Year: 2020

Association of Ascending Aortic Dilatation and Long-term Endurance Exercise Among Older Masters-Level Athletes

Churchill, Timothy W ; Groezinger, Erich ; Kim, Jonathan H ; Loomer, Garrett ; Guseh, J Sawalla ; Wasfy, Meagan M ; Isselbacher, Eric M ; Lewis, Gregory D ; Weiner, Rory B ; Schmied, Christian ; Baggish, Aaron L

Abstract: Importance Aortic dilatation is frequently encountered in clinical practice among aging endurance athletes, but the distribution of aortic sizes in this population is unknown. It is additionally uncertain whether this may represent aortic adaptation to long-term exercise, similar to the well-established process of ventricular remodeling. Objective To assess the prevalence of aortic dilatation among long-term masters-level male and female athletes with about 2 decades of exercise exposure. Design, Setting, and Participants This cross-sectional study evaluated aortic size in veteran endurance athletes. Masters-level rowers and runners aged 50 to 75 years were enrolled from competitive athletic events across the United States from February to October 2018. Analysis began January 2019. Exposures Long-term endurance exercise. Main Outcomes and Measures The primary outcome was aortic size at the sinuses of Valsalva and the ascending aorta, measured using transthoracic echocardiography in accordance with contemporary guidelines. Aortic dimensions were compared with age, sex, and body size-adjusted predictions from published nomograms, and z scores were calculated where applicable. Results Among 442 athletes (mean [SD] age, 61 [6] years; 267 men [60%]; 228 rowers [52%]; 214 runners [48%]), clinically relevant aortic dilatation, defined by a diameter at sinuses of Valsalva or ascending aorta of 40 mm or larger, was found in 21% (n = 94) of all participants (83 men [31%] and 11 women [6%]). When compared with published nomograms, the distribution of measured aortic size displayed a rightward shift with a rightward tail (all P < .001). Overall, 105 individuals (24%) had at least 1 z score of 2 or more, indicating an aortic measurement greater than 2 SDs above the population mean. In multivariate models adjusting for age, sex, body size, hypertension, and statin use, both elite competitor status (rowing participation in world championships or Olympics or marathon time under 2 hours and 45 minutes) and sport type (rowing) were independently associated with aortic size. Conclusions and Relevance Clinically relevant aortic dilatation is common among aging endurance athletes, raising the possibility of vascular remodeling in response to long-term exercise. Longitudinal follow-up is warranted to establish corollary clinical outcomes in this population.

JAMA Cardiology | **Original Investigation**

Association of Ascending Aortic Dilatation and Long-term Endurance Exercise Among Older Masters-Level Athletes

Timothy W. Churchill, MD; Erich Groezinger, MS; Jonathan H. Kim, MD; Garrett Loomer, MS; J. Sawalla Guseh, MD; Meagan M. Wasfy, MD; Eric M. Isselbacher, MD, MHCDS; Gregory D. Lewis, MD; Rory B. Weiner, MD; Christian Schmied, MD; Aaron L. Baggish, MD

➕ **Author Audio Interview**

➕ **Supplemental content**

IMPORTANCE Aortic dilatation is frequently encountered in clinical practice among aging endurance athletes, but the distribution of aortic sizes in this population is unknown. It is additionally uncertain whether this may represent aortic adaptation to long-term exercise, similar to the well-established process of ventricular remodeling.

OBJECTIVE To assess the prevalence of aortic dilatation among long-term masters-level male and female athletes with about 2 decades of exercise exposure.

DESIGN, SETTING, AND PARTICIPANTS This cross-sectional study evaluated aortic size in veteran endurance athletes. Masters-level rowers and runners aged 50 to 75 years were enrolled from competitive athletic events across the United States from February to October 2018. Analysis began January 2019.

EXPOSURES Long-term endurance exercise.

MAIN OUTCOMES AND MEASURES The primary outcome was aortic size at the sinuses of Valsalva and the ascending aorta, measured using transthoracic echocardiography in accordance with contemporary guidelines. Aortic dimensions were compared with age, sex, and body size–adjusted predictions from published nomograms, and z scores were calculated where applicable.

