Physiological Right Ventricular Adaptation in Elite Athletes of African and Afro-Caribbean Origin

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Background—Regular, intensive exercise results in physiological biventricular cardiac adaptation. Ethnicity is an established determinant of left ventricular remodeling; black athletes (BAs) exhibit more profound LV hypertrophy than white athletes (WAs). Right ventricular (RV) remodeling has not been characterized in BAs, although the issue is pertinent because BAs commonly exhibit ECG anomalies that resemble arrhythmogenic RV cardiomyopathy.

Methods and Results—Between 2006 and 2012, 300 consecutive BAs (n=243 males) from 25 sporting disciplines were evaluated by use of ECG and echocardiography. Results were compared with 375 WAs and 153 sedentary control subjects (n=69 blacks). There were no ethnic differences between RV parameters in control subjects. Both BAs and WAs exhibited greater RV dimensions than control subjects. RV dimensions were marginally smaller in BAs than in WAs (proximal outflow tract, 30.9±5.5 versus 32.8±5.3 mm, P<0.001; longitudinal dimension, 86.6±9.5 versus 89.8±9.6 mm, P<0.001), although only 2.3% of variation was attributable to ethnicity. RV enlargement compatible with diagnostic criteria for arrhythmogenic RV cardiomyopathy was frequently observed (proximal outflow tract ≥32 mm; 45.0% of BAs, 58.5% of WAs). Anterior T-wave inversion was present in 14.3% of BAs versus 3.7% of WAs (P<0.001). Marked RV enlargement with concomitant anterior T-wave inversion was observed in 3.0% of BAs versus 0.3% of WAs (P=0.005). Further investigation did not diagnose arrhythmogenic RV cardiomyopathy in any athlete.

Conclusions—Physiological RV enlargement is commonly observed in both black and white athletes. The impact of ethnicity is minimal, which obviates the need for race-specific RV reference values. However, in the context of frequent ECG repolarization anomalies in BAs, the potential for erroneous diagnosis of arrhythmogenic RV cardiomyopathy is considerably greater in this ethnic group. (Circulation. 2013;127:1783-1792.)

Key Words: cardiomyopathy ■ echocardiography ■ electrocardiographic screening ■ ethnicity ■ exercise

Individuals engaging in regular, intensive sporting activity demonstrate a constellation of electric and structural cardiac alterations that are collectively described as the “athlete’s heart.” Although such training-induced changes are generally considered physiological and benign,1,2 they may occasionally overlap with phenotypic features of inherited cardiomyopathies, in which vigorous exercise is associated with an increased risk of sudden cardiac death (SCD).3 Consequently, athletic remodeling of the left side of the heart has been studied extensively, driven by the requirement for rigorous clinical algorithms to differentiate between physiological left ventricular (LV) remodeling and hypertrophic cardiomyopathy.4

In contrast, the athlete’s right ventricle (RV) has been relatively neglected. Limited data in white athletes indicate that the RV is subject to the same preload as the LV during exercise and exhibits structural and functional adaptation in synergy with the left side of the heart.5,6 As such, physiological remodeling of the athlete’s RV may mimic changes observed in arrhythmogenic right ventricular cardiomyopathy (ARVC),7 which is responsible for as many as 22% of SCDs in young athletes in Europe.7,8

The magnitude of athletic cardiac remodeling is dependent on a variety of demographic and sport-specific variables; large, adult male athletes engaging in endurance sports generally exhibit the greatest dimensions.7 Athletes of African and Afro-Caribbean origin (black athletes [BAs]) develop more profound LV hypertrophy than their white counterparts (white athletes [WAs]). This is responsible for as many as 22% of SCDs in young athletes in Europe.7,8

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The influence of ethnicity on athletic RV remodeling has never been characterized, even though healthy BAs frequently reveal ECG repolarization anomalies that resemble those observed in ARVC. Furthermore, BAs comprise a growing number of elite sports participants worldwide, and for reasons that remain incompletely understood, they demonstrate greater risk of sports-related SCD than WAs. The aim of the present study was to assess the impact of ethnicity on structural remodeling of the RV in athletes and to delineate the overlap between the black athlete’s heart and ARVC.

Methods

Athletes

Between 2006 and 2012, 675 consecutive athletes competing at the regional, national, or international level underwent preparticipation cardiovascular evaluation by means of a health questionnaire, physical examination, ECG, and 2-dimensional echocardiography. The cohort was aged between 14 and 35 years, and 44% of athletes (n=300) were black. All participants provided written consent, and ethical approval was obtained from the local research ethics committee. Black ethnicity was determined through a self-reported questionnaire that included terms such as black African, black Afro-Caribbean, and black British. Athletes with any previous history of cardiac or pulmonary disease, systemic hypertension, diabetes mellitus, anabolic steroid use, family history of cardiomyopathy, or family history of premature (≤40 years) SCD were excluded from the study. Athletes with echocardiographic evidence of intracardiac shunting or valvular heart disease were also excluded.

