



The relationship between right heart and aerobic capacity in large cohort of young elite athletes

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Abstract

We sought to investigate right heart remodeling and function in elite athletes, as well as the relationship between parameters of right ventricular (RV) and right atrial (RA) remodeling and indices of aerobic capacity. Elite male athletes ($n = 352$) underwent echocardiographic examination including the evaluation of RV and RA parameters. Maximal cardiopulmonary exercise testing was performed to measure maximal oxygen consumption (VO_{2max}), ventilatory anaerobic threshold (VAT) and heart rate reserve (HRR). The right heart remodeling was different between groups. Soccer players had significantly higher RV and RA diameters indexed for BSA. RV filling pressure assessed by tricuspid E/e' ratio was the lowest in soccer players, suggesting somewhat better RV diastolic function. Functional capacity also varies between groups of athletes. VO_{2max} was the highest among soccer players, somewhat lower in basketball players and the lowest among water polo players (55.3 ± 5.6 vs. 52.1 ± 5.9 vs. 53.5 ± 4.8 ml/kg/min, $p < 0.001$). Age, average weekly duration of training, percentage of body fat, as well as parameters of cardiopulmonary fitness (VO_{2max} , O_2 pulse, HRR), correlated well with parameters of RV and RA structure and function in the whole study population. However, systolic blood pressure at rest, VO_{2max} and LV mass index are independently associated with RV and RA structure, whereas duration of training shows the best association with parameters of RV systolic and diastolic function. Even though soccer, water polo and basketball belong to the same group of sports, there is a significant difference in RV and RA remodeling between these three groups. It seems that right heart adaptation is the most pronounced in soccer players, who also have the highest maximal oxygen consumption. Further studies are necessary to investigate the mechanisms of these differences.

Keywords Athletes · Right ventricle · Right atrium · Aerobic capacity

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Introduction

The right ventricle (RV) has been considered as dispensable cardiac chamber that is not essential for overall cardiac function. This is even more noticeable in studies focused on cardiac adaptation to long-term intensive exercise training, known as the “athlete’s heart”. The majority of studies are investigating left ventricular (LV) remodeling going into details with mechanical analysis [1, 2], whereas data regarding right heart adaptation to the enlarged workload of high-level training are still limited. What is more important, the relationship between right heart structure and function and functional capacity in elite athletes is poorly investigated.

D’Andrea et al. reported range of normal values of right heart (right atrial and right ventricular) echocardiographic parameters in top-level athletes separating them into strength and endurance athletes [3]. Recently D’Ascenzi published

study that included 1009 Olympic athletes participating in skill, power, mixed, and endurance sport [4]. However, the majority of investigations included a wide range of sports, whereas limited number of studies involved homogenous groups of sports.

Previous trials showed the association between LV remodeling and maximal oxygen uptake or effort workload in elite athletes [5–7]. La Gerche et al. revealed a strong correlation between RV volumes, ejection fraction and mass obtained by cardiac magnetic resonance and maximal oxygen uptake in a small population consisted of non-athletes, 32 amateur and 8 elite athletes [8]. To the best of our knowledge, there is no study with large cohort of elite athletes in only three disciplines that investigated the association between aerobic capacity and right heart remodeling.

The aim of the present investigation was to evaluate echocardiographic parameters of the right heart and aerobic capacity in large number of soccer, water polo and basketball players and assess their mutual relationship.

Methods

Our cross-sectional study involved 352 elite young male Caucasian athletes, who were referred for preparticipation screening in the mid-season for cardiopulmonary exercise testing in the Institute of Physiology, Medical faculty, University of Belgrade. All athletes, irrespective of type of sport, were examined in the mid-season. They were engaged in 3 different mixed type sports: 160 soccer players (45%), 92 water polo players (26%) and 100 basketball players (28%).

All subjects were non-smokers, and none of them was taking any medication at the time of testing. Exclusion criteria were the following: diabetes mellitus, arterial hypertension, symptoms or signs of coronary artery disease or heart failure, congenital heart disease, malignant arrhythmias, liver or kidney failure, or neoplastic disease.

All participants underwent anthropometric evaluation, physical examination with ECG and echocardiographic assessment, and afterwards, cardiopulmonary exercise testing. All tests were performed in the morning hours on the same day. Complete medical history was assessed by questionnaire. All procedures were performed in accordance with the Helsinki Declaration. The study protocol was approved by the local Ethical Committee.

Anthropometric evaluation

Body height and weight were measured with minimal clothing and without shoes. Body height was assessed using a portable stadiometer (Seca, 214). Body weight and percentage of body fat were measured using the bioimpedance

segmental body composition analyzer (UM-017, Tanita, USA). Body surface area was calculated for each subject.

Blood pressure measurement

Subjects were seated in the quiet room for at least 15 min before the blood pressure assessment. Brachial systolic (SBP) and diastolic blood pressures (DBP) were measured using a mercury sphygmomanometer with an appropriately sized cuff. Three consecutive recordings, taken at 5 min intervals, were averaged.

Echocardiography

Echocardiographic examination was performed by using a Vivid 4 ultrasound machine (GE Healthcare, Horten, Norway). All echocardiographic examinations were performed by the same examiner (MA).

Reported values of all echocardiographic parameters were obtained as the average value of 3 consecutive cardiac cycles. Left ventricular diameters, septum and relative wall thickness, were measured according to the current recommendations [1]. LV ejection fraction (EF) was calculated by using the biplane method. LV mass (LVM) was calculated by using the corrected ASE method and indexed for BSA [9].

