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ORIGINAL RESEARCH

RV Remodeling in Olympic Athletes

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ABSTRACT

OBJECTIVES The aim of this study was to assess the impact of sex and different sports on right ventricular (RV) remodeling and compare the derived upper limits with widely used revised Task Force (TF) reference values.

BACKGROUND Uncertainties exist regarding the extent and physiological determinants of RV remodeling in highly trained athletes. The issue is important, considering that in athletes RV size occasionally exceeds the cutoff limits proposed to diagnose arrhythmogenic RV cardiomyopathy.

METHODS A total of 1,009 Olympic athletes (mean age 24 $\pm$ 6 years; n = 647 [64%] males) participating in skill, power, mixed, and endurance sport were evaluated by 2-dimensional echocardiography and Doppler/tissue Doppler imaging. The right ventricular outflow tract (RVOT) in parasternal long-axis (PLAX) and short-axis views, fractional area change, s′ velocity, and morphological features were assessed.

RESULTS Indexed RVOT PLAX was greater in females than in males (15.3 $\pm$ 2.2 mm/m^2 vs. 14.4 $\pm$ 1.9 mm/m^2; $p < 0.001$). Both RVOT PLAX and parasternal short-axis view were significantly different among skill, power, mixed, and endurance sports: 14.3 $\pm$ 2.1 mm/m^2 versus 14.7 $\pm$ 1.9 mm/m^2 versus 14.0 $\pm$ 1.8 mm/m^2 versus 15.7 $\pm$ 2.2 mm/m^2, respectively ($p < 0.001$); and 15.2 $\pm$ 2.7 mm/m^2 versus 15.3 $\pm$ 2.4 mm/m^2 versus 14.8 $\pm$ 2.1 mm/m^2 versus 16.2 $\pm$ 2.5 mm/m^2, respectively ($p < 0.001$). The 95th percentile for indexed RVOT PLAX and parasternal short-axis view was 18 mm/m^2 and 20 mm/m^2, respectively. Fractional area change and s′ velocity did not differ among the groups ($p = 0.34$ for both). RV enlargement compatible with major and minor TF diagnostic criteria for arrhythmogenic RV cardiomyopathy was observed in 41 (4%) and 319 (32%) athletes. A rounded apex was described in 823 (81%) athletes, prominent trabeculations in 378 (37%) athletes, and a prominent/hyperreflective moderator band in 5 (0.5%) athletes.

CONCLUSIONS RV remodeling occurs in Olympic athletes, with male sex and endurance practice playing the major impact. A significant subset (up to 32%) of athletes exceeds the normal TF limits; therefore, we recommend referring to the 95th percentiles here reported as referral values; alternatively, only major diagnostic TF criteria for arrhythmogenic RV cardiomyopathy may be appropriate. (J Am Coll Cardiol Img 2017;10:385–93) © 2017 by the American College of Cardiology Foundation.

Cardiac remodeling associated with intensive exercise training has been identified, for many years, on the morphologic changes of the left ventricle (LV) (1-3). More recently, the awareness of the relevant role of arrhythmogenic right ventricular cardiomyopathy (ARVC) as cause of athletic field events (4) and the refined Task Force criteria for the diagnosis (5) have prompted a vast scientific literature describing RV remodeling in athletes (6-8). Interest for understanding the morphologic characteristics and clinical correlates of RV changes in athletes has been heightened by recent observations suggesting that strenuous, chronic exercise training may ultimately cause, per se, RV dysfunction (i.e., exercise-induced RV cardiomyopathy) (9-12).

Previous observations already reported that RV chamber is enlarged in athletes (6-8,13,14), and occasionally exceeds the dimensional cutoff limit

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ABBREVIATIONS AND ACRONYMS

ARVC = arrhythmogenic right ventricular cardiomyopathy

EDD = end-diastolic diameter

FAC = fractional area change

LV = left ventricular

PLAX = parasternal long-axis view

PSAX = parasternal short-axis view

RA = right atrial

RV = right ventricular

RVOT = right ventricular outflow tract

proposed by the Task Force for the diagnosis of ARVC (5). At present, however, scarce data exist regarding the normal values and upper limits of the physiologic RV remodeling in highly trained athletes, with limited observations available, usually comprising limited cohorts of athletes, engaged in a restricted number of sport (6–8,13,14).

Therefore, we planned the present study to assess the RV dimensional normal values and upper limits in a large population of Olympic athletes, to be used as referral values for highly trained individuals; and to compare these data with the widely implemented criteria proposed by the American Society of Echocardiography (15) and the Task Force criteria for the diagnosis of AVRC (5).

METHODS

STUDY DESIGN. From January 2012 to January 2014, a total of 1,016 consecutive Olympic athletes were evaluated by 2-dimensional Doppler and tissue Doppler echocardiography at the Institute of Sports Medicine and Science in Rome, as members of the Italian teams qualified for participation to the 2012 London Summer or the 2014 Sochi Winter Olympic Games.

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All athletes denied cardiac symptoms and reported negative family history for cardiomyopathies or sudden death. Seven were eventually excluded because of cardiac abnormalities (n = 4; 1 hypertrophic cardiomyopathy, 2 hypertension, 1 bicuspid aortic valve) or technically inadequate images (n = 3). Thus, the final population comprised 1,009 Olympic athletes judged free of cardiovascular disease.