RESULTS Among 442 athletes (mean [SD] age, 61 [6] years; 267 men [60%]; 228 rowers [52%]; 214 runners [48%]), clinically relevant aortic dilatation, defined by a diameter at sinuses of Valsalva or ascending aorta of 40 mm or larger, was found in 21% (n = 94) of all participants (83 men [31%] and 11 women [6%]). When compared with published nomograms, the distribution of measured aortic size displayed a rightward shift with a rightward tail (all P < .001). Overall, 105 individuals (24%) had at least 1 z score of 2 or more, indicating an aortic measurement greater than 2 SDs above the population mean. In multivariate models adjusting for age, sex, body size, hypertension, and statin use, both elite competitor status (rowing participation in world championships or Olympics or marathon time under 2 hours and 45 minutes) and sport type (rowing) were independently associated with aortic size.

CONCLUSIONS AND RELEVANCE Clinically relevant aortic dilatation is common among aging endurance athletes, raising the possibility of vascular remodeling in response to long-term exercise. Longitudinal follow-up is warranted to establish corollary clinical outcomes in this population.

Author Affiliations: Cardiovascular Performance Program, Massachusetts General Hospital, Boston (Churchill, Groezinger, Loomer, Guseh, Wasfy, Lewis, Weiner, Baggish); Echocardiography Laboratory, Massachusetts General Hospital, Boston (Churchill, Wasfy, Isselbacher, Weiner, Baggish); Division of Cardiology, Emory Clinical Cardiovascular Research Institute, Atlanta, Georgia (Kim); Thoracic Aortic Center, Massachusetts General Hospital, Boston (Isselbacher); University Heart Center, Zurich, Switzerland (Schmied).

Corresponding Author: Aaron L. Baggish, MD, Cardiovascular Performance Program, Massachusetts General Hospital, 55 Fruit St, Yawkey Ste 5B, Boston, MA 02114 (abaggish@partners.org).

D ilatation of the aortic root and ascending aorta represents the principal risk factor for the acute aortic syndromes,[1] a highly morbid group of conditions with in-hospital mortality exceeding 25%.[2,3] Guideline-directed therapy of patients with asymptomatic aortic dilatation includes blood pressure control, prohibition of intense isometric physical activity, and serial imaging to assess for progression sufficient to justify surgical intervention.[2,4] Established risk factors for aortic dilatation include advancing age, male sex, increasing body size, hypertension, and numerous genetic syndromes including bicuspid aortic valve and multiple connective tissue disorders.[5,6] Collectively, however, these attributes fail to account for much of the aortic dilatation encountered in clinical practice.

Routine vigorous exercise stimulates cardiac remodeling that often results in myocardial wall thickening and chamber dilatation, which in turn may overlap with common forms of cardiomyopathy.[7,8] Prior work suggests that the ascending aorta may also respond to high levels of exercise training but insufficiently to cause dilatation above common thresholds for distinguishing pathology. A 2013 meta-analysis reported minor and clinically insignificant aortic dilatation at the sinuses of Valsalva among competitive athletes compared with nonathletic controls.[9] Several large cohort studies have shown that clinically significant aortic dilatation among competitive athletes (conventionally defined as ≥40 mm for men and ≥34 mm for women) is exceedingly uncommon,[10-14] even among athletes at the extremes of body size.[15,16] Notably, however, this prior work has largely been confined to competitive athletes in the first 2 to 3 decades of life, leaving the effect of long-term exercise training and/or intense exercise training later in life on the aorta unknown.

Masters-level athletes (ie, men and women beyond the fourth decade of life who perform routine exercise training with competitive athletic goals) are increasingly encountered in clinical cardiovascular practice.[17] To date and to our knowledge, the prevalence and magnitude of aortic dilatation in this population has not been defined. Our primary hypothesis was that masters-level athletes participating in endurance sports would have a higher prevalence of aortic dilatation than similarly aged, less active people. We additionally hypothesized that rowing, a sport with concomitant pressure and volume hemodynamic stress, would be associated with more aortic dilatation than long-distance running, a sport primarily characterized by isolated isotonic physiology. To address these hypotheses, we prospectively enrolled a cohort of asymptomatic aging competitive runners and rowers with goal of defining the prevalence of aortic dilatation in this population.

Methods

We performed a prospective assessment of aortic dimensions among competitive masters-level male and female rowers and runners. Aortic dimensions were measured using a transthoracic echocardiographic protocol designed to optimize measurements of the ascending aorta. Runners were recruited

Key Points

Question What is the prevalence of aortic dilatation among long-term endurance athletes?