The RV basal, mid-cavity and longitudinal diameters were measured in the apical four-chamber view according to the current guidelines [10]. The right atrial (RA) short-axis and long-axis diameters were measured in the apical four-chamber view at the ventricular end-systole [10]. All diameters were indexed for BSA. Tricuspid flow velocities were achieved by the standard pulsed wave Doppler technique in the apical four-chamber view. The following parameters were determined: early diastolic peak flow velocity (E), late diastolic flow velocity (A), their ratio (E/A) and E velocity deceleration time (DT). Tissue Doppler imaging was used to evaluate the RV myocardial velocities in the apical four-chamber view with a sample volume placed at the lateral segment of the tricuspid annulus during early diastole (e') and systole (s') [10]. Tricuspid E/e' ratio was calculated by using previously estimated Doppler values.

Cardiopulmonary exercise testing

All participants underwent the progressive maximal cardiopulmonary test on treadmill. The gas exchange analysis was done using the breath-by-breath system (Jaeger, Oxycon pro, Wurzburg, Germany), with the continuous 12-canal ECG monitoring. The ramp, individualized protocol was used in all individuals. The aim was to achieve a maximum effort between 8 and 12 min. Heart rate (HR) was obtained from ECG trace. Heart rate was noted before the exercise testing, at peak exercise, and

during the recovery period (first, second, and third minutes). Blood pressure was measured manually before the test, every 3 min during the test, and immediately after cessation of exercise. At least two of four criteria were needed to consider a maximal effort: a plateau in VO_2 (≤ 2 ml/kg/min) despite increased exercise intensity, respiratory exchange ratio (RER) valued ≥ 1.10 , age predicted maximal heart rate (calculated by the following formula: $\text{HR}_{\text{max}} = 220 - \text{age}$), or volitional fatigue. The ventilatory anaerobic threshold (VAT) was obtained by using the dual approach (V-slope and ventilatory equivalents method).

Statistical analysis

Continuous variables were presented as mean \pm standard deviation and compared by the analysis of equal variance (ANOVA), as they showed normal distribution. Tuckey post hoc analysis was used for the comparison between different groups. Pearson's correlation coefficients were used for determining the correlation between different demographic, clinical and echocardiographic parameters. The multivariate regression analysis was used to determine the association between different RV and RA echocardiographic parameters as dependent variables and age, training time, body fat, SBP, VO_2 max and LV mass index as independent variables. Therefore, 9 different statistical models were established with the same dependent variables and various dependent variables (one model for each RV or RA structural or functional parameter). The p -value < 0.05 was considered statistically significant.

Results

There was no difference in age and years of training between three observed groups of athletes (Table 1). However, average training during week within the season is significantly longer in water polo and basketball players than in soccer (Table 1). Body height progressively increased from soccer, throughout water polo, to basketball players. Consequently, body surface area (BSA) and body mass index (BMI) are significantly higher in basketball players than in soccer. Body fat percentage gradually decreased from water polo, across soccer, to basketball (Table 1).

The levels of glucose, triglycerides and cholesterol are similar between the observed groups (Table 1). Serum creatinine level was the highest among soccer players, urea level was higher in water polo and basketball players, whereas hemoglobin level was the highest among water polo players (Table 1).

Echocardiographic parameters

Left ventricle and left atrium

LV diameters progressive and significantly increased from soccer, across water polo, to basketball players. However, after indexation for BSA the results are completely different and actually soccer players have larger LV than other two groups of athletes (Table 1). LV mass index was the highest in water polo players, but there was no large difference between different sports. Biplane LV ejection fraction was somewhat higher in soccer than in water polo and basketball players (Table 1). Left atrial diameter was higher in water polo and basketball players. However, after indexation for BSA left atrial diameter gradually and significantly increased from basketball, throughout water polo, to soccer. It is interesting that after indexation for BSA all statistical significance change the direction.

Right atrium and right ventricle

RV diameters were higher in basketball players than in other two groups. Nevertheless, after indexation for BSA, RV diameters were actually the highest among soccer players (Table 1; Fig. 1). Similar results were obtained in regard with RA diameters. Non-indexed RA long- and short-axis diameters gradually and significantly increased from soccer, across water polo, to basketball (Table 1). After indexation for BSA both diameters remained the largest in soccer players.

Early and late tricuspid flows (E and A) measured by pulsed Doppler were significantly higher among soccer than in other two groups of players. Consequently, E/A ratio was somewhat lower in soccer group than in water polo and basketball groups (Table 1). Tricuspid deceleration time was similar between three observed groups. E/e' ratio gradually and significantly increased from soccer, across basketball, to football players (Table 1; Fig. 1). Parameter that corresponds with RV systolic function – s' was significantly higher in basketball players than in the other two groups.