Sporting disciplines were categorized as predominantly endurance or strength. Endurance sports were defined as those typically resulting in >70% of maximal oxygen uptake (VO2max) and included badminton, basketball, boxing, canoeing, cycling, handball, hockey, long-distance running, middle-distance running, rowing, soccer, speed-skating, squash, swimming, tennis, and triathlon. All other sports were categorized as strength disciplines (cricket, diving, gymnastics, rugby, sailing, taekwondo, volleyball, water polo, and weightlifting). A prespecified subgroup of athletes engaging in sports that typically use >70% of VO2max, in concert with >50% of maximal voluntary muscle contraction (high dynamic, high static [HD-HS]) was also defined for study, because this group has previously been demonstrated to exhibit the most profound physiological LV remodeling. The HD-HS category included boxing, canoeing, cycling, rowing, speed-skating, and triathlon.

Control Subjects

In the United Kingdom, the charitable organization Cardiac Risk in the Young offers cardiovascular evaluation to any young individual (14–35 years) wishing to be tested, irrespective of athletic status, aimed at detecting conditions predisposing to SCD. The protocol comprises a health questionnaire, physical examination, and 12-lead ECG. As part of the recruitment of healthy control subjects for the present study, we offered all individuals attending for evaluation an onsite echocardiogram. The primary criterion for inclusion as a control subject was a sedentary lifestyle (≤2 hours of organized physical activity per week). Exclusion criteria were identical to those applied in athletes. The final cohort comprised 84 white control subjects and 69 black control subjects.

Twelve-Lead ECG

A standard 12-lead ECG was performed with the subject in the supine position with either a MAC 5000 or MAC 5500 digital resting ECG recorder (GE Medical Systems, Milwaukee, WI) as described elsewhere. Measurements were made with calipers. LV hypertrophy and RV hypertrophy were defined according to the Sokolow-Lyon voltage criteria (LV hypertrophy, SV1+RV5/6>3.5 mV; RV hypertrophy, SV1+RV5/6>1.05 mV). T-wave inversion (TWI) −0.1 mV or greater in ≥2 contiguous leads was considered significant. Deep TWI was defined as greater than or equal to −0.2 mV. Leads V1 through V6 were subclassified as anterior precordial leads. ST-segment shift was considered significant if ≥0.1 mV in ≥2 contiguous leads. Partial right bundle-branch block was defined as QRS duration >100 ms but <120 ms, with rSR′ morphology in lead V1 and QRs in V6. Additional ECG markers compatible with ARVC were also sought, including terminal activation duration of the QRS complex ≥255 ms in leads V1, V5, or V6, and the epsilon (ε) wave. Transthoracic Echocardiography

Echocardiographic examinations were performed with the subject at rest, in the left lateral decubitus position, with the following commercially available ultrasound systems: Vivid-I (GE Healthcare, Milwaukee, WI), CX50, or iE33 (Philips Medical, Bothel, WA). A complete echocardiographic study of the left and right sides of the heart was performed according to current guidelines from the European Society of Cardiology and the American Society of Echocardiography. All measurements were recorded as absolute values and were also indexed to body surface area (BSA) according to the DuBois and DuBois formula. Echocardiographic studies were saved to compact discs as numeric files to generate anonymity, and cardiac measurements were repeated independently by an experienced cardiologist (A.Z.) blinded to the identity of the athlete. Detailed RV assessment was performed as demonstrated in Figure 1. All measurements were made from end-diastolic frames acquired with the breath held in end-expiration, unless stated otherwise. RV outflow tract (RVOT) diameter was measured in the parasternal long-axis view from the RV free wall to the aortic annulus, perpendicular to the interventricular septum. Two measurements of RVOT diameter were made in the parasternal short-axis view: from the RV free wall to the anterior aortic wall (RVOT1) and immediately proximal to the pulmonary valve (RVOT2). The apical 4-chamber view was modified by adjusting the echocardiography probe to optimize RV size (RV-focused apical view). RV basal (RV1), midcavity (RV2), and longitudinal (RV3) diameters were assessed. Planimetry was used to trace right atrial area at the end of ventricular systole, RV end-diastolic area (RVEDA), and RV end-systolic area. Trabeculations were included within cavity measurements. RV end-diastolic free wall thickness was measured in the focused subcostal view. RV systolic function was assessed by tricuspid annular plane systolic excursion, tissue Doppler-derived RV peak systolic velocity (RV S′), and RV fractional area change. RV diastolic function was assessed as the ratio between pulsed-wave Doppler-derived early and late inflow velocities across the tricuspid valve (tricuspid E/A), as well as tissue Doppler-derived RV early myocardial relaxation velocity (RV E′). Pulmonary artery systolic pressure was estimated from the peak tricuspid regurgitant jet velocity. RV regional wall-motion abnormalities (WMAs) were defined as akinetic, dyskinetic, or aneurysmal, in accordance with diagnostic criteria for ARVC. BSA-indexed values are reported with the suffix “-i.”