Findings In this cross-sectional study of 442 masters-level athletes, 94 individuals (21%) were found to have an ascending aortic size of 40 mm or larger, representing a marked increase in the prevalence of aortic dilatation compared with that predicted by established age- and sex-specific population nomograms.

Meaning This study identified an elevated prevalence of aortic dilatation among aging endurance athletes without clear explanatory risk factors, suggesting that long-term endurance exercise is associated with aortic enlargement.

based on participation in the Boston Athletic Association's Boston Marathon, while rowers were recruited based on membership in competitive rowing clubs and/or participation in US national-level competitions. All aspects of this study were approved by the Partners Human Research Committee, the institutional review board of Partners HealthCare. All participants provided written informed consent.

Study Population

Rowers and runners were enrolled from February to October 2018. Rower participants were recruited from competitive rowing clubs (Cambridge Boat Club, Cambridge, Massachusetts; Upper Valley Rowing Foundation, Hanover, New Hampshire) and at national competitions (CRASH-Bs Indoor Rowing Championships, Boston, Massachusetts; US Masters Rowing Championships, Oakland, California; Head of the Charles Regatta, Cambridge, Massachusetts). Rowers were studied at club facilities or at designated sites adjacent to competitions. Runners were recruited based on their registration in the Boston Marathon and were studied at the prerace exposition. Participation was voluntary, and participants were not compensated monetarily.

Inclusion criteria included age 50 to 75 years and a minimum of 10 years of endurance training after age 40 years, including participation in organized competition. Elite athlete status was defined for subsequent analysis based on prior competition in world championships or Olympics (rowers) or completion of a marathon under 2 hours and 45 minutes (runners). Exclusion criteria, designed to exclude known drivers of aortic pathology and to align with published population data on aortic size,[18-20] included personal or family history of aortopathy, first-degree family member with a history of thoracic aortic aneurysm, bicuspid aortic valve, connective tissue disorder (including Marfan, Loeys-Dietz, and Ehlers-Danlos syndromes), or failure to meet the inclusion criteria above. All participants completed an investigator-developed questionnaire to characterize prior training and competition, lifestyle habits, and medical history. Weight was measured using a commercially available digital scale (Etekcity); blood pressure was assessed using a manual sphygmomanometer after 10 minutes of quiet rest.

Echocardiography

A full description of echocardiographic methods is presented in the eMethods in the Supplement. Briefly, we performed a

transthoracic echocardiographic protocol using a commercially available system (Vivid-Q; GE Healthcare) and standard imaging techniques[21] with particular focus on the ascending aorta. Measurements of myocardial structure and function were performed according to guideline specifications.[22] Aortic size was measured in the parasternal long axis view at end diastole at 4 levels: (1) aortic annulus, (2) sinuses of Valsalva, (3) sinotubular junction, and (4) ascending aorta (2-3 cm above the sinotubular junction at the maximal visualized diameter).

Aortic measurements, performed in triplicate over 3 separate cardiac cycles, were made using both leading edge-to-leading edge and inner edge-to-inner edge conventions, given guideline endorsement of the former[22] and common clinical and scientific use of the latter.[18] Leading edge-to-leading edge measurements are presented unless otherwise noted. Inner edge-to-inner edge measurements were used to align with the nomogram by Saura et al.[18] Clinically relevant aortic dilatation was defined as a measured dimension of 40 mm or more based on prior studies defining this as the 99th percentile for aortic size for young male athletes[12,14] and the codification of this cut point as a threshold triggering active clinical surveillance.[23]

Intraobserver variability analysis was performed through blinded reassessment of 10 randomly selected individuals. Interobserver variability was assessed in a group of 10 randomly selected individuals by 2 investigators (T.W.C. and A.L.B.) blinded to each other's measurements. Correlation for each measurement was assessed using linear regression with the following results: intraobserver at sinuses of Valsalva (R^2 = 0.94) and ascending aorta (R^2 = 0.97) and interobserver at the sinuses of Valsalva (R^2 = 0.93) and ascending aorta (R^2 = 0.94).

