.175). Using these calculated effect sizes, we performed power analysis on the participants identified from our database retrospectively. In all cases, the statistical power exceeded 0.80, reassuring that the outlined sample size that we proposed for our current study was appropriate despite its unbalanced nature. Statistical analysis was performed using dedicated software (StatSoft Statistica, v12, Tulsa, OK, USA). Continuous variables are presented as mean ± standard deviation (SD), whereas categorical variables are reported as frequencies and percentages. After verifying the normal distribution of each variable using the Kolmogorov-Smirnov test, groups were compared with the unpaired Student's *t* test or Mann-Whitney *U* test for continuous variables and

▸ **Table 1** Baseline and training-specific characteristics of athlete and control groups.

	Athletes (n = 215)	Controls (n = 38)	P
Baseline characteristics			
Age (years)	15.8 ± 1.4	15.3 ± 2.0	0.060
Male, n (%)	169 (78.6)	28 (73.7)	0.503
Height (cm)	175.6 ± 10.3	169.4 ± 11.8	0.022
Weight (kg)	67.0 ± 12.9	61.0 ± 10.4	0.072
BSA (m²)	1.80 ± 0.2	1.69 ± 0.2	0.045
SBP (mmHg)	129.8 ± 14.5	119.2 ± 13.2	0.005
DBP (mmHg)	71.4 ± 9.0	75.5 ± 6.4	0.076
HR (bpm)	70.5 ± 12.1	78.4 ± 15.0	0.014
Training specific characteristics			
Type of sport			
▪ **Mixed, n (%)**	180 (83.7)	–	
▪ **Endurance, n (%)**	26 (12.1)	–	
▪ **Power, n (%)**	3 (1.4)	–	
▪ **Skill, n (%)**	6 (2.8)	–	
Since (years)	8.4 ± 3.0	–	
Training time (h/week)	12.3 ± 6.1	–	
VO$_2$(L/min)	3.6 ± 0.8	–	
VO$_2$/kg (mL/kg/min)	54.4 ± 6.9	–	

Continuous variables are presented as means ± SD, categorical variables are reported as frequencies (%). BSA: body surface area, DBP: diastolic blood pressure, HR: heart rate, SBP: systolic blood pressure, VO$_2$: peak oxygen uptake, VO$_2$/kg: peak oxygen uptake indexed to body weight.

▸ **Table 2** Conventional 2D echocardiographic parameters of athlete and control groups.

	Athletes (n = 215)	Controls (n = 38)	P
LVIDd (mm)	49.3 ± 4.1	45.1 ± 4.1	<0.001
IVSd (mm)	9.5 ± 1.4	8.4 ± 1.3	<0.001
PWd (mm)	8.6 ± 1.2	7.4 ± 1.1	<0.001
RWT	0.35 ± 0.05	0.33 ± 0.05	0.072
LV Mi (g/m²)	86.3 ± 15.5	66.0 ± 12.8	<0.001
E (cm/s)	91.3 ± 17.0	100.4 ± 13.1	0.002
A (cm/s)	58.0 ± 15.5	60.0 ± 13.4	0.445
E/A	1.66 ± 0.47	1.75 ± 0.42	0.299
DT (ms)	168.9 ± 33.3	161.8 ± 34.4	0.230
Mitral lateral s′ (cm/s)	11.8 ± 2.4	12.6 ± 2.5	0.048
Mitral lateral e′ (cm/s)	18.2 ± 3.0	19.5 ± 3.4	0.017
Mitral lateral a′ (cm/s)	6.2 ± 1.9	7.6 ± 2.1	<0.001
Mitral medial s′ (cm/s)	9.1 ± 1.4	9.7 ± 1.5	0.019
Mitral medial e′ (cm/s)	13.6 ± 2.2	15.7 ± 2.7	<0.001
Mitral medial a′ (cm/s)	6.7 ± 1.6	7.4 ± 1.7	0.015
E/e′ average	5.92 ± 1.10	5.89 ± 0.90	0.893
LAVi (mL/m²)	24.6 ± 7.8	21.4 ± 5.7	0.121
RVd (mm)	33.0 ± 4.2	30.2 ± 2.9	<0.001
RVSP (mmHg)	23.8 ± 4.1	19.7 ± 4.1	<0.001
TAPSE (mm)	23.3 ± 3.7	23.7 ± 3.4	0.618
FAC (%)	47.7 ± 6.1	51.9 ± 5.9	<0.001
RVSLS (%)	− 23.4 ± 4.7	− 22.4 ± 4.1	0.229
RVFWLS (%)	− 29.6 ± 4.2	− 31.4 ± 3.7	0.017
RAVi (mL/m²)	26.1 ± 6.6	25.9 ± 9.1	0.888