Further Evaluation

Subjects exhibiting ECG or echocardiographic features compatible with an underlying cardiomyopathy were invited to undergo detailed assessment for broader phenotypic features of inherited cardiac disease. Specific triggers for referral were TWI in ≥2 contiguous leads in subjects ≥14 years of age, the presence of an ε-wave, or RV WMAs at echocardiography. Athletes deemed to exhibit excessive LV hypertrophy (males with LVWT >14 mm; females with LVWT >11 mm) were assessed further to exclude hypertrophic cardiomyopathy. Additional investigations included 24-hour Holter monitoring, maximal exercise stress test, signal-averaged ECG, and cardiac magnetic resonance imaging (cMRI) with gadolinium administration.

Holter Monitoring

Twenty-four-hour ambulatory ECG recording (Lifecard CF Holters, Spacelabs Healthcare, Issaquah, WA) was used to detect ventricular arrhythmias. Subjects were encouraged to continue day-to-day activities, including exercise during monitoring.
Exercise Stress Testing

Upright treadmill stress testing was performed with the standard Bruce protocol.21 Athletes were exercised to volitional exhaustion and assessed specifically for the development of ischemic changes, attenuated blood pressure response, or arrhythmias.

Signal-Averaged ECG

Signal-averaged ECG was acquired according to accepted methodology with the same machines used for standard electrocardiography, with use of a 40-Hz high-pass bidirectional filter.22 Late potentials were defined as abnormal values in ≥1 of the following parameters (in accordance with current diagnostic criteria for ARVC):16 (1) duration of filtered QRS complex >114 ms (with QRS duration <110 ms on standard ECG), (2) duration of terminal QRS (with amplitude <40 μV) >38 ms, and (3) root-mean-square voltage of the terminal 40 ms of filtered QRS <20 μV.

Cardiac MRI

cMRI was performed with a Philips Achiever 3.0T TX (Amsterdam, Netherlands) scanner. Late gadolinium enhancement images were acquired 10 minutes after administration of intravenous gadolinium-DTPA ("Guerbet Dotarem," Obex Medical Limited, Auckland, New Zealand; 0.2 mmol/kg) with an inversion-recovery gradient echo sequence. Ventricular volumes and function were measured for both ventricles by standard techniques and analyzed with semiautomated software (Extended MR workspace, Philips, Amsterdam, Netherlands).23 All measures were indexed to BSA.

Statistical Analysis

The Kolmogorov-Smirnov test was used to assess normality of distributions. Values are expressed as mean±SD or percentages, as appropriate. Group differences were tested with 1-way ANOVA (with Sidak’s post hoc test) or the Kruskal-Wallis test (with Dunn’s post hoc test). The χ² test or Fisher exact test was used to test proportional differences between groups. Two-way ANOVA with interaction was used to assess the relative impacts of exercise and ethnicity on RV dimensions. Multivariable linear regression models were subsequently constructed to identify determinants of RV dimensions among athletes. RVOT1 and RVEDA were selected as dependent variables on the basis of evidence of high reproducibility and correlation with cMRI-derived RV volumes in athletes.24 Independent variables were selected on the basis of associations with LV or RV size in previous studies of athletes (age, sex, BSA, endurance sports, HD-HS sports, ethnicity, training intensity, LV end-diastolic diameter, LV mass index, pulmonary artery systolic pressure, and partial or complete right bundle-branch block).5,6,11,24,26,27 Nonspecific ECG markers of pathology were also entered into analyses (left- and right-axis deviation, LV hypertrophy, RV hypertrophy, any TWI, and anterior TWI). Reproducibility of RV measurements was assessed with intraclass correlation coefficient analysis and reported as intraclass correlation coefficient (95% confidence interval [CI]). Upper reference values for RV dimensions were calculated as mean+2 SD. All analyses were performed with SPSS software, version 17 (Chicago, IL). A 2-tailed probability value <0.05 was considered to indicate significance.