Cardiopulmonary exercise testing

Rest heart rate was the highest in water polo players, SBP was the highest in basketball, whereas DBP was similar between different the observed groups (Table 2). Maximum HR during exercise and respiratory exchange ratio was the highest in soccer players. Maximum SBP, VO_2 at ventilatory threshold and anaerobic threshold were similar between groups (Table 2). Maximum oxygen consumption was the largest in soccer players (Fig. 2). However, oxygen pulse gradually and significantly increased from soccer, across

Table 1 Demographic characteristics, clinical and echocardiographic parameters in the study population

	Soccer (n = 160)	Water polo (n = 92)	Basketball (n = 100)	p
Age (years)	19.6 ± 3.4	18.6 ± 3.1	19.6 ± 3.0	0.136
Years of training (years)	11.7 ± 3.0	10.8 ± 3.1	10.7 ± 2.5	0.057
Training per week (h/week)	12.5 ± 5.0	20.7 ± 5.0 ^a	19.4 ± 5.4 ^a	<0.001
Height (cm)	181 ± 7	189 ± 6	198 ± 12	<0.001**
Weight (kg)	74 ± 9	87 ± 12 ^a	90 ± 16 ^a	<0.001
BMI (kg/m ²)	22.5 ± 2.0	24.3 ± 2.7 ^a	22.8 ± 2.6 ^b	<0.001
BSA (m ²)	1.94 ± 0.15	2.14 ± 0.17 ^a	2.24 ± 0.26 ^{a,b}	<0.001
Body fat (%)	8.8 ± 3.4	10.6 ± 3.9	6.6 ± 3.6	<0.001**
Plasma glucose (mmol/l)	4.8 ± 0.5	4.9 ± 0.5	4.8 ± 0.4	0.476
Triglycerides (mmol/l)	0.8 ± 0.4	0.8 ± 0.4	0.8 ± 0.3	0.351
Serum creatinine (umol/l)	90 ± 12	83 ± 11 ^a	88 ± 11 ^d	<0.001
Urea (mmol/l)	5.4 ± 1.4	6.0 ± 1.1 ^a	6.0 ± 1.3 ^a	<0.001
Hemoglobin (g/l)	149 ± 9	152 ± 11	146 ± 11 ^d	<0.001
Left ventricular and atrial parameters				
LVEDD (mm)	53.2 ± 3.2	55.6 ± 3.3	57.3 ± 3.4	<0.001**
LVEDD/BSA (mm/m ²)	27.6 ± 2.0	26.0 ± 1.9 ^a	25.8 ± 2.8 ^a	<0.001
LVESD (mm)	33.2 ± 3.1	35.1 ± 3.1	36.5 ± 3.3	<0.001**
LVESD/BSA (mm/m ²)	17.2 ± 1.6	16.5 ± 1.7 ^a	16.4 ± 2.2 ^a	0.001
IVS (mm)	9.5 ± 1.1	9.8 ± 0.9 ^c	9.3 ± 1.1 ^b	0.005
RWT	0.36 ± 0.04	0.35 ± 0.03	0.33 ± 0.03 ^{a,b}	<0.001
LA (mm)	36.1 ± 3.1	38.2 ± 3.1 ^a	37.8 ± 3.6 ^a	<0.001
LA/BSA (mm/m ²)	18.7 ± 1.7	17.9 ± 1.5	17.0 ± 2.4	<0.001**
LVM/BSA (g/m ²)	98.1 ± 16.9	101.4 ± 15.0	94.9 ± 14.9 ^b	0.024
EF (%)	67 ± 7	65 ± 5 ^c	65 ± 5 ^a	0.003
Right ventricular and atrial parameters				
RVD basal (mm)	30.7 ± 3.3	32.9 ± 2.8 ^a	34.2 ± 3.4 ^{a,d}	<0.001
RVD basal/BSA (mm/m ²)	15.9 ± 1.8	15.4 ± 1.3	15.4 ± 2.2 ^c	0.024
RVD mid-cavity (mm)	30.0 ± 3.1	30.4 ± 2.4	31.3 ± 2.7 ^a	0.003
RVD mid-cavity/BSA (mm/m ²)	15.6 ± 2.1	14.3 ± 1.4 ^a	14.1 ± 2.4 ^a	<0.001
RVD longitudinal (mm)	74.8 ± 4.7	75.5 ± 3.5	77.1 ± 4.4 ^{a,d}	<0.001
RVD longitudinal/BSA (mm/m ²)	38.8 ± 3.3	35.4 ± 2.4 ^a	34.7 ± 4.7 ^a	<0.001
RA short axis (mm)	37.1 ± 4.6	38.9 ± 3.3	40.8 ± 4.0	<0.001**
RA short axis/BSA (mm/m ²)	19.2 ± 2.6	18.2 ± 1.6 ^a	18.4 ± 2.5 ^c	0.001
RA long axis (mm)	47.6 ± 5.2	50.8 ± 4.2 ^a	52.4 ± 4.5 ^{a,d}	<0.001
RA long axis/BSA (mm/m ²)	24.7 ± 2.7	23.8 ± 1.8 ^c	23.5 ± 2.5 ^a	0.001
E (cm/s)	64 ± 9	61 ± 6 ^a	62 ± 8 ^d	0.001
A (cm/s)	35 ± 6	31 ± 5 ^a	31 ± 5 ^a	<0.001
E/A	1.9 ± 0.4	2.0 ± 0.3 ^c	2.0 ± 0.4 ^c	0.019
DT (ms)	168 ± 20	163 ± 19	163 ± 18	0.130
E/e'	3.0 ± 1.0	4.5 ± 0.7	3.9 ± 1.2	<0.001**
s' (cm/s)	13 ± 3	13 ± 1	15 ± 2 ^{a,b}	<0.001

A late diastolic tricuspid flow (pulse Doppler), *BSA* body surface area, *DT* deceleration time across tricuspid annulus, *E* early diastolic tricuspid flow (pulse Doppler), *e'* the peak early diastolic relaxation velocity (*e'*) of the lateral tricuspid annulus (tissue Doppler), *EF* ejection fraction, *IVS* interventricular septum, *LA* left atrium, *LVM* left ventricle mass, *LVEDD* left ventricle end-diastolic dimension, *LVESD* left ventricle end-systolic dimension, *RA* right atrium, *RV* right ventricle, *RVD* right ventricular diameter, *RVT* right ventricular wall thickness, *RWT* relative wall thickness, *s*, systolic flow velocity across lateral segment of tricuspid annulus (tissue Doppler)