Continuous variables are presented as means ± SD, categorical variables are reported as frequencies (%). A: mitral inflow velocity during atrial contraction, a': peak late (atrial) diastolic annular velocity, DT: deceleration time, E: early diastolic mitral inflow velocity, e': early diastolic annular velocity, FAC: fractional area change, IVSd: interventricular septal thickness at end-diastole, LAVi: left atrial volume index, LV: left ventricle, LVIDd: LV internal diameter at end-diastole, Mi: mass index, PWd: posterior wall thickness at end-diastole, RAVi: right atrial volume index, RV: right ventricle, RVd: RV basal diameter, RVFWLS: RV free wall longitudinal strain, RVSLS: RV septal longitudinal strain, RVSP: right ventricular systolic pressure, RWT: relative wall thickness, s': systolic annular velocity, TAPSE: tricuspid annular plane systolic excursion.

the $\chi2$ or Fisher's exact test for categorical variables, as appropriate. The Pearson or Spearman test was computed to assess the correlation between continuous variables. A two-sided P-value of < 0.05 was considered statistically significant.

Results

Basic demographic, anthropometric and hemodynamic data of the adolescent athletes and control population are summarized in ▸ **Table 1**. Athletes had significantly higher values of height and body surface area (BSA) compared with the sedentary control group. Athletes also demonstrated significantly higher resting systolic blood pressures and lower heart rates than controls, whereas diastolic blood pressure was similar in the two groups. Most of the athletes participated in mixed and endurance classes of sports, predominantly soccer (46.0%), water polo (33.4%), and swimming (10.2%); however, other types of sports, such as power and skill, were represented as well in our cohort of athletes (i. e. wrestling, boxing, kenpo, fencing, squash) [22]. The athletes have been participating in competitive sports for 8 ± 3 years with a training duration of 12 ± 6 h/week at the time of the echocardiographic evaluation, and 94 out of the 215 (43.7%) participants were members of the national team in the corresponding age group. The athlete's CPET-derived peak exercise capacity was also quantified with an average value of 54 ml/kg/min (▸ **Table 1**).

Conventional 2D echocardiographic parameters of athletes and controls are shown in ▸ **Table 2**. Left ventricular end-diastolic internal diameter, wall thicknesses, and calculated LV Mi were significantly higher in athletes compared with controls. Regarding diastolic function, transmitral E-wave velocities were significantly lower in athletes. Systolic, early diastolic and atrial velocities of the mitral septal and lateral annuli were significantly lower in athletes. Concerning the right heart, RV basal diameter was larger, along with RV systolic pressure, which also showed significantly higher values among the athlete population. In athletes, right ventricular FAC and RV free wall longitudinal strain showed decreased resting values (▸ **Table 2**).

3D echocardiographic characteristics of athletes and controls are summarized in ▸ **Table 3**. As expected, there were significant differences between the athlete and the control group concerning

▶ **Table 3** Three-dimensional echocardiographic data of athlete and control groups.