Results

Subjects

None of the study participants reported symptoms suggestive of underlying cardiovascular pathology or a family history of premature SCD or cardiomyopathy. All subjects were normotensive (blood pressure ≤120/80 mm Hg). All 4 groups (BAs, WAs, black control subjects, and white control subjects) were of similar age and sex (Table 1). BAs trained for fewer hours per week than WAs (16.5±6.1 versus 20.3±7.0 h/wk, P<0.001). Athletes competed in a total of 25 different sports. A similar proportion of BAs and WAs competed in endurance disciplines (73.0% versus 68.8%, P=0.23), although fewer BAs than WAs competed in HD-HS sports (6.0% versus 27.2%, P<0.001).

ECG Findings

Athletes exhibited lower resting heart rates and more frequent RV hypertrophy by voltage criterion than control subjects (Table 1). ST-segment elevation was more prevalent in BAs compared with WAs (73.7% versus 61.0%, P<0.001). TWI
Anterior TWI in BAs was preceded by convex ST-segment elevation in 35 (81.4%) of 43 cases. Only 2 (4.7%) of 43 cases revealed preceding isoelectric segments, and none revealed preceding ST-segment depression. None of the study subjects demonstrated an ε-wave or terminal QRS activation delay in the anterior precordial leads.

Left-Sided Cardiac Dimensions and Function
Athletes of both ethnicities exhibited greater values for left atrial area, LV end-diastolic dimension, and LV mass index than control subjects (Table 1). There were no significant differences between BAs and WAs with respect to any structural or functional parameters of the left side of the heart. There was a trend toward a greater maximal LVWT in BAs, which did not achieve statistical significance (BAs, 10.2±1.5 mm versus WAs, 10.0±1.3 mm; P=0.058). The range of LVWT values in BAs was 7 to 16 mm compared with 6 to 14 mm in WAs. A greater proportion of BAs than WAs exhibited a maximal LVWT that exceeded 12 mm (7.8% versus 2.9%, P=0.007).

Right-Sided Cardiac Dimensions and Function
All groups revealed normal RV systolic and diastolic function, end-diastolic wall thickness, and pulmonary artery systolic pressure (Table 1). There were no baseline differences in RV
linear or area measurements between black control subjects and white control subjects. Athletes exhibited greater values for right atrial area, RVEDA, and all RV linear dimensions than control subjects of the same ethnicity. Athletes demonstrated significantly lower values for RVD3 and all 3 measures of RVOT dimension (parasternal long-axis view, RVOT1, and RVOT2). There were no ethnic differences between athletes with respect to right atrial area, RVEDA, RVD1, and RVD2. Absolute values for all RV and RA parameters were greater in male than female athletes (Table 2). BSA-indexed RV dimensions were, however, generally larger in female athletes, a phenomenon that has been reported previously.28 Apparent RV WMAs were observed in 8 athletes (BAs, n=4; WAs, n=4) but none of the control subjects. All 8 cases manifested as an akinetic segment confined to the RV apex, apparent only in the apical 4-chamber view.

Subsequent Investigations
A total of 110 athletes revealed features at initial evaluation that warranted further investigation to exclude a cardiomyopathy (TWI, n=67; apparent RV WMA, n=8; echocardiographic LV hypertrophy, n=18; TWI and echocardiographic LV hypertrophy, n=17). Of these, 14 athletes (12.7%) declined investigation or attended other cardiac institutions for assessment. A further 25 athletes (22.7%) did not undergo cMRI. The remaining 71 athletes (64.5%) were investigated comprehensively. None of the athletes exhibited cardiovascular symptoms, arrhythmias, or attenuated blood pressure response during exercise; >500 ventricular extrasystoles or nonsustained ventricular tachycardia during Holter monitoring36, or evidence of RV WMA or delayed gadolinium enhancement at cMRI. The mean ratio of LV end-diastolic volume to RV end-diastolic volume in athletes subjected to cMRI was 0.94±0.09. This figure is similar to that reported in previous studies of both athletes and sedentary control subjects, which suggests a balanced biventricular response to training.38 Of the athletes who were subjected to signal-averaged ECG, 17.8% exhibited 1 or more abnormal parameters (1 parameter, 11.5%; 2 parameters, 4.2%; 3 parameters, 2.1%). The majority of abnormal signal-averaged ECG findings consisted of filtered QRS prolongation (60.0%), a phenomenon that has been reported previously in healthy athletes.7,29 The above investigations did not result in a diagnosis of ARVC in any athlete.