The mean age was 24 ± 6 years, and 647 (64%) were males. Athletes were arbitrarily divided into 4 groups in relation to the type of sport (16): 1) skill (i.e., primarily technical disciplines [n = 277]), including golf, table tennis, equestrian, gymnastic, shooting, fencing, karate, taekwondo, and sailing; 2) power (i.e., primarily isometric disciplines [n = 216]), including weightlifting, wrestling, and short-distance running (100 to 200 m); 3) mixed disciplines (i.e., activities with isometric and isotonic components [n = 254]), including soccer, basketball, volleyball, handball, water polo, and tennis; and 4) endurance disciplines (i.e., primarily isotonic activities [n = 262]), including rowing and canoeing, swimming, long-distance running and marathon, cycling, triathlon, and pentathlon. Athletes had competed at the national level for >3 years (mean 8 ± 5 years), and were examined in our Institute during period of active training in preparation for the Olympic Games.

After the rationale and protocol of the study were explained, the participants gave their written informed consent. The study was approved by the institutional review board, and was supported by the Italian National Olympic Committee.

ECHOCARDIOGRAPHIC EXAMINATION. Echocardiographic examination was performed using an iE33 system (Philips Medical Systems, Andover, Massachusetts) equipped with an S3 probe (2 to 4 MHz). The RV chamber was assessed according to the guidelines (15); specifically, basal and mid-cavity end-diastolic diameters (EDDs), and RV length were obtained (**Figure 1**) (15). RV outflow tract (RVOT) diameter was measured at the proximal level in the parasternal long-axis (PLAX) and at subvalvular level in the parasternal short-axis (PSAX) view (15); measurements were also indexed to body surface area (17).

RV end-diastolic and RV end-systolic areas were calculated tracing endocardial contour from an RV focused apical 4-chamber view, and RV fractional area change (FAC) was obtained. An accurate assessment of the global RV function and presence of regional wall motion abnormalities was investigated (15). Tricuspid annular plane systolic excursion was measured as an index of RV longitudinal systolic function (15).

The RV basal diameter/RVOT PLAX (named hereafter RV inflow/outflow ratio) was used as an index of the symmetric/asymmetric adaptation of the RV inflow versus outflow tracts. LV EDD was calculated as recommended (18) and the RV basal diameter/LV EDD (named hereafter RV/LV ratio) was measured as an index of RV versus LV symmetric/asymmetric enlargement (15). Morphologic characterization of the RV was completed by the visual assessment of the presence of hypertrabeculation, increased reflectivity/prominence of the moderator band, and rounded-shaped apex (6,15).

Myocardial tissue Doppler imaging signals were recorded with the pulse-wave Doppler sample in the lateral tricuspid annulus as velocity of basal RV free wall excursion (s′ wave) (19).

All measurements were compared with the revised Task Force criteria for the diagnosis of ARVC, and the reference values proposed by the American Society of Echocardiography (5,15).

Specifically, referring to Task Force criteria (5), RV dilation was defined as RVOT PLAX ≥32 mm or ≥19 mm/m^2 and RVOT PSAX ≥36 mm or 21 mm/m^2, and RV dysfunction was FAC ≤33%. Notably, the echocardiographic components of the ARVC diagnostic criteria require RV dilation to be accompanied by wall-motion abnormalities. With regard to the criteria proposed by the American Society of Echocardiography, RV dilation was RVOT PLAX >33 mm and RVOT PSAX >35 mm (15), and RV dysfunction was FAC <35% (15).

STATISTICAL ANALYSES. Continuous data were expressed as mean ± SD and categorical data as frequencies, with normal distribution assessed by the Shapiro-Wilk test. The 95th percentile of RV and RA parameters were regarded as reference values for our athlete's population.

Differences between proportions were calculated by the chi-square test. Differences between male and female were evaluated with unpaired samples Student *t* test and Levene test for the equality of variance. According to the potential impact of sex on RV size (20), data were presented separately for male and female athletes.

One-way analysis of variance was used to assess differences among different sports disciplines. Univariate correlation analysis was performed to find the association between RV and LV dimensions. Statistical significance was set for a 2-tailed p value <0.05. Analysis was performed with SPSS version 22.0 (Statistical Package for the Social Sciences, Chicago, Illinois).

RESULTS

MORPHOLOGICAL AND FUNCTIONAL CHARACTERISTICS OF THE RIGHT VENTRICLE. The distribution of values for RVOT PLAX, RVOT PSAX, and FAC in the population of Olympic athletes is reported in Figure 2, with distinct values according to sex.