	Athletes (n = 215)	Controls (n = 38)	P
LEFT VENTRICLE			
LV EDVi (mL/m²)	80.0 ± 13.0	64.2 ± 9.5	< 0.001
LV ESVi (mL/m²)	34.2 ± 7.2	25.0 ± 5.0	< 0.001
LV SVi (mL/m²)	45.7 ± 7.3	39.2 ± 5.8	0.001
LV Mi (g/m²)	83.8 ± 13.5	67.9 ± 13.0	< 0.001
LV EF (%)	57.3 ± 3.9	61.4 ± 3.4	< 0.001
RIGHT VENTRICLE			
RV EDVi (mL/m²)	80.7 ± 14.3	67.6 ± 10.0	0.001
RV ESVi (mL/m²)	36.3 ± 8.5	27.6 ± 4.2	< 0.001
RV SVi (mL/m²)	44.4 ± 7.3	40.0 ± 7.3	0.024
RV EF (%)	55.3 ± 4.5	60.4 ± 4.9	< 0.001
RV LEF (%)	25.1 ± 5.3	24.3 ± 4.7	0.364
RV REF (%)	22.4 ± 6.0	29.9 ± 5.2	< 0.001
RV AEF (%)	26.0 ± 5.2	30.4 ± 5.4	< 0.001
LEF/RVEF	0.45 ± 0.08	0.40 ± 0.07	0.001
REF/RVEF	0.40 ± 0.10	0.49 ± 0.06	< 0.001
AEF/RVEF	0.47 ± 0.08	0.50 ± 0.07	0.018
LEF' (%)	19.0 ± 4.0	17.4 ± 3.3	0.025
REF' (%)	16.8 ± 4.2	21.3 ± 3.2	< 0.001
AEF' (%)	19.5 ± 3.5	21.7 ± 3.4	0.001

Continuous variables are presented as means ± SD, categorical variables are reported as frequencies (%). AEF: anteroposterior ejection fraction, EDVi: end-diastolic volume index, EF: ejection fraction, ESVi: end-systolic volume index, LEF: longitudinal ejection fraction, LV: left ventricle, Mi: mass index, REF: radial ejection fraction, RV: right ventricle, SVi: stroke volume index.

▶ **Table 4** Comparison of training-specific characteristics and 3D echocardiographic data in female and male athletes.

	Male athletes (n = 169)	Female athletes (n = 46)	P
Age (years)	15.6 ± 1.4	16.4 ± 1.2	< 0.001
Since (years)	8.7 ± 3.0	7.3 ± 2.8	0.007
Training time (h/week)	10.7 ± 4.7	17.9 ± 7.1	< 0.001
VO₂/kg (mL/kg/min)	56.1 ± 6.1	48.1 ± 5.7	< 0.001
LEFT VENTRICLE			
LV EDVi (mL/m²)	82.5 ± 12.5	70.6 ± 10.5	< 0.001
LV ESVi (mL/m²)	35.7 ± 6.9	28.9 ± 5.5	< 0.001
LV SVi (mL/m²)	46.7 ± 7.2	41.6 ± 6.6	< 0.001
LV Mi (g/m²)	86.2 ± 12.8	75.1 ± 12.4	< 0.001
LV EF (%)	56.8 ± 3.7	59.0 ± 4.2	0.001
RIGHT VENTRICLE			
RV EDVi (mL/m²)	83.4 ± 13.4	70.8 ± 13.0	< 0.001
RV ESVi (mL/m²)	37.8 ± 8.2	30.8 ± 7.3	< 0.001
RV SVi (mL/m²)	45.6 ± 6.9	39.9 ± 7.0	< 0.001
RV EF (%)	55.0 ± 4.5	56.7 ± 4.3	0.023
RV LEF (%)	25.6 ± 5.5	23.5 ± 4.1	0.017
RV REF (%)	21.7 ± 6.2	24.9 ± 4.6	0.002
RV AEF (%)	25.5 ± 4.9	27.9 ± 5.9	0.005
LEF/RVEF	0.46 ± 0.09	0.41 ± 0.07	< 0.001
REF/RVEF	0.39 ± 0.10	0.44 ± 0.07	0.005
AEF/RVEF	0.46 ± 0.08	0.49 ± 0.08	0.047
LEF' (%)	19.4 ± 4.1	17.5 ± 2.9	0.004
REF' (%)	16.4 ± 4.3	18.5 ± 3.3	0.002
AEF' (%)	19.2 ± 3.4	20.7 ± 3.7	0.014

Continuous variables are presented as means ± SD, categorical variables are reported as frequencies (%). AEF: anteroposterior ejection fraction, EDVi: end-diastolic volume index, EF: ejection fraction, ESVi: end-systolic volume index, LEF: longitudinal ejection fraction, LV: left ventricle, Mi: mass index, REF: radial ejection fraction, RV: right ventricle, SVi: stroke volume index.