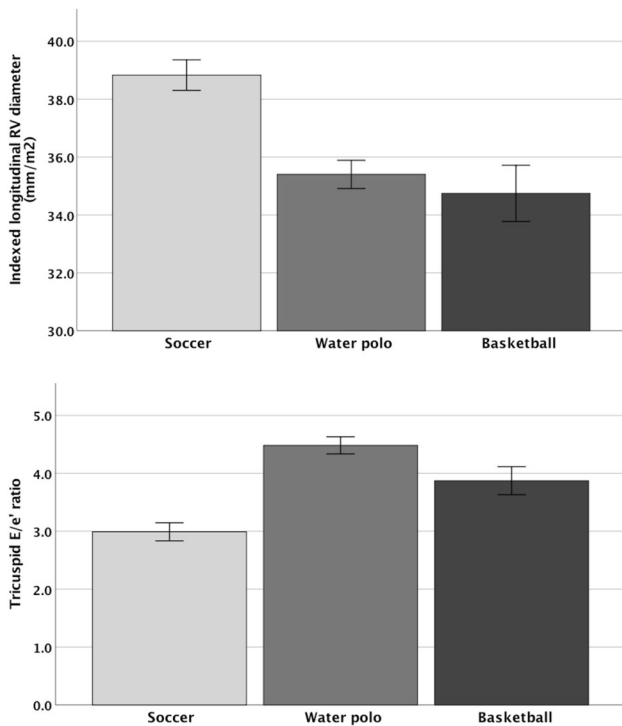


Fig. 1 Indexed RV diameter (upper panel) and tricuspid E/e' ratio (lower panel) among the observed groups

water polo, to basketball players (Table 2). Heart rate after 1.min of recovery was similar between three observed groups. Interestingly, the drop of heart rate was the lowest

in soccer group. Therefore, heart rate after 3.min of recovery was the highest in this group of athletes.

Correlation and regression analyses

Main demographic and clinical parameters such as age, training per week during season, body fat percentage and SBP in rest correlated well with parameters of the right heart structure and function – RV and RA diameters (indexed and non-indexed) and tricuspid flow velocities in the whole study population (Table 3).

Maximum VO₂ and oxygen pulse showed also good correlation with parameters of RV and RA structure and function in the entire study population. However, oxygen pulse showed somewhat better correlation than VO_{2max} (Table 3; Fig. 3).

HRR1 correlates better than HRR3 with RV and RA parameters in the whole study population (Table 3).

Using 9 different models with same independent variables (age, training time per week, body fat percentage, SBP in rest, VO_{2max} and LV mass index) and 9 various dependent variables we showed that VO_{2max} and LV mass index were independently of other mentioned independent variables associated with RV and RA structural parameters—diameters (Table 4). On the other side, the average training time per week during the season had more important role in determination of RV function—diastolic (E/A, DT, E/e') and systolic (s').

Table 2 Cardiopulmonary exercise testing results in study population

	Soccer (n=160)	Water polo(n=92)	Basketball (n=100)	p
Rest				
HR rest (beats/min)	59 ± 10	63 ± 11 ^a	60 ± 11	0.008
SBP rest (mmHg)	112 ± 10	115 ± 8	116 ± 11 ^c	0.011
DBP rest (mmHg)	71 ± 7	73 ± 8	72 ± 8	0.326
Exercise				
Maximum exercise				
HR peak (beats/min)	193 ± 8	190 ± 10 ^c	188 ± 9 ^a	<0.001
HR max (% predicted)	96 ± 4	94 ± 4 ^a	94 ± 4 ^a	<0.001
SBP max (mmHg)	178 ± 16	181 ± 22	179 ± 18	0.467
Respiratory exchange ratio	1.12 ± 0.06	1.08 ± 0.05 ^a	1.09 ± 0.07 ^a	<0.001
VO ₂ at ventilatory threshold (ml/kg/min)	48.3 ± 6.1	47.1 ± 6.0	47.5 ± 6.3	0.460
Ventilatory threshold (% of VO ₂ max)	89 ± 7	91 ± 6	89 ± 10	0.225
VO ₂ max (ml/kg/min)	55.3 ± 5.6	52.1 ± 5.9 ^a	53.5 ± 4.8 ^c	<0.001
O ₂ pulse max (ml/beat)	21.5 ± 2.6	23.8 ± 3.6	26.2 ± 3.7	<0.001**
Recovery				
HRR1 (beats/min)	164 ± 20	164 ± 15	166 ± 12	0.679
HRR2 (beats/min)	134 ± 16	129 ± 17 ^c	132 ± 14	0.056
HRR3 (beats/min)	113 ± 13	107 ± 13 ^a	108 ± 12 ^c	0.001