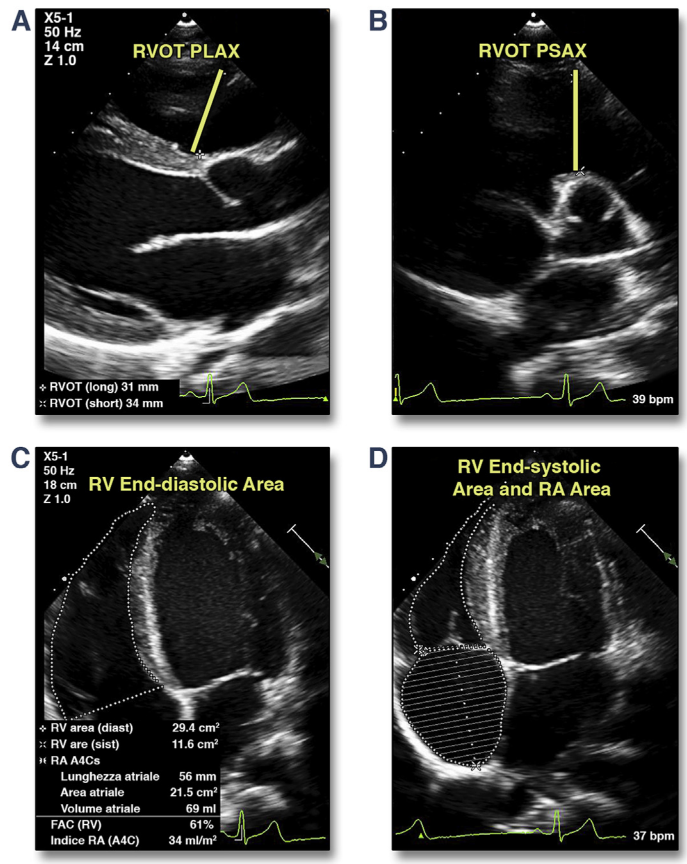
The RV morphologic characteristics according to sex are reported in Table 1. Absolute RV dimensions and right atrial (RA) size were larger in male compared with female athletes. Instead, RV functional parameters showed no differences in relation to sex.

RV morphologic and functional characteristics according to type of sport are reported in Table 2. Endurance had the greatest RV dimensions compared with the remaining athletes (p < 0.001). Specifically, RVOT dimensions, RV basal and mid-cavity diameters, and RV diastolic and systolic area showed increasing values from skill, power, mixed, or endurance sports. A similar trend was also observed for RA size.

With regard to RV functional indexes, both FAC and s′ velocity did not differ among the groups (p = 0.34 for both), with endurance athletes having the highest tricuspid annular plane systolic excursion value (p < 0.001).

RV REFERENCE VALUES IN ATHLETES. In the overall athlete's population, the 95th percentile of RV end-diastolic area was 32 cm², for end-systolic area was 17 cm², and for RA area was 25 cm². The 95th percentile for RVOT PLAX index was 18 mm/m², and for RVOT PSAX was 20 mm/m² (Figure 2).

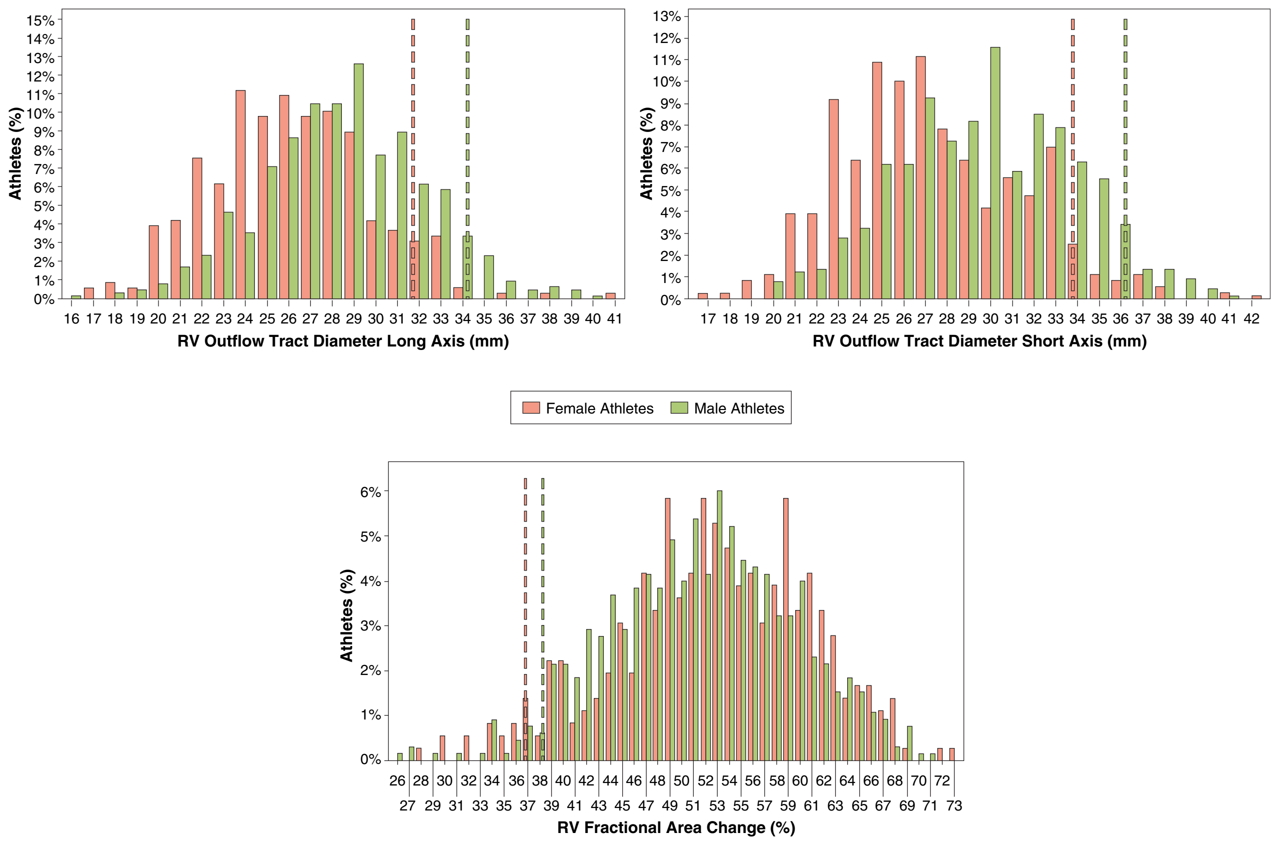
FIGURE 1 Echocardiographic Assessment of the Right Ventricle