LV and RV morphological and functional parameters. Athletes demonstrated significantly higher LV and RV EDVi, ESVi and SVi values along with a significantly higher LV Mi. In athletes, resting LV and RV EF values were significantly lower compared with control adolescents; however, remained within a normal range. Concerning the contraction pattern of the RV, values of REF and AEF were lower in athletes compared with controls, whereas values of LEF did not show any difference between the two groups. The relative contribution of radial (REF/RVEF, REF') and anteroposterior (AEF/RVEF, AEF') motion components to global RV function was significantly lower in athletes, whereas the relative contribution of the longitudinal (LEF/RVEF, LEF') motion component was higher compared with controls (▶ **Table 3**).

Sex-differences are summarized in ▶ **Table 4**. We have compared male (n = 169) and female (n = 46) athletes based on training-specific characteristics and 3D echocardiographic data. Male athletes were younger, and they have been participating in competitive sports for longer periods of time; however, females had a longer average weekly training duration. Male athletes also showed higher values of CPET-derived peak exercise capacity compared with females. Regarding the 3D echocardiographic results, specific morphological and functional differences were observed between male and female athletes. Male sex was associated with higher values of LV and RV EDVi, ESVi and SVi. Similarly, LVMi, values were higher among male athletes compared with females. In male athletes, LVEF, along with RVEF showed significantly decreased resting values compared with females. Concerning the RV mechanics, values of REF and AEF were significantly lower, whereas LEF showed higher values in male athletes. The relative contribution of radial (REF/RVEF, REF') as well as the anteroposterior (AEF/RVEF, AEF') component was significantly lower in male athletes, while the longitudinal contribution (LEF/RVEF, LEF') was higher compared to female athletes (▶ **Table 4** and ▶ **Fig. 2**). Conventional 2D echocardiographic parameters of male and female athletes were compared in **Supplementary Table 1**. We have also compared athletes competing in mixed-type (n = 180) and endurance-type (n = 26) sport disciplines in **Supplementary Tables 2 and 3**.

Univariable correlations between 3D echocardiography-derived parameters and VO₂/kg were assessed using the athlete population (**Supplementary Table 4**). LV volumes, such as LV EDVi (r = 0.377, P < 0.001), LV ESVi (r = 0.340, P < 0.001), and LV SVi (r = 0.344, P < 0.001) as well as LV Mi (r = 0.369, P < 0.001) correlated moderately with VO₂/kg. LV EF (r = − 0.272, P < 0.001) showed a weak inverse correlation with peak exercise capacity. Regarding the
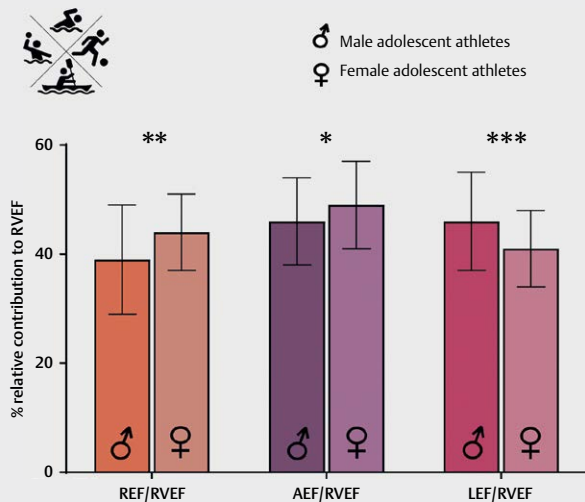
▶ **Fig. 2** Sex-related differences in right ventricular (RV) contraction pattern in adolescent athletes. Male sex was associated with significantly lower radial contribution to RV ejection fraction (REF/RVEF) as well as anteroposterior shortening (AEF/RVEF), while the contribution of longitudinal shortening (LEF/RVEF) was higher compared to female athletes.
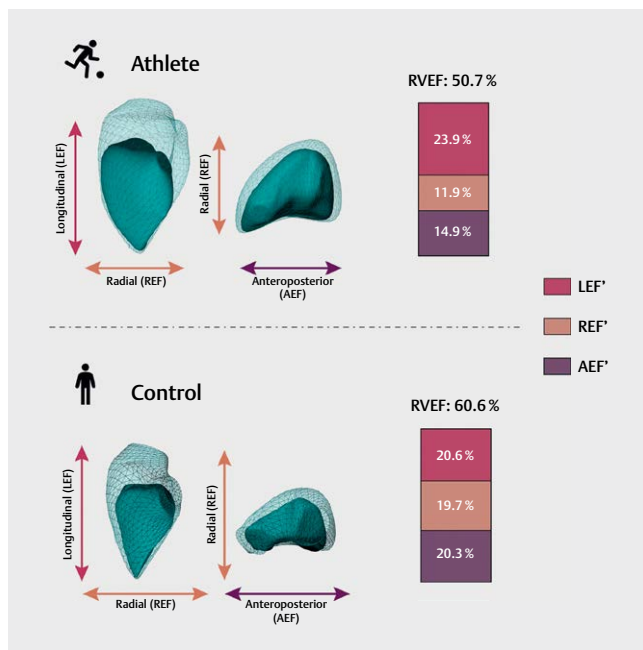
▶ **Fig. 3** Graphical representation of an elite adolescent water polo athlete versus a healthy, sedentary volunteer, in terms of three-dimensional right ventricular (RV) contraction patterns. The relative contributions of radial (REF') and anteroposterior (AEF') motion components to overall RV function were significantly lower in the athlete, whereas the relative contribution of the longitudinal (LEF') motion component was higher compared with the control child.