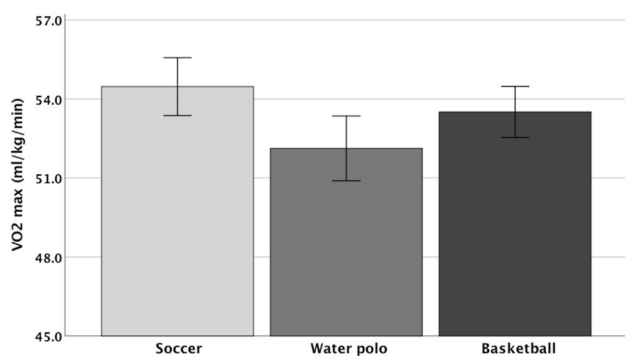


Fig. 2 VO₂ max among observed athletes

Discussion

Our investigation showed several new findings: (i) the right heart remodeling is different in elite athletes involved in mixed sports (soccer, water polo and basketball). Namely, the most remarkable changes in RV and RA dimensions were detected in soccer players who had significantly higher RV and RA diameters indexed for BSA than water polo and basketball players. At the same time, RV filling pressure assessed by tricuspid E/e' ratio was the lowest, suggesting that RV diastolic function was better in this group of athletes. Interestingly, RV systolic function, evaluated by tricuspid s' velocity, was significantly higher in basketball players than in other two groups. (ii) Peak oxygen consumption and peak oxygen pulse emphasized the importance of body size and maximal achieved heart rate in athlete population because VO_{2max} showed the highest level among soccer players, and VO₂ pulse gradually and significantly increase from soccer, across water polo, to basketball players. (iii) Our findings revealed that age, average weekly duration of training, percentage of body fat, as well as parameters of cardiopulmonary exercise test (VO_{2max}, O₂ pulse, SBP_{max}, HRR), correlated well with parameters of RV and RA structure and function in the whole study population. Interestingly, SBP at rest, VO_{2max} and LV mass index represent the best indicators of RV and RA structure, while duration of training shows the best independent association with parameters of RV systolic and diastolic function.

The difference in RV remodeling between different groups of sports was reported before [3, 4]. However, the authors were mostly focused to compare different groups of sports or investigated different types of endurance group of sports. Namely, D'Andrea et al. compared strength vs. endurance sports and found that endurance athletes have significantly higher RV and RA diameters [3]. Interestingly, the authors did not use RV and RA diameters indexed for BSA. D'Ascenzi et al. included large cohort of 1009 Olympic

athletes divided in 4 group of sports: skill, power, mixed and endurance [4]. Comparing these 4 large groups the investigators demonstrated that RV and RA diameters indexed for BSA are the lowest in the mixed group of sport where soccer, water polo and basketball belongs. Interestingly, the prevalence of athletes with RV enlargement using different criteria in mixed group of sports was higher than in skill and power sports, and somewhat lower than in endurance sports [4]. La Gerche et al. investigated different disciplines of endurance sport (marathon, triathlon, alpine cycling, ultra triathlon) and did not find any difference in RV structure and function or aerobic capacity at the baseline [11]. However, the authors reported significantly increased RV volumes, worsened RV function and decreased all functional measures after race. RV parameters mostly recovered one week after race [11]. RV ejection fraction, as a reliable parameter of RV systolic function, significantly more reduced in alpine cycling and ultra triathlon comparing with marathon and triathlon [11]. Ultra triathlon athletes have significantly lower RV fractional area change and global RV systolic strain rate, additional indicators of RV systolic function, than other three groups. Remarkably, LV volumes reduced and function was preserved during race.

Large Scandinavian study that included 504 football players demonstrated that all RV and RA structural parameters were significantly higher in athletes than in controls [12]. However, the authors did not compare different sports. Study that involved endurance and strength-trained athletes showed that even conventional echocardiographic parameters of RV and RA structure and function showed that endurance sports are associated with larger right heart, somewhat better RV diastolic and worse RV systolic function, there was just a few meaningful differences in deformation [13]. Steding et al. compared male and female handball, soccer and triathlon players and found no difference in RV volumes between different sports among men, whereas it gradually increased from handball to triathlon athletes among women [14].

Investigation that compared controls and 100 top-level soccer, basketball and volleyball athletes showed significantly higher RA volume index, RV diameter and tricuspid E/A ration in athletes' group [15]. The difference was confirmed by strain analysis. Nevertheless, the authors did not make comparison between different disciplines included in this study.

Our findings indicate that soccer players have the largest RV and RA indexed for BSA. These changes are in line with left heart changes because LV and LA indexed diameters are significantly higher in soccer than in water polo or basketball players. Interestingly, these athletes have the shortest average training time and the best maximum oxygen consumption in comparison with other groups. Meta-analysis showed

Table 3 Association between demographic, clinical and echocardiographic parameters in study population