Schematic representation of the echocardiographic measurements of the RV dimensions. **(A)** RVOT in the long-axis view (PLAX). **(B)** RVOT in the short-axis view (PSAX). **(C)** RV end-diastolic area. **(D)** RV end-systolic area and RA systolic area. PLAX = parasternal long-axis view; PSAX = parasternal short-axis view; RA = right atrial; RV = right ventricular; RVOT = right ventricular outflow tract.

When RV dimensions of the Olympic athletes were compared with clinically used cutoff values, 231 (23%) had RVOT PLAX exceeding the criteria proposed by the American Society of Echocardiography, whereas 160 (16%) and 410 (41%), respectively, fulfilled the major and minor Task Force criteria for the diagnosis of ARVD. Similarly, 61 (6%) had RVOT PSAX exceeding the criteria from the American Society of Echocardiography, whereas 61 (6%) and 299 (30%) fulfilled the major and minor criteria, respectively, for the diagnosis of ARVD (Figure 3). When indexed values for RVOT were considered, 41 (4%) and 319 (32%) had RVOT PLAX fulfilling the major and minor criteria, respectively. Similarly, 27 (3%) and 197 (20%) had RVOT PSAX fulfilling the major and minor

FIGURE 2 Distribution of RV Parameters in Male and Female Athletes



Distribution in the overall athlete's population of RV outflow tract dimensions (parasternal long-axis and short-axis views) and RV fractional area change, according to sex (**green bars** for male athletes, **pink bars** for female athletes). The 95th percentile values according to sex are shown by **dashed lines**. Abbreviation as in **Figure 1**.

criteria, respectively. Athletes exceeding the cutoff values were most frequently male and engaged in endurance disciplines.

Despite marked RV enlargement, athletes maintained normal RV systolic function, as shown by the values of tricuspid annular plane systolic excursion and s′ velocity. Moreover, none exhibited RV global dysfunction and none of the athletes with RV enlargement compatible with the diagnosis of ARVC showed RV wall-motion abnormalities. Three athletes with RV enlargement compatible with the diagnosis of ARVC showed also negative T waves from V1 to V3 or ventricular arrhythmias originating from the RVOT, even if no RV wall-motion abnormalities were found. They underwent cardiac magnetic resonance in absence of pathological findings.

CHARACTERISTIC FEATURES OF THE RIGHT VENTRICLE IN OLYMPIC ATHLETES. In terms of qualitative assessment, a rounded-shaped apex was described in 823 (81%) and prominent trabeculations in 378 (37%) athletes; a prominent or hyperreflective moderator band was found in 5 athletes (0.5%) (**Figure 4**).

The RV inflow/outflow ratio in the overall population was 1.4 ± 0.1 and, as assessed by analysis of variance, did not differ among athletes engaged in different disciplines (i.e., 1.4 ± 0.3 in endurance, 1.4 ± 0.2 in mixed, 1.4 ± 0.2 in power, and 1.4 ± 0.3 in skill sports; $p = 0.47$).

In the overall athlete's population, a significant correlation between RV EDD and LV EDD was observed ($R = 0.62$; $p < 0.001$) (**Figure 5**). The RV/LV ratio in the overall population was 0.74 ± 0.08 and did not show differences across the sport disciplines (i.e., 0.75 ± 0.09 in endurance, 0.74 ± 0.08 in mixed, 0.75 ± 0.08 in power, and 0.73 ± 0.09 in skill sports; $p = 0.21$).

DISCUSSION

RV enlargement is a common phenotypic expression and one of the criteria for the diagnosis of ARVC (5,6);

however, this finding is not uncommonly reported in other conditions, including the "athlete's heart" (6). Thus, accurate definition of the normal limits and characteristics of morphologic RV changes in athletes are relevant to distinguish the physiological from pathological RV remodeling. The present study was planned to address this issue, taking advantage of the large population of Olympic athletes consecutively evaluated at the Institute of Sport Medicine and Science with an echocardiographic protocol focused on the right heart.