Statistical Analysis

Normality for all variables was assessed using the Shapiro-Wilk test. Continuous variables are reported as mean (SD) or median (interquartile range). Measured aortic dimensions were compared with sizes predicted by population nomograms,[18-20] and z scores were calculated when possible.[19,20] While imperfect, these nomograms represent the best available data with which to assess normal aortic size and are commonly used for this purpose in clinical practice. The primary analysis focused on the sinus of Valsalva nomogram by Devereux et al,[19] the data most commonly cited in guideline documents.[23] We additionally compared our data with the height-normalized ascending aorta nomogram by Saura et al.[18] As this tool does not present z scores, the ascending aorta z score from Campens et al[20] was used in assessing the prevalence of abnormal z scores. All 3 nomograms excluded individuals with bicuspid aortic valves, and the data from Saura et al[18] excluded trained athletes.[24] Distributions of actual vs predicted aortic sizes were compared using 2-tailed t tests. Univariate associations were assessed using linear regression. Stepwise forward multivariate regression was performed to determine variables independently associated with aortic size, with raw aortic sizes serving as the outcome variable given their central role in clinical decision-making. While not independently associated in all models, hypertension (defined as reported hyper-

tension or use of antihypertensive medication) was included in final models given its established effect on aortic disease. Statin use was additionally included as a covariate to account for potential established atherosclerotic disease. All P values were 2-sided, and the significance threshold was less than .05 for all testing. All data analysis was performed using Stata, version 15.1 (StataCorp). Analysis began January 2019.

Results

A total of 442 masters-level athletes (mean [SD] age, 61 [6] years; 267 men [60%]; **Table 1**) completed all aspects of the study protocol (eFigure 1 in the Supplement). Rowers and runners constituted 52% (n = 228) and 48% (n = 214) of the total cohort, respectively. The prevalence of cardiovascular diagnoses, risk factors, and prescription medications use were low, with 34 (7%) reporting antihypertensive medication use and 40 (9%) reporting statin use. Athletic experience was extensive (mean [SD], 23 [10] years of training and competition in their respective primary sport) with runners having completed a mean (SD) of 33 (39) prior marathons. A total of 35 individuals (8%; 28 men and 7 women; 23 rowers and 12 runners) met criteria for elite status.

Myocardial Structure and Function

Selected echocardiographic parameters, stratified by sex and sport, are shown in Table 1 (full echocardiographic data are reported in eTable 1 in the Supplement). Measures of ventricular size and function were broadly similar across sports with several notable exceptions. Rowers had lower indexed left ventricular (LV) end-diastolic volumes than the runners (mean [SD], 60 [14]; 95% CI, 58-62 vs 72 [14]; 95% CI, 70-74; P < .001 for both sexes), while indexed LV mass was not statistically different between sports. Early diastolic tissue velocities were also lower among male rowers than male runners.

Aortic Dimensions

Distributions of aortic size, measured using the leading edge-to-leading edge convention, are shown in **Figure 1**. Among men, 83 of 267 (31%) had at least 1 aortic dimension of 40 mm or larger. Specifically, 66 of 267 (25%) and 45 of 249 (18%) demonstrated maximal aortic dimensions 40 mm or larger at the sinuses of Valsalva and the ascending aorta, respectively. Raw aortic size was greater at both the sinuses of Valsalva (mean [SD], 39.2 [3.9] mm; 95% CI, 38.5-39.9 vs 36.7 [3.5] mm; 95% CI, 36.1-37.2; P < .001) and ascending aorta (mean [SD], 37.6 [3.9] mm; 95% CI, 36.9-38.4; vs 35.6 [3.2] mm; 95% CI, 35.1-36.2; P < .001) among male rowers than among male runners. Male rowers also represented the majority of individuals with aortic dimensions exceeding 40 mm, with 51 of 114 (45%) found to have at least 1 aortic measurement of 40 mm or larger. Fewer women (11 of 175 [6%]) had aortas that were 40 mm or larger. However, when considered against a conventional standard of 34 mm,[13,14] 63 (36%) met this criterion in the aortic root and 63 (40%) in the ascending aorta. Aortic size at the sinuses of Valsalva was slightly larger among female rowers than runners (mean [SD], 33.7 [3.3] mm; 95% CI,