	Age (years)	Training (h/week)	Body fat (%)	SBP _{rest} (mmHg)	VO _{2max} (ml/kg/min)	O ₂ pulse (ml/beat)	SBP _{max} (mmHg)	HRR1 (beat/min)	HRR3 (beat/min)
	r	r	r	r	r	r	r	r	r
RVD basal (mm)	0.285 ^a	0.311 ^a	0.107 ^b	0.172 ^a	-0.049	0.548 ^a	0.104	-0.237 ^a	-0.239 ^a
RVD basal/BSA (mm/m ²)	-0.110 ^b	-0.248 ^a	-0.059	-0.180 ^a	0.312 ^a	-0.199 ^a	-0.070	-0.066	-0.073
RVD mid-cavity (mm)	0.149 ^a	0.085	0.065	0.039	-0.059	0.260 ^a	0.002	-0.052	-0.084
RVD mid-cavity/BSA (mm/m ²)	-0.223 ^a	-0.398 ^a	-0.091	-0.268 ^a	0.336 ^a	-0.436 ^a	-0.142 ^b	0.110 ^b	0.066
RVD longitudinal (mm)	0.300 ^a	0.282 ^a	0.006	0.244 ^a	-0.091	0.446 ^a	0.163 ^b	-0.107 ^b	-0.140 ^b
RVD longitudinal/BSA (mm/m ²)	-0.242 ^a	-0.426 ^a	-0.168 ^a	-0.239	0.344 ^a	-0.564 ^a	-0.104	0.113 ^b	0.077
RA short axis (mm)	0.307 ^a	0.315 ^a	0.138 ^b	0.208 ^a	0.016	0.533 ^a	0.074	-0.217 ^a	-0.109 ^b
RA short axis/BSA (mm/m ²)	-0.063	-0.211 ^a	-0.011	-0.125 ^b	0.339 ^a	-0.186 ^a	-0.105	-0.050	0.041
RA long axis (mm)	0.362 ^a	0.402 ^a	0.052	0.233 ^a	-0.176 ^a	0.575 ^a	0.125 ^b	-0.218 ^a	-0.250 ^a
RA long axis/BSA (mm/m ²)	-0.043	-0.188 ^a	-0.112 ^b	-0.146 ^a	0.224 ^a	-0.210 ^a	-0.069	-0.045	-0.080
E (cm/s)	-0.148 ^a	-0.057	0.080	-0.043	0.073	0.018	-0.030	0.116 ^b	0.026
A (cm/s)	-0.007	-0.064	-0.108	0.046	0.026	0.019	-0.047	-0.092	-0.046
E/A	-0.368 ^a	-0.015	0.190 ^a	-0.204 ^a	0.157 ^a	-0.065	-0.020	0.146 ^a	0.048
DT (ms)	0.074	0.039	-0.057	0.004	0.031	0.025	-0.008	0.025	0.046
E/e'	0.097	0.365 ^a	0.066	0.172 ^a	-0.199 ^a	0.242 ^a	-0.019	-0.234 ^a	-0.108 ^b
s' (cm/s)	0.110 ^a	0.140 ^a	0.093	0.092	-0.058	0.152 ^a	0.048	-0.142 ^a	-0.050

A late diastolic tricuspid flow (pulse Doppler), BSA body surface area, DT_t deceleration time across tricuspid annulus, E early diastolic tricuspid flow (pulse Doppler), e' the peak early diastolic relaxation velocity (e') of the lateral tricuspid annulus (tissue Doppler), HRR heart rate recovery, RA right atrium, RV right ventricle, RVD right ventricular diameter, s, systolic flow velocity across lateral segment of tricuspid annulus (tissue Doppler), SBP systolic blood pressure

^b p < 0.05

^a p < 0.01

that intense prolonged exercise is related with a reduction in RV function (ejection fraction, fractional area change, TAPSE and longitudinal strain), whereas LV function is relatively unaffected [16]. The similar results were obtained in study that investigated elite endurance athletes before and after the race [11]. La Gerche et al. showed that RV enlarged and RV systolic function decreased after the race

[11]. Additionally, researcher showed that RV remodeling is the most intensive in mid-season [17], which also could partly explain our results. The ventricular interdependence through interventricular septum could also be responsible for RV and RA remodeling in soccer players and mentioned differences from water polo and basketball players. Nevertheless, greater RV enlargement could be a consequence of

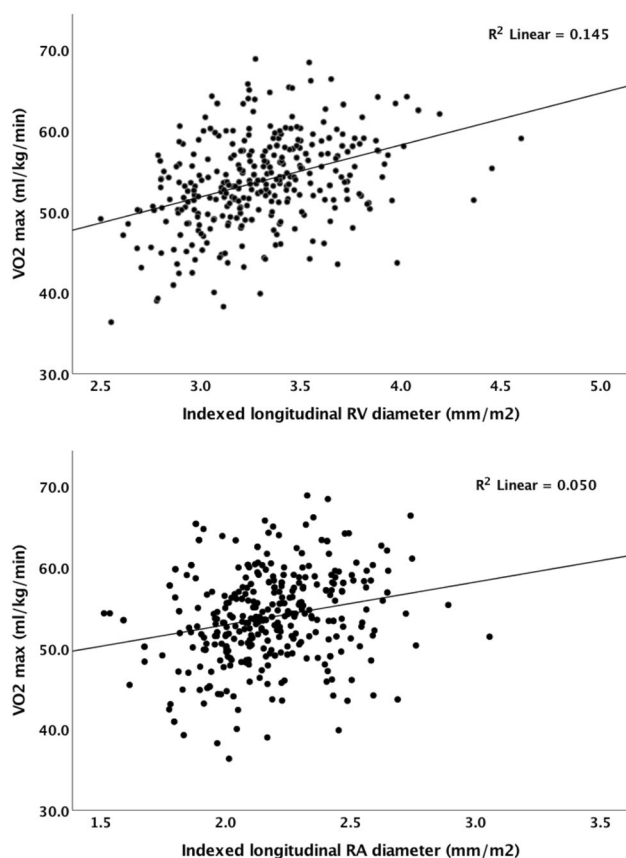


Fig. 3 Correlation between indexed RV (upper panel) and RA (lower panel) longitudinal diameter and VO_2 max in the whole study group. *Footnotes* RA right atrium, RV right ventricle, VO_{2max} maximal oxygen uptake

disproportionate load excess that was discovered in endurance athletes [18, 19]. Furthermore, soccer players in our study have the lowest RV filling pressure assessed by tricuspid E/e' ratio and consequently better RV diastolic function, which also could contribute to better VO_{2max} in these subjects. Pavlik et al. in Hungarian population of athletes showed that VO_{2max} in water polo players was intermediate between power and endurance sports [20]. The association with echocardiographic parameters was unfortunately not provided.