The major findings of this study were: 1) a large proportion of athletes (about one-third) presented increased RV dimensions exceeding the reference values commonly used in clinical practice (5,15); 2) male sex and endurance sport were associated with the greatest extent of RV enlargement; and 3) athletes commonly exhibit peculiar morphological features, such as a rounded-shaped apex and prominent trabeculations, which may make diagnosis of the athlete's heart more complicate.

The observation that trained athletes exhibit a dimensional increase of the right chambers is not novel (6,7,21,22), but most of the previous studies were limited to the dichotomous distinction between endurance and strength-trained athletes (21,22), and have not systematically explored the RV and RA adaptations associated with intense exercise conditioning (23,24). In our large athlete's population, we observed a significant trend for an increasing enlargement of the RV (and RA) chamber in athletes, from those engaged in skill, strength, mixed, or endurance disciplines. The different extent of RV and RA remodeling across the athletic disciplines is likely an expression of the hemodynamic overload associated with the type of sport: the greater the duration and the intensity of isotonic exercise, the larger the cardiac output and higher the RV filling and ultimately the hemodynamic stimulus for dimensional increase of the RV and RA chambers.

Despite differences in morphological RV remodeling, however, RV systolic function (as indicated by FAC and s′ velocity values) remained unchanged, supporting the intrinsic physiological nature of RV remodeling observed in athletes, and providing insights for the differential diagnosis between athlete's heart and ARVC.

Although the potential influence of sex on RV size provides important information in clinical cardiology, data on the normal-sized RV are limited and recent guidelines on echocardiographic assessment of the right heart in adults lack information concerning a potential impact not only of body size, but also of sex (15). However, previous studies demonstrated that sex significantly affects the normal heart size not only in normal individuals or in subjects with cardiovascular disease (18,25,26), but also in athletes (8). In this study we confirmed that the extent of RV remodeling differs also according to sex. Indeed, although absolute values for RV size were greater in male than female athletes, the body surface area-indexed RV dimensions were relatively larger in females, consistent with previous reports (8,24). These findings suggest that sex needs to be taken into account when evaluating the right heart of an athlete.

TABLE 1 Echocardiographic Characteristics Observed in Male and Female Olympic Athletes

	Male Athletes (n = 646)	Female Athletes (n = 363)	p Value
BSA, m^2	2.0 ± 0.2 (1.67-2.31)	1.7 ± 0.2 (1.45-2.00)	<0.05
RVOT PLAX, mm	28.4 ± 3.8 (22-34)	26.1 ± 3.6 (20-32)	<0.001
RVOT PSAX, mm	29.8 ± 4.1 (23-36)	27.3 ± 4.1 (21-34)	<0.001
RVOT PLAX index, mm/m^2	14.4 ± 1.9 (11-18)	15.3 ± 2.2 (12-19)	<0.001
RVOT PSAX index, mm/m^2	15.0 ± 2.3 (12-19)	15.9 ± 2.6 (12-21)	<0.001
RV basal diameter, mm	40.6 ± 5.1 (33-49)	35.2 ± 4.8 (27-44)	<0.001
RV basal diameter index, mm/m^2	20.5 ± 2.7 (16-26)	20.5 ± 2.8 (17-25)	0.95
RV mid-cavity diameter, mm	27.3 ± 4.7 (20-35)	23.9 ± 4.2 (18-31)	<0.001
RV mid-cavity diameter index, mm/m^2	13.8 ± 2.5 (10-18)	14.0 ± 2.4 (10-18)	0.23
RV longitudinal diameter, mm	89.4 ± 8.7 (76-104)	79.0 ± 9.3 (64-95)	<0.001
RV longitudinal diameter index, mm/m^2	45.2 ± 5.0 (37-56)	46.2 ± 5.6 (38-53)	0.001
RV diastolic area, cm^2	25.1 ± 4.7 (18-33)	19.3 ± 3.9 (14-27)	<0.001
RV diastolic area index, cm^2/m^2	12.6 ± 2.2 (8-15)	11.3 ± 2.1 (9-16)	<0.001
RV systolic area, cm^2	12.1 ± 3.1 (7-18)	9.0 ± 2.5 (5-14)	<0.001
RV systolic area index, cm^2/m^2	6.1 ± 1.5 (3-8)	5.3 ± 1.4 (4-9)	<0.001
Fractional area change, %	52.0 ± 7.8 (39-65)	53.4 ± 8.4 (38-66)	0.034
TAPSE, mm	24.5 ± 3.8 (19-31)	23.9 ± 3.3 (19-30)	0.006
s′, cm/s	14.8 ± 2.2 (12-19)	14.2 ± 1.9 (11-17)	<0.001
RA area, cm^2	18.9 ± 3.6 (14-25)	14.8 ± 3.4 (10-20)	<0.001
LV end-diastolic diameter, mm	54.1 ± 3.7 (48-60)	48.8 ± 3.3 (44-54)	<0.001
LV ejection fraction, %	65 ± 6 (56-75)	67 ± 6 (57-77)	<0.001

Values are mean ± SD (5th-95th percentile).

BSA = body surface area; LV = left ventricular; PLAX = parasternal long-axis view; PSAX = parasternal short-axis view; RV = right ventricular; RVOT = right ventricular outflow tract; TAPSE = tricuspid annular plane systolic excursion.