Comparison of ECG and Echocardiography Data With ARVC Diagnostic Criteria
RV enlargement compatible with diagnostic criteria for ARVC was frequently observed in athletes of both ethnicities (Figures 2 and 3). However, ECG criteria were observed with far greater frequency in BAs than WAs (Table 3). Consequently, 3.0% of BAs and only 0.3% of WAs exhibited marked RV dilatation with concomitant TWI in leads V1 through V3, compatible with 2 major diagnostic criteria for ARVC. None of the 4 WAs with apparent RV WMA fulfilled ECG criteria for

| Table 2. Comparison of Echocardiographic Right Ventricular Measurements in Athletes According to Sex, Ethnicity, and Body Surface Area |
|-----------------------------------------------|-----------------|-------------------|------------------|-------------------|-------------------|
| Black Male Athletes (n=243)                    | Black Female Athletes (n=57) | White Male Athletes (n=301) | White Female Athletes (n=74) |      |
| RAA, cm²                                      | 19.4±3.9        | 14.4±3.1           | 19.5±4.5          | 17.1±4.0          | <0.001*§         |
| RVEDA, cm²                                    | 28.4±4.8        | 21.6±3.8           | 28.8±5.5          | 24.1±4.2          | <0.001*§         |
| RVOTP, mm                                     | 29.2±4.7        | 26.7±3.8           | 30.6±4.7          | 29.9±4.0          | <0.001*         |
| RVOT1, mm                                     | 31.6±5.5        | 28.1±4.5           | 33.1±5.3          | 31.5±4.9          | <0.001*‡        |
| RVOT2, mm                                     | 23.3±3.7        | 21.2±3.2           | 24.8±4.4          | 22.4±3.4          | <0.001*§        |
| RVD1, mm                                      | 44.0±5.4        | 38.0±4.1           | 43.4±5.6          | 40.4±4.7          | <0.001*§        |
| RVD2, mm                                      | 36.5±5.7        | 31.3±5.1           | 35.3±5.0          | 33.5±4.7          | <0.001*‡        |
| RVD3, mm                                      | 88.2±8.9        | 79.8±8.7           | 90.7±9.9          | 86.4±6.6          | <0.001*§        |
| RW1T, mm                                      | 4.2±1.0         | 3.7±0.9            | 4.0±1.0           | 3.7±0.8           | <0.001*         |
| RAA-i, cm²/m²                                 | 9.6±1.8         | 8.6±1.8            | 9.9±2.0           | 9.5±2.1           | <0.001*‡        |
| RVEDA-i, cm²/m²                               | 14.1±2.3        | 12.7±2.2           | 14.6±2.5          | 13.4±2.3          | <0.001*§        |
| RVOTP-i, mm/m²                                | 14.5±2.3        | 16.0±2.2           | 15.5±2.3          | 16.7±2.4          | <0.001*§        |
| RVOT1-i, mm/m²                                | 15.7±2.8        | 16.5±2.8           | 16.9±3.0          | 17.6±2.9          | <0.001‡         |
| RVOT2-i, mm/m²                                | 11.6±1.8        | 12.6±1.9           | 12.7±2.4          | 12.5±1.9          | <0.001*‡        |
| RVD1-i, mm/m²                                 | 21.9±2.9        | 22.3±2.4           | 22.1±2.8          | 22.5±2.7          | 0.38            |
| RVD2-i, mm/m²                                 | 18.1±3.2        | 18.4±3.5           | 18.0±2.8          | 18.7±2.9          | 0.24            |
| RVD3-i, mm/m²                                 | 43.7±5.0        | 47.4±5.7           | 46.0±5.4          | 48.1±4.0          | <0.001*‡        |

RAA indicates right atrial area; RVEDA, right ventricular end-diastolic area; RVD1, right ventricular basal dimension; RVD2, right ventricular midventricular dimension; RVD3, right ventricular longitudinal dimension; RVOTP, right ventricular outflow tract dimension (parasternal); RVOT1, proximal right ventricular outflow tract dimension; RVOT2, distal right ventricular outflow tract dimension; and RW1T, right ventricular free wall thickness. The suffix “-i” indicates that the value has been indexed to body surface area.

*Statistically significant between black males and black females.
†Statistically significant between black males and white males.
‡Statistically significant between black females and white females.
§Statistically significant between white males and white females.
ARVC. In contrast, 2 of the 4 BAs with apparent RV WMA also revealed marked RVOT dilatation and concomitant TWI in leads V1 through V4, a combination that would have been sufficient to secure a diagnosis of ARVC in both athletes, although subsequent cMRI did not support the existence of RV WMA in either case.