The present investigation showed that SBP at rest, VO_{2max} and LV mass index are independently of other demographic and echocardiographic parameters associated with RV and RA structural indices, while duration of training represents the best independent indicator of RV systolic and diastolic function parameters. Previous investigations demonstrated that intensive and long-lasting effort induces reduction in RV function, but our study went one step further and determined

other parameters that should also be taken into account during RV assessment in elite athletes.

Perspective

Along with the structural and functional adaptation of the left heart in athletes, exercise-induced remodeling of the right heart occurs. While the relationship between LV remodeling and aerobic capacity is well documented, the association between right heart adaptation and VO_{2max} and O_2 pulse in athletes represents a novel finding. Our results showed that peak oxygen consumption is the highest among soccer players and associated with parameters of RV and RA structural and functional remodeling. This is in line with the results of the previous studies which assessed RV volumes by magnetic resonance imaging [8, 14]. Arrhythmogenic right ventricular cardiomyopathy (ARVC), which is responsible for almost quarter of SCD in young athletes, is characterized with RV dilatation that could resembles physiological RV remodeling. Knowing the morphological and functional characteristics of athlete's right heart, as well as their association with aerobic capacity could be valuable to distinguish it from ARVC.

Limitations

The present investigation has several limitations. First, the study involved only male subjects. Second, not all parameters of right heart remodeling such as TAPSE, fractional change area, RA volume, as well as RV and RA strain, were available for all participants. Third, to obtain the VO_2 max in 8–12 min, which is the recommended time for reliable functional assessment, subjects performed different, individualized treadmill protocols. However, all of participants performed ramped, incremental protocols and maximal exercise test and reached a similar level of effort, so the impact of the exercise protocol is negligible.

Conclusion

The right heart remodeling is different in soccer, water polo and basketball players. The results indicate that RV and RA after indexation for BSA are the largest in soccer players. The same group of athletes has the highest VO_{2max} . Demographic, clinical and parameters of cardio-pulmonary fitness correlate well with indices of RV and RA structure and function. Different parameters influence

Table 4 Multivariate regression analysis in study population (different statistical models)

Multivariate regression analysis	β	p	β	p
RVD basal/BSA (Model 1)			E/A _i (Model 6)	
Age (years)	0.023	0.717	0.019	0.788
Training (h/week)	-0.052	0.394	0.191	0.005
Body fat (%)	-0.050	0.433	0.034	0.634
SBP _{rest} (mmHg)	-0.137	0.029	-0.128	0.064
VO ₂ max (ml/kg/min)	0.208	0.002	-0.016	0.827
LVM/BSA (g/m ²)	0.322	<0.001	-0.004	0.949
r ²		0.220		0.045
RVD mid-cavity/BSA (Model 2)			DT _i (Model 7)	
Age (years)	-0.075	0.212	-0.032	0.658
Training (h/week)	-0.236	<0.001	0.016	0.812
Body fat (%)	-0.014	0.817	-0.121	0.094
SBP _{rest} (mmHg)	-0.163	0.006	-0.023	0.747
VO ₂ max (ml/kg/min)	0.204	0.002	-0.097	0.198
LVM/BSA (g/m ²)	0.224	<0.001	-0.021	0.756
r ²		0.293		0.017
RVD longitudinal/BSA (Model 3)			E/e' (Model 8)	
Age (years)	-0.124	0.030	-0.097	0.127
Training (h/week)	-0.292	<0.001	-0.419	<0.001
Body fat (%)	-0.100	0.070	-0.057	0.369
SBP _{rest} (mmHg)	-0.091	0.101	0.040	0.521
VO ₂ max (ml/kg/min)	0.205	0.001	0.088	0.186
LVM/BSA (g/m ²)	0.329	<0.001	0.085	0.155
r ²		0.389		0.227
RA short axis/BSA (Model 4)			s' (Model 9)	
Age (years)	0.021	0.753	0.064	0.335
Training (h/week)	-0.036	0.567	0.296	<0.001
Body fat (%)	-0.043	0.517	-0.212	0.002
SBP _{rest} (mmHg)	-0.051	0.427	0.043	0.509
VO ₂ max (ml/kg/min)	0.263	<0.001	-0.118	0.091
LVM/BSA (g/m ²)	0.260	<0.001	-0.057	0.364
r ²		0.177		0.160
RA long axis/BSA (Model 5)				
Age (years)	0.010	0.884		
Training (h/week)	-0.038	0.552		
Body fat (%)	-0.020	0.761		
SBP _{rest} (mmHg)	-0.101	0.121		
VO ₂ max (ml/kg/min)	0.113	0.107		
LVM/BSA (g/m ²)	0.327	<0.001		
r ²		0.158		

BSA body surface area, LVM left ventricle mass, SBP systolic blood pressure

right heart structure and function. Therefore, systolic blood pressure at rest, VO₂max and LV mass index are independently associated with RV and RA structure, whereas duration of training shows the best association with parameters of RV systolic and diastolic function. Further follow-up investigations are necessary to investigate the influence of right heart remodeling in elite athletes.

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Compliance with ethical standards

Conflict of interest The authors report no relationships that could be construed as a conflict of interest.