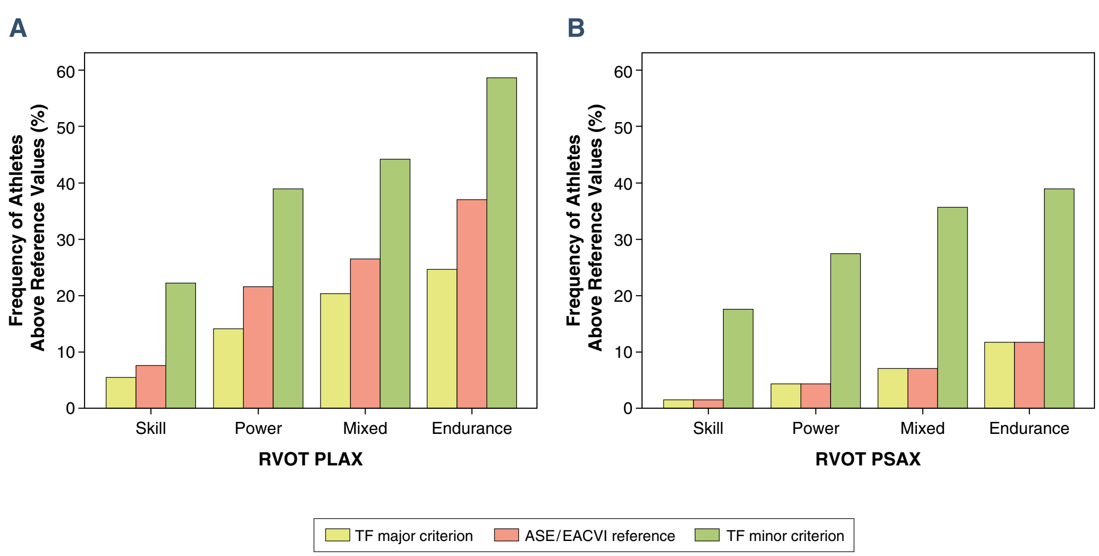
TABLE 2 Echocardiographic Characteristics Observed in Olympic Athletes According to the Discipline Practiced

	Skill (n = 277)	Power (n = 216)	Mixed (n = 254)	Endurance (n = 262)	p Value
BSA, m^2	1.8 ± 0.2	1.9 ± 0.2	2.0 ± 0.2	1.9 ± 0.2	<0.001
RVOT PLAX, mm	25.8 ± 3.5	27.4 ± 3.8	28.1 ± 3.6	29.2 ± 3.8	<0.001
RVOT PSAX, mm	27.4 ± 3.9	28.6 ± 4.2	29.5 ± 4.4	30.1 ± 4.2	<0.001
RVOT PLAX index, mm/m^2	14.3 ± 2.1	14.7 ± 1.9	14.0 ± 1.8	15.7 ± 2.2	<0.001
RVOT PSAX index, mm/m^2	15.2 ± 2.7	15.3 ± 2.4	14.8 ± 2.1	16.2 ± 2.5	<0.001
RV basal diameter, mm	36.4 ± 5.6	38.5 ± 5.7	39.4 ± 5.1	40.4 ± 5.3	<0.001
RV basal diameter index, mm/m^2	20.1 ± 2.6	20.7 ± 2.6	20.0 ± 2.5	21.7 ± 3.0	<0.001
RV mid-cavity diameter, mm	24.7 ± 5.1	26.0 ± 4.9	26.8 ± 4.5	26.8 ± 4.5	<0.001
RV mid-cavity diameter index, mm/m^2	13.7 ± 2.6	14.0 ± 2.5	13.4 ± 2.3	14.4 ± 2.4	<0.001
RV longitudinal diameter, mm	82.3 ± 10.2	84.5 ± 10.7	87.5 ± 8.7	88.5 ± 10.1	<0.001
RV longitudinal diameter index, mm/m^2	45.5 ± 5.5	45.4 ± 5.1	43.7 ± 4.5	47.5 ± 5.1	<0.001
RV diastolic area, cm^2	21.2 ± 5.3	22.6 ± 5.2	23.7 ± 4.6	24.7 ± 5.2	<0.001
RV diastolic area index, cm^2/m^2	11.6 ± 2.3	12.1 ± 2.2	11.8 ± 1.9	13.1 ± 2.3	<0.001
RV systolic area, cm^2	10.1 ± 3.2	10.8 ± 3.4	11.4 ± 3.0	11.7 ± 3.3	<0.001
RV systolic area index, cm^2/m^2	5.5 ± 1.5	5.8 ± 1.5	5.7 ± 1.3	6.3 ± 1.6	<0.001
Fractional area change, %	53.1 ± 8.2	52.4 ± 8.9	51.9 ± 7.5	52.5 ± 7.6	0.34
TAPSE, mm	23.7 ± 3.3	24.1 ± 3.7	24.1 ± 3.5	25.1 ± 3.9	<0.001
s′, cm/s	14.5 ± 2.1	14.4 ± 2.0	14.7 ± 2.3	14.7 ± 2.1	0.21
RA area, cm^2	15.6 ± 3.7	17.1 ± 3.9	18.1 ± 3.7	19.0 ± 4.0	<0.001

Values are mean ± SD.
Abbreviations as in Table 1.