right heart, RV EDVi (r = 0.377, P < 0.001), RV ESVi (r = 0.340, P < 0.001), and RV SVi (r = 0.344, P < 0.001) showed moderate correlations with VO_2/kg. Right ventricular EF had no significant correlation with VO_2/kg. In terms of RV mechanics, LEF/RVEF (r = 0.138, P = 0.044) showed a weak positive correlation with VO_2/kg, while AEF/RVEF (r = -0.155, P = 0.023) showed a weak inverse correlation with it (**Supplementary Table 4**).

Discussion

To the best of our knowledge, our study is the first that specifically aimed at investigating athlete's heart in adolescents using advanced 3D echocardiography and its association with exercise capacity measured by same-day CPET. Our main findings are the following: (i) adolescent athletes have already presented with characteristic athletic features on echocardiography to adults, (ii) the RV contraction pattern changes to a dominant longitudinal direction (see representative cases on ▶ **Fig. 3**), and (iii) biventricular morphological and functional remodeling – including the altered RV contraction pattern – is weakly to moderately correlated with peak exercise capacity measured by CPET.

Historically, there was a debate whether classical athlete's heart features could be present during childhood; however, recent evidence clearly showed that pediatric subjects are also on the phenotypic spectrum. A recent systematic review and meta-analysis confirmed about 27 % increase in LV mass accompanied by less prominent but significant increases in LV and LA dimensions [7]. Our results are in line with these observations irrespective of the method used for the evaluation (conventional or 3D). Moreover, the development of the exercise-induced changes in LV morphology is fast in adolescents: a study established LV remodeling within 10-weeks of supervised endurance training for 8–10 hours per week [23]. Another study showed that similarly to other exercise-naïve age groups, pre-adolescent athletes initially present with a concentric-type hypertrophy which later transitions into an excentric-type [24]. Adolescence may be perceived as a physiological, however, strong anabolic state also affecting the cardiovascular system, and may act synergistically with physical exercise [25, 26]. The development and regression dynamics of exercise-induced changes are burning questions of sports cardiology that can have important differential diagnostic and also prognostic consequences [27]. However, these questions are even more complex when considering pediatric subjects, therefore, further, large-scale, longitudinal studies are warranted in this age category. Nevertheless, growing body of data indicates that robust changes of cardiac structure and function can be expected in both male and female adolescent athletes [4, 7, 23, 28, 29].