References

- Calderón Montero FJ, Benito Peinado PJ, Di Salvo V, Pigozzi F, Maffulli N (2007) Cardiac adaptation to training and decreased training loads in endurance athletes: a systematic review. *Br Med Bull* 84:25–35
- Beaumont A, Grace F, Richards J, Hough J, Oxborough D, Sculthorpe N (2016) Left ventricular speckle tracking-derived cardiac strain and cardiac twist mechanics in athletes: a systematic review and meta-analysis of controlled studies. *Sports Med* 47:1145–1170
- D'Andrea A, Riegler L, Golia E, Cocchia R, Scarafile R, Salerno G, Pezzullo E, Nunziata L, Citro R, Cuomo S, Caso P, Di Salvo G, Cittadini A, Russo MG, Calabrò R, Bossone E (2013) Range of right heart measurements in top-level athletes: the training impact. *Int J Cardiol* 164(1):48–57
- D'Ascenzi F, Pisicchio C, Caselli S, Di Paolo FM, Spataro A, Pelliccia A (2017) RV remodeling in Olympic athletes. *JACC Cardiovasc Imaging* 10(4):385–393
- van Buuren F, Mellwig KP, Butz T, Langer C, Prinz C, Freund A, Kottmann T, Bogunovic N, Dahm JB, Faber L, Horstkotte D (2013) Left ventricular mass and oxygen uptake in top handball athletes. *Int J Sports Med* 34(3):200–206
- Al-Hazzaa HM, Chukwuemeka AC (2001) Echocardiographic dimensions and maximal oxygen uptake in elite soccer players. *Saudi Med J* 22(4):320–325
- D'Andrea A, Limongelli G, Caso P, Sarubbi B, Della Pietra A, Brancaccio P, Cice G, Scherillo M, Limongelli F, Calabrò R (2002) Association between left ventricular structure and cardiac performance during effort in twomorphological forms of athlete's heart. *Int J Cardiol* 86(2–3):177–184
- La Gerche A, Burns AT, Taylor AJ, Macisaac AI, Heidbüchel H, Prior DL (2012) Maximal oxygen consumption is best predicted by measures of cardiac size rather than function in healthy adults. *Eur J Appl Physiol* 112(6):2139–2147
- Lang RM, Badano LP, Mor-Avi V, Afzalalo J, Armstrong A, Ernande L, Flachskampf FA, Foster E, Goldstein SA, Kuznetsova T, Lancellotti P, Muraru D, Picard MH, Rietzschel ER, Rudski L, Spencer KT, Tsang W, Voigt JU (2015) Recommendations for cardiac chamber quantification by echocardiography in adults: an update from the American society of echocardiography and the European association of cardiovascular imaging. *J Am Soc Echocardiogr* 28:1–39
- Rudski LG, Lai WW, Afzalalo J, Hua L, Handschumacher MD, Chandrasekaran K, Solomon SD, Louie EK, Schiller NB (2010) Guidelines for the echocardiographic assessment of the right heart in adults: a report from the American Society of Echocardiography endorsed by the European Association of Echocardiography, a registered branch of the European Society of Cardiology, and the Canadian Society of Echocardiography. *J Am Soc Echocardiogr* 23:685–713
- La Gerche A, Burns AT, Mooney DJ, Inder WJ, Taylor AJ, Bogaert J, Macisaac AI, Heidbüchel H, Prior DL (2012) Exercise induced right ventricular dysfunction and structural remodeling in endurance athletes. *Eur Heart J* 33(8):998–1006
- Gjerdalen GF, Hisdal J, Solberg EE, Andersen TE, Radunovic Z, Steine K (2014) The Scandinavian athlete's heart; echocardiographic characteristics of male professional footballplayers. *Scand J Med Sci Sports* 24(5):e372–e380
- Pagourelas ED, Kouidi E, Efthimiadis GK, Deligiannis A, Geleris P, Vassilikos V (2013) Right atrial and ventricular adaptations to training in male Caucasian athletes: an echocardiographic study. *J Am Soc Echocardiogr* 26(11):1344–1352
- Steding K, Engblom H, Buhre T, Carlsson M, Mosén H, Wohlfart B, Arheden H (2010) Relation between cardiac dimensions and peak oxygen uptake. *J Cardiovasc Magn Reson* 12:8
- D'Ascenzi F, Cameli M, Padeletti M, Lisi M, Zacà V, Natali B, Malandrino A, Alvino F, Morelli M, Vassallo GM, Meniconi C, Bonifazi M, Causarano A, Mondillo S (2013) Characterization of right atrial function and dimension in top-level athletes: a speckle tracking study. *Int J Cardiovasc Imaging* 29(1):87–94
- Elliott AD, La Gerche A (2015) The right ventricle following prolonged endurance exercise: are we overlooking the more-important side of the heart? A meta-analysis. *Br J Sports Med* 49(11):724–729
- D'Ascenzi F, Pelliccia A, Corrado D, Cameli M, Curci V, Alvino F, Natali BM, Focardi M, Bonifazi M, Mondillo S (2016) Right ventricular remodelling induced by exercise training in competitive athletes. *Eur Heart J Cardiovasc Imaging* 17(3):301–307
- La Gerche A, Roberts T, Claessen G. The response of the pulmonary circulation and right ventricle to exercise: exercise-induced rightventricular dysfunction and structural remodeling in endurance athletes (2013 Grover Conference series). *Pulm Circ* 2014;4(3):407–416
- La Gerche A, Heidbüchel H, Burns AT, Mooney DJ, Taylor AJ, Pflugger HB, Inder WJ, Macisaac AI, Prior DL (2011) Disproportionate exercise load and remodeling of the athlete's right ventricle. *Med Sci Sports Exerc* 43(6):974–981
- Pavlik G, Kemény D, Kneffel Z, Petrekanits M, Horváth P, Sidó Z (2005) Echocardiographic data in hungarian top-level water polo players. *Med Sci Sports Exerc* 37(2):323–328

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