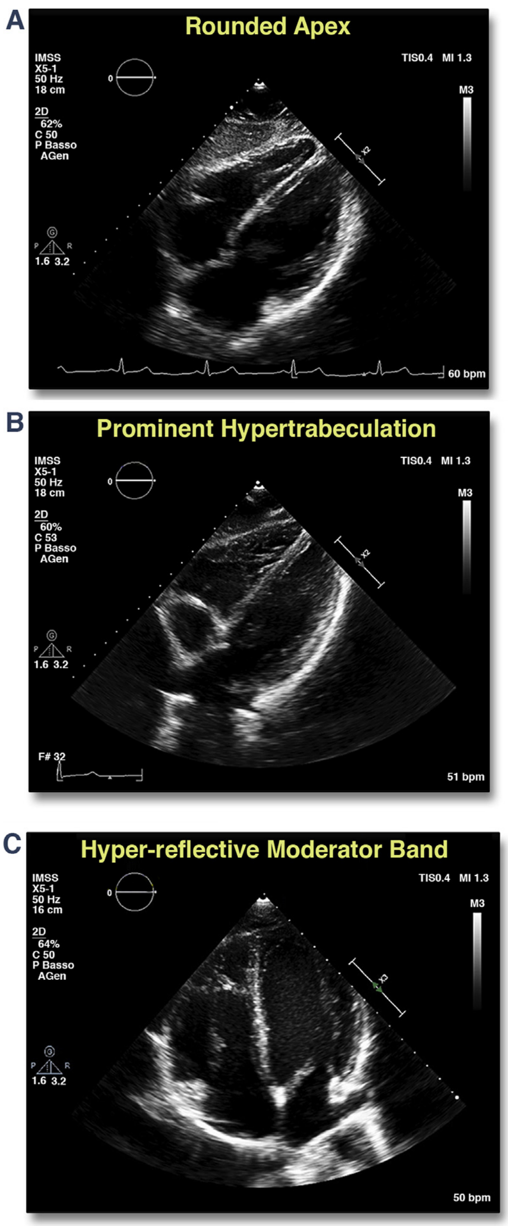
We assessed the ratio of RV inflow to outflow tract, as an index of a symmetric remodeling of the right chamber, and we observed that this ratio does not change in athletes, irrespective of the extent of the remodeling. At difference, ARVC patients often present a disproportionate dilation of the RVOT (6); thus, RVOT size may represent, per se, a criterion to differentiate ARVC from athlete's heart; a

FIGURE 3 Athletes Exceeding the Normal Cutoff Values for the Right Ventricle



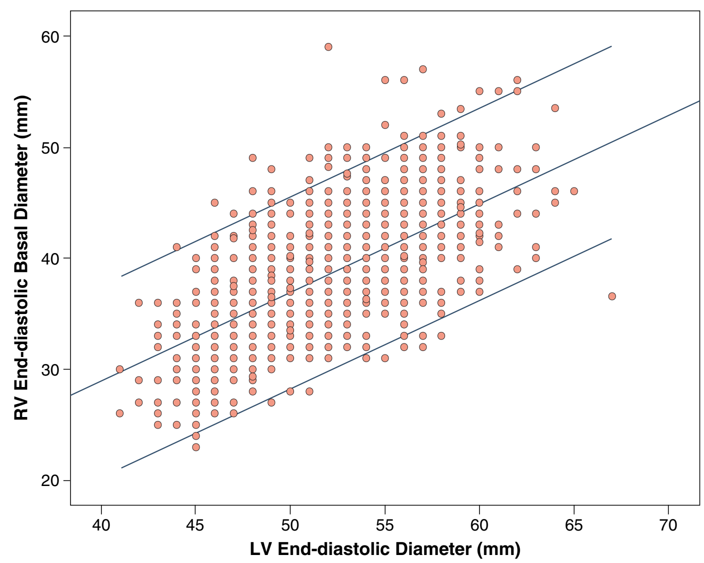
Proportion of Olympic athletes meeting the criteria of RV enlargement according to the reference of normality recommended by the American Society of Echocardiography (15), and fulfilling the minor and major echocardiographic dimensional criteria for the diagnosis of arrhythmogenic right ventricular cardiomyopathy (5). **(A)** RVOT diameter measured in PLAX. **(B)** RVOT diameter measured in PSAX. ASE = American Society of Echocardiography; EACVI = European Association of Cardiovascular Imaging; TF = Task Force; other abbreviations as in Figure 1.

FIGURE 4 Morphological Features of the Right Ventricle in Athletes



Representation of certain right ventricular morphological peculiarities observed in Olympic athletes: **(A)** rounded apex, **(B)** hypertrabeculation, and **(C)** hyperreflective moderator band.

FIGURE 5 Correlation Between RV and LV Size



Linear correlation between RV basal end-diastolic diameter and LV end-diastolic diameter in the overall population of Olympic athletes. LV = left ventricular; other abbreviation as in Figure 1.

disproportionate RVOT enlargement is unlikely to represent a physiologic RV adaptation to training and more likely suggests a pathological enlargement in the context of the ARVC.