Table 1. Participant Data and Select Echocardiographic Parameters

Characteristic	Mean (SD)			
	Male		Female	
	Rowers (n = 114)	Runners (n = 153)	Rowers (n = 114)	Runners (n = 61)
Age, y	63 (6)	59 (6)	62 (7)	59 (6)
Height, in	72 (3)	70 (2)	66 (2)	65 (3)
Weight, kg	87 (13)	74 (8)	67 (10)	57 (8)
BMI	25 (3)	24 (2)	23 (3)	21 (2)
Blood pressure, mm Hg				
Systolic	125 (15)	132 (15)	119 (13)	122 (14)
Diastolic	75 (9)	78 (9)	71 (9)	75 (10)
Medical history, No. (%)				
Coronary artery disease	6 (5)	6 (4)	1 (1)	1 (2)
Hypertension	24 (21)	19 (12)	7 (6)	5 (8)
Hyperlipidemia	26 (23)	31 (20)	19 (17)	8 (13)
Diabetes mellitus	3 (3)	2 (1)	1 (1)	2 (3)
Smoking (current or former)	18 (16)	19 (12)	26 (23)	16 (26)
Atrial fibrillation	10 (9)	2 (1)	4 (4)	0
Medications				
No medications	50 (44)	104 (68)	41 (37)	31 (51)
Antihypertensive medication	19 (17)	9 (6)	4 (4)	2 (3)
Statin	25 (22)	11 (7)	3 (3)	1 (2)
Antiplatelet/anticoagulant	8 (7)	7 (5)	6 (5)	0
Athletic history				
Cumulative years training	26 (11)	24 (11)	20 (8)	22 (9)
Annual training volume, h	244 (96)	243 (98)	239 (96)	237 (77)
No. of marathons[a]	6 (9)	32 (31)	7 (13)	33 (54)
Marathon time (personal best), min	NA	196 (23)	NA	222 (21)
Select echocardiographic parameters				
Left ventricular volume index, end-diastole, mL/m²	66 (14)	75 (13)	55 (12)	64 (11)
Left ventricular mass index, g/m²	75 (11)	78 (12)	68 (9)	73 (11)
Lateral e', cm/s	7.9 (2.3)	9.4 (2.2)	8.5 (2.0)	9.0 (1.9)
Medial e', cm/s	6.5 (2.0)	7.2 (1.6)	7.0 (1.6)	7.3 (1.5)

Abbreviations: BMI, body mass index (calculated as weight in kilograms divided by height in meters squared); e', early tissue velocity; NA, not applicable.

[a] Mean number of marathons reported for only individuals who had completed at least 1.

33.1-34.3; vs 32.3 [2.9] mm; 95% CI, 31.6-33.1; P = .008), but there was no difference across sports in the ascending aorta (mean [SD], 33.3 [3.1] mm; 95% CI, 32.7-33.9; vs 33.2 [3.5] mm; 95% CI, 32.3-34.2; P = .88). Among elite competitors, 14 of 35 (40%) had at least 1 aortic measurement 40 mm or larger, including 13 of 28 men (46%).

Raw and indexed aortic sizes are shown in **Table 2**. Differences between men and women were less pronounced after indexing for body surface area (BSA) or height. Women had slightly larger aortic sizes when indexed to BSA, while height indexing resulted in the opposite pattern at the sinuses of Valsalva with similar sizes in the ascending aorta. Body surface area–indexed aortic dimensions were greater in rowers than in runners, while height indexing yielded similar values across sports with the exception of sinus of Valsalva dimensions, which were slightly larger among male rowers vs runners (eTable 2 in the Supplement).

Comparison With Population Data

Aortic dimensions among masters rowers and runners relative to age, sex, and BSA or height-adjusted nomograms are presented in **Figure 2**. In all cases, the distribution of measured aortic size among participants displayed a distinct rightward shift with a rightward tail when compared with predicted values (all P < .05). A total of 105 individuals (24%) had at least 1 z score of 2 or more, indicating an aortic measurement greater than 2 SDs above the population mean. Breakdown of abnormal z scores by sex and by sport is shown in eTable 3 in the Supplement, and comparison with all available population nomograms is shown in eFigure 2 in the Supplement.

Factors Associated With Aortic Size

Univariate associations with aortic size are shown in **Table 3**. Age, sex, and body size (both BSA and height) were all significantly associated with aortic size at both the sinuses of Valsalva and the ascending aorta. The presence of hypertension was also significantly associated with aortic size at both locations, while other clinical markers of cardiovascular risk and prevalent disease were not. Cumulative years of athletic training and elite competitor status were both associated with aortic dimensions. Finally, we detected strong univariate

**Figure 1. Distribution of Aortic Sizes by Sport and by Sex**