Reproducibility of RV Measurements
RV measurements were highly reproducible at both the interobserver and intraobserver level. Interobserver intraclass correlation coefficients were as follows: right atrial area, 0.93 (0.82–0.97); RVEDA, 0.95 (0.80–0.99); RVOT1, 0.94 (0.78–0.98); and RVD1, 0.87 (0.68–0.95). Intraobserver intraclass correlation coefficients were as follows: right atrial area, 0.94 (0.85–0.98); RVEDA, 0.97 (0.93–0.99); RVOT1, 0.94 (0.78–0.98); and RVD1, 0.93 (0.81–0.97).

Determinants of RV Dimensions
Multivariable linear regression analysis identified independent predictors of increased RVOT1 dimension in athletes to be LV end-diastolic diameter ($\beta=0.198$; 95% CI, 0.104–0.290; $P<0.001$), Caucasian ethnicity ($\beta=0.163$; 95% CI, 0.084–0.242; $P<0.001$), and BSA ($\beta=0.162$; 95% CI, 0.06–0.263; $P=0.002$). The $R^2$ value for ethnicity was 0.023, which indicates that only 2.3% of observed variation in RVOT size was attributable to this factor. Predictors of RVEDA in athletes were BSA ($\beta=0.310$; 95% CI, 0.217–0.403; $P<0.001$), LV end-diastolic diameter ($\beta=0.222$; 95% CI, 0.137–0.307; $P<0.001$), male sex ($\beta=0.185$; 95% CI, 0.105–0.264; $P<0.001$), HD-HS sports participation ($\beta=0.141$; 95% CI, 0.062–0.221; $P=0.001$), ECG partial right bundle-branch block ($\beta=0.115$; 95% CI, 0.046–0.185; $P=0.001$), and age ($\beta=-0.112$; 95% CI, −0.185 to −0.040; $P=0.003$). Two-way ANOVA applied to athletes and control subjects revealed that there was no interaction between exercise and ethnicity in determining RV dimensions (RVOT1, $F=0.092, P=0.762$; RVEDA, $F=0.599, P=0.439$).

Discussion

RV Remodeling in BAs
The present study is the first to characterize RV remodeling in BAs. Balanced, physiological RV enlargement was observed in a large proportion of both black and white athletes, although absolute dimensions were generally smaller in blacks. This effect was most consistently evident in the RVOT, which is of relevance because quantification of RVOT size is an essential component of the ARVC diagnostic criteria. Perhaps the most obvious postulation against a differential adaptive response in BAs and WAs relates to the fact that a greater proportion of WAs participated in HD-HS sports. This discrepancy may also explain the fact that BAs exhibited a similar mean LVWT to WAs, contrary to previous studies10–12 However, multivariable analysis confirmed that ethnicity was an independent predictor of RVOT dimensions, although it must be noted that only 2.3% of the observed variation could be attributed to this factor. Furthermore, the lack of statistical interaction between ethnicity and athletic status in determining RV dimensions indicates that these findings may represent baseline racial differences, a phenomenon that has been reported previously in nonathletes.30 For practical purposes, we would suggest that these considerations obviate the requirement for ethnicity-specific RV reference values for athletes.

Correlation Between ECG and Echocardiography
The most striking ethnic difference in ECG patterns relates to the presence of TWI, which was observed in almost 22% of BAs compared with only 5% of WAs. This finding, which is
consistent with previous reports,\textsuperscript{10–12} raises the question as to whether an anatomic substrate might underlie this phenomenon in BAs, particularly with regard to the anterior precordial leads that lie in close proximity to the RV. The present data indicate that TWI, and in particular anterior TWI, is not associated with increased RV size in athletes. Partial or complete right bundle-branch block was an independent predictor of increased RVEDA, a finding that has been reported previously and probably reflects increased conduction time through an enlarged RV body.\textsuperscript{26}

The ARVC Overlap in BAs

Physiological RV remodeling may result in diagnostic overlap with ARVC. The issue is particularly important in BAs because anterior precordial TWI, which is pertinent to the diagnostic criteria for ARVC, is present in a significant proportion of cases. Consequently, marked RVOT enlargement in conjunction with anterior TWI extending beyond lead V\textsubscript{2} is almost exclusively observed in BAs. The result is a diagnostic “gray zone” between athlete’s heart and ARVC of 3% in BAs compared with only 0.3% in WAs. Although the echocardiographic components of the ARVC diagnostic criteria require RVOT dilatation to be accompanied by WMAs, visual assessment of the latter is unreliable and may lead to false-positive results. In a recent study by Teske et al,\textsuperscript{31} apparent RV WMAs were observed in 15% of healthy control subjects, although detailed tissue deformation imaging failed to replicate these anomalies in the same individuals. Our own experience in the present study was of 2 healthy BAs with apparent RV WMAs, RVOT dilatation, and anterior TWI that satisfied the diagnostic criteria for ARVC at initial assessment. In both cases, further investigation did not support the presence of WMAs, nor did it reveal any other features consistent with such a diagnosis. The study underscores the superior ability of cMRI to assess morphological characteristics of the RV compared with echocardiography (online-only Data Supplement Figure I). As such, subtle echocardiographic WMAs should be confirmed with cMRI before a diagnosis of ARVC is made in athletes.