The RV remodeling occurs in athletes in association with LV remodeling (8,24,27–29), as supported by the positive linear correlation we observed between the RV and LV size. Our findings suggest the occurrence of a balanced, symmetric RV and LV cavity enlargement in athletes. Furthermore, we demonstrated for the first time that the balanced biventricular remodeling does not differ among athletes practicing different sports disciplines and that the RV/LV ratio is not influenced by the type of sport. A practical implication is the concept that a disproportionate increase, either the RV or LV cavity, should instinctively suggest a nonphysiological remodeling. To this regard, a RV/LV ratio <0.9 has been recently proposed as a parameter to distinguish between RV physiological remodeling and ARVC (30). In a large population of highly trained athletes we found a RV/LV ratio of 0.74 ± 0.08 with a 95% confidence interval of 0.73 to 0.75, with a RV/LV ratio <0.73 indicating a disproportional remodeling in favor of a dilation of the LV and a RV/LV ratio >0.75 indicating a disproportional remodeling in favor of a dilation of the RV, in highly trained athletes. We therefore suggest using this ratio as an additional parameter to interpret RV enlargement in borderline cases.

When compared with the widely used morphologic cutoff of normalcy for RV, we observed that a small proportion of athletes (up to 4%) exceed the major criteria for the diagnosis of ARVC (5). Conversely, a significant proportion (up to 32%) fulfilled the minor criteria currently proposed for the diagnosis of ARVC (5) and a large subset (up to 23%) exceeded the reference values for RV enlargement proposed by the American Society of Echocardiography (15). Therefore, we recommend not applying the conventional criteria of RV enlargement from the American Society of Echocardiography in top-level athletes, but referring to the 95th percentile values that we derived in our large cohort of top-level athletes (**Figure 2**), or alternatively only to the major Task Force criteria normalized to body surface area (15).

Interestingly, reduction in RV function (i.e., FAC <33%) was rarely found in our cohort of healthy athletes (2% when using the reference value from the American Society of Echocardiography and 1% when using major Task Force for ARVC). However, none of these athletes presented other indicators of RV dysfunction, either reduced systolic peak velocity at tissue Doppler imaging or segmental wall-motion abnormalities.

Finally, we found that a large proportion of Olympic athletes exhibited peculiar morphological characteristics, such as a more rounded-shaped RV apex, prominent RV trabeculations, and/or a hyperreflective moderator band, which likely represent the epiphenomena of the hemodynamic overload induced by intensive and chronic exercise. Although these findings could complicate the correct diagnosis of athlete's heart in the presence of a marked RV enlargement, we believe that these morphological findings in the absence of symptoms, family history of sudden cardiac death, or segmental RV wall abnormalities represent just a benign variant of the physiologic RV remodeling.

STUDY LIMITATIONS. This study was conducted in a Caucasian population of athletes. Although this represents a limitation, the ethnicity was proven not to affect RV remodeling (8). Therefore, the present population can be considered representative of most Olympic athletes. Conversely, according to the high level of physical conditioning exhibited by Olympic athletes, the represented results cannot be extended to other nonathletic populations, such as noncompetitive or amateur athletes.

Finally, the assessment of RV morphology and function was performed by 2-dimensional echocardiography. Although this is the tool commonly used in clinical practice, cardiac magnetic resonance remains the gold standard technique to evaluate the RV.

CONCLUSIONS

RV morphologic remodeling is common in Olympic athletes, with male sex and endurance disciplines playing the major impact on the extent of morphological changes. A significant subset of athletes exceed the reference dimensional limits proposed for the diagnosis of ARVC; therefore, we suggest using the 95th percentile value derived from our Olympic athletes as referral values, or alternatively to refer uniquely to the major diagnostic criteria of ARVC.

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PERSPECTIVES

COMPETENCY IN MEDICAL KNOWLEDGE: The impact of sex and different sports on RV remodeling has now been demonstrated in a large cohort of highly trained athletes. We found that male sex and endurance type of sport are associated with the greatest impact on RV remodeling, suggesting that these are the main characteristics to be taken into account when assessing the RV in highly trained athletes.

COMPETENCY IN PRACTICE-BASED LEARNING: The upper limits of RV dimensions derived by the present cohort of highly trained athletes were compared with the widely used Task Force major and minor criteria to diagnose ARVC, one of the leading causes of sudden cardiac death in young athletes. A significant subset of athletes exceeds the reference dimensional limits used in the general population to diagnose ARVC. However, no RV wall-motion abnormalities were observed in trained athletes. When evaluating highly trained athletes we suggest using the 95th percentile value derived from our Olympic athletes as referral dimensional values.

TRANSLATIONAL OUTLOOK: Contrary to the objectivity of dimensional parameters, the inherent subjectivity of the visual assessment of RV wall-motion abnormalities remains the major limitation in clinical practice for evaluating RV remodeling. Future studies should evaluate the sensitivity and specificity of novel echocardiographic techniques (i.e., speckle-tracking echocardiography) to raise timely suspicion of ARVC in trained athletes presenting increased RV dimensions. Finally, longitudinal observational studies are needed to understand the ultimate clinical significance of the RV remodeling in trained athletes.

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