Mainly because it is harder to evaluate using conventional methods, we know relatively little about the RV. It has been shown that 5 months of training results in a greater degree of RV dilation compared to what can be seen in non-athletic children during natural growth [28]. Also, there is an association between weekly training hours and RV size [24]. A previous study also showed that endurance-trained adolescents have increased RV longitudinal function (assessed by TAPSE and TDI-derived s' velocity) [29]. Our results reinforce these findings using more advanced methods, including 3D echocardiography-derived volumetric models. Additionally, this

relative increase in longitudinal shortening is accompanied by a decrease in radial and anteroposterior shortening. This phenomenon was already established in adult water polo athletes – and RV mechanical shift also correlated with better exercise capacity [21]. We hypothesize that the exercise-induced RV adaptation incorporates changes in the myofiber arrangement resulting in a more oblique, more longitudinal direction [30]. Thus, longitudinal shortening will predominate while the other two components (radial shortening representing the RV free wall inward motion, and anteroposterior shortening representing the traction of the free wall by LV contraction) will be reduced relatively. Here we have shown that this characteristic feature is present already in adolescent athletes, which highlights its relationship with a better exercise capacity. Our study is unique in that regard that we have quantified LV and RV volumes and mechanics using 3D echocardiography. Most recently, using 3D echocardiography, Jone et al. provided sex-specific reference values for pediatric RV volumes, EF, and z-score equations from children across five centers in North America [31]. The RV volumes measured in our athletic population are remarkably higher, also pointing to significant remodeling of not only the left heart but also its right counterpart [32]. Importantly, female adolescent athletes are also presented with the above-mentioned phenomena – but with less of a degree. As such, we should consider young female athletes as part of the spectrum as well. Furthermore, evidence suggests that the classical hypothesis of Morganroth (more concentric hypertrophy in strength-trained athletes versus more dilation in endurance-trained athletes) is applicable for the female athlete's heart [33]. All these results imply that during a clinical evaluation, irrespective of age and sex, "outliers" (i. e. high ventricular volumes, high LV mass, etc., in a moderately trained athlete or amateur) should be evaluated downstream with more advanced modalities (i. e. stress testing, cardiac MRI, genetic testing) to exclude the presence of an underlying disease.

Of note, the phenotypic features of these diseases often overlap with the ones of a normal athletic heart [34]. The examination of the pediatric athlete's heart, however, is even more challenging due to several confounders, like sex differences, maturation, and growth [35]. Therefore, a deeper understanding of the physiology of the healthy pediatric athlete's heart is a prerequisite for further research and clinical evaluation. Physical examination, family history and even ECG do not provide granular information and therefore, echocardiography is gaining momentum to be included as an essential screening tool in clinical protocols. Still, emerging echocardiographic techniques (speckle tracking or 3D echocardiography) that already started to permeate cardiology practice are underutilized in sports medicine despite their additional value in geometrical and functional characterization of the heart [36]. 3D echocardiography provides characteristic morphological and functional features of the athlete's heart even during resting conditions that are correlated with exercise capacity. Thus, our current results promote further research using advanced echocardiographic techniques in the clinical context of adolescent athletes to test their capability distinguishing between a healthy athlete's heart and different pathologies.

Limitations

Several limitations have to be acknowledged. First, this is a single-center, retrospective, cross-sectional study with a limited number of adolescent athletes. Nevertheless, advanced echocardiographic techniques along with a same-day CPET elevates its value. Due to the relatively low number of athletes, we could not assess differences between sports classes or different ethnicities. Female athletes were relatively underrepresented in our cohort, and their partly different characteristics (i. e. older age, higher weekly training load) also limit the sex comparability. In some of the youngest male athletes, it is possible that they have not started their adolescent growth spurt. Lastly, we could not compare our measurements to a gold standard. However, all of the post-processing software is validated extensively against CMR [18, 37].

Conclusions

We have investigated a large number of adolescent athletes using advanced echocardiographic techniques and CPET. We have found that both conventional and relatively new features of the athlete's heart (including specific changes in RV contraction pattern) are present even in pediatric athletes and are associated with peak exercise capacity. Further research is warranted in pediatric populations using advanced imaging modalities that may help to distinguish the healthy adolescent athlete's heart from those rare cases that overlap with pathological states.

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Conflict of Interest

AF, BKL, and AK report personal fees from Argus Cognitive, Inc., outside the submitted work. All other authors have no competing interests to disclose.

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