<table>
<thead>
<tr>
<th>ARVC Diagnostic Criterion</th>
<th>BA, %</th>
<th>WA, %</th>
<th>BC, %</th>
<th>WC, %</th>
<th>(P)</th>
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<tr>
<td>RVOTP Minor (≥29 mm to &lt;32 mm)</td>
<td>23.0</td>
<td>23.5</td>
<td>14.9</td>
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<td>Major (≥32 mm)</td>
<td>27.5</td>
<td>40.7</td>
<td>6.0</td>
<td>9.6</td>
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<td>RVOT1 Minor (≥32 to &lt; 36 mm)</td>
<td>23.0</td>
<td>29.9</td>
<td>20.0</td>
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<td>0.150</td>
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<tr>
<td>Major (≥36 mm)</td>
<td>22.0</td>
<td>28.6</td>
<td>6.2</td>
<td>8.5</td>
<td>&lt;0.001</td>
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<td>ECG (TWI) Minor (V1-V2 or V4-V6)</td>
<td>7.3</td>
<td>3.2</td>
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<td>2.4</td>
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<tr>
<td>Major (V1-V3)</td>
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<td>0</td>
<td>0</td>
<td>&lt;0.001</td>
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<tr>
<td>ECG + echocardiography Major ECG + Major echo</td>
<td>3.0</td>
<td>0.3</td>
<td>0</td>
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</tbody>
</table>

ARVC indicates arrhythmogenic right ventricular cardiomyopathy; BA, black athletes; BC, black control subjects; RVOTP, right ventricular outflow tract dimension (parasternal); RVOT1, proximal right ventricular outflow tract dimension; TWI, T-wave inversion; WA, white athletes; and WC, white control subjects.
Clinical Implications
The present study provides insight into the diagnostic overlap between physiological RV remodeling and ARVC. Current task force criteria, which were developed from patients with an established diagnosis of the disease, demonstrate poor utility when applied to low-risk populations. Accordingly, concomitant enlargement of the left and right sides of the heart with normal wall motion should not trigger further evaluation for ARVC in asymptomatic athletes without an adverse family history. Although the absence of anterior TWI or partial right bundle-branch block demonstrates high specificity for a truly negative diagnosis in athletes (91.6% and 94.7%, respectively), neither finding has any positive predictive value for ARVC in this context. In BAs, RV dilatation in conjunction with convex ST-segment elevation and biphasic anterior TWI appears to be a benign finding in the absence of other relevant clinical indicators. Conversely, symmetrical anterior TWI that extends beyond lead V1, preceded by isoelectric or downsloping ST segments, should prompt further investigation to exclude ARVC (Figure 4). Awareness of these issues has the potential to reduce the burden of investigations after screening and to prevent erroneous disqualification from sport.

Proposed Reference Limits for Right-Sided Cardiac Dimensions in Athletes
Relatively large differences in absolute RV dimensions were observed between male and female athletes in the present study; hence, sex-specific reference values are quoted. Furthermore, because BSA was the strongest and most consistent predictor of RV dimensions, indexed reference values are also recommended. The present data indicate that RVOT1 should not exceed 22 mm/m² in male athletes and 23 mm/m² in female athletes, whereas RVD1 should not exceed 28 mm/m² in athletes of either sex. Reference limits for all major RV and right atrial dimensions in athletes are presented in Table 4. These values may also be applied to adolescent athletes, because one third of the subjects participating in the study were ≤18 years old, and age was only weakly associated with RV dimensions.

Comparison With Previously Published Data
The largest echocardiographic study of training-induced RV remodeling to date assessed 650 subjects and provided an invaluable starting point for the evaluation of athletes. The study, however, was limited by the absence of nonwhite and adolescent athletes, and it lacked correlation with ECG data. Mean values for RVOT dimensions and RV end-diastolic free wall thickness were similar to those observed in the present study. Measures of RV body size (RVD1 through RVD3) were generally lower than we have observed, although values similar to our own have been reported elsewhere in elite athletes. In the present study, and in accordance with current American Society of Echocardiography guidelines, considerable care was taken to ensure that RV size was maximized in the apical views, that RVD1 was measured at the widest point of the basal third of the ventricle, and that trabeculations were included within the cavity measurement. Failure to ensure 1 or more of these factors may be responsible for the lower values documented in the previous study.

Study Limitations
The present study does exhibit certain limitations worthy of mention. The proportion of female BAs studied was small,
Table 4. Upper Reference Values for Right Ventricular Measurements in Athletes, Corrected for Sex and Body Surface Area

<table>
<thead>
<tr>
<th></th>
<th>Male Athletes</th>
<th>Female Athletes</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAA, cm² (cm²/m²)</td>
<td>28 (14)</td>
<td>24 (13)</td>
</tr>
<tr>
<td>RVEDA, cm² (cm²/m²)</td>
<td>39 (19)</td>
<td>32 (18)</td>
</tr>
<tr>
<td>RVOTP, mm (mm/m²)</td>
<td>40 (20)</td>
<td>37 (21)</td>
</tr>
<tr>
<td>RVOT1, mm (mm/m²)</td>
<td>43 (22)</td>
<td>40 (23)</td>
</tr>
<tr>
<td>RVOT2, mm (mm/m²)</td>
<td>32 (17)</td>
<td>29 (16)</td>
</tr>
<tr>
<td>RVD1, mm (mm/m²)</td>
<td>55 (28)</td>
<td>49 (28)</td>
</tr>
<tr>
<td>RVD2, mm (mm/m²)</td>
<td>47 (24)</td>
<td>43 (25)</td>
</tr>
<tr>
<td>RVD3, mm (mm/m²)</td>
<td>109 (56)</td>
<td>100 (57)</td>
</tr>
<tr>
<td>RWTT, mm (mm/m²)</td>
<td>6 (3)</td>
<td>5 (3)</td>
</tr>
</tbody>
</table>

Absolute values are quoted followed by body surface area–indexed values (parentheses).

RAA indicates right atrial area; RVOT1, right ventricular basal dimension; RVOT2, right ventricular midventricular dimension; RVD3, right ventricular longitudinal dimension; RVEDA, right ventricular end-diastolic area; RVOTP, right ventricular outflow tract dimension (parasternum); RVOT1, proximal right ventricular outflow tract dimension; RVOT2, distal right ventricular outflow tract dimension; and RWTT, right ventricular free wall thickness.

which is a reflection of the fact that this subgroup constitutes fewer than 10% of sportspersons competing at the national level in the United Kingdom. A smaller proportion of BAs competed in HD-HS sports than WAs. However, professional participation in sports such as cycling and rowing is predominated by whites in most Western countries; hence, the limited number of black HD-HS athletes in the present study is an accurate representation of sporting demographics in the United Kingdom and the United States. Data relating to athletes requiring further investigation were incomplete in approximately one third of cases. We believe this is a reflection of the difficulties involved in coordinating a nationwide screening service for young athletes, who are often reluctant to undergo evaluation of minor anomalies that might result in exclusion from future sports participation. Nonetheless, the majority were investigated comprehensively, with no compelling evidence of ARVC in any case. Furthermore, athletes with incomplete data did not differ from those who were investigated fully with respect to any demographic or clinical parameters that might increase the likelihood of quiescent cardiac pathology. Finally, although the study was cross-sectional in nature, no adverse clinical events have occurred in any participating athlete since study enrolment commenced >6 years ago. Nonetheless, continued longitudinal surveillance of athletes who exhibit marked repolarization anomalies is required to categorically exclude subclinical cardiomyopathic disorders.

Conclusions

Physiological RV enlargement is frequently observed in both black and white athletes; however, in the context of a high prevalence of ECG repolarization anomalies in BAs, the potential for erroneous diagnosis of ARVC is considerably greater in this ethnic group. Recognition of this phenomenon is necessary to prevent unwarranted exclusion from sports participation in this emergent group of athletes.

Acknowledgments

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Disclosures

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Supplemental Material

Supplemental Figure S1: Side-by-side echocardiographic and cardiac magnetic resonance images of an apparent right ventricular wall motion abnormality. 

A, Echocardiographic right ventricular focused apical view. The apical segment of the right ventricle appears akinetic, giving rise to a bulging morphology (arrow). B, Four chamber cardiac magnetic resonance imaging view in the same athlete. The right ventricular free wall tapers smoothly towards the apex without the appearance of a bulge (arrowhead). All segments contract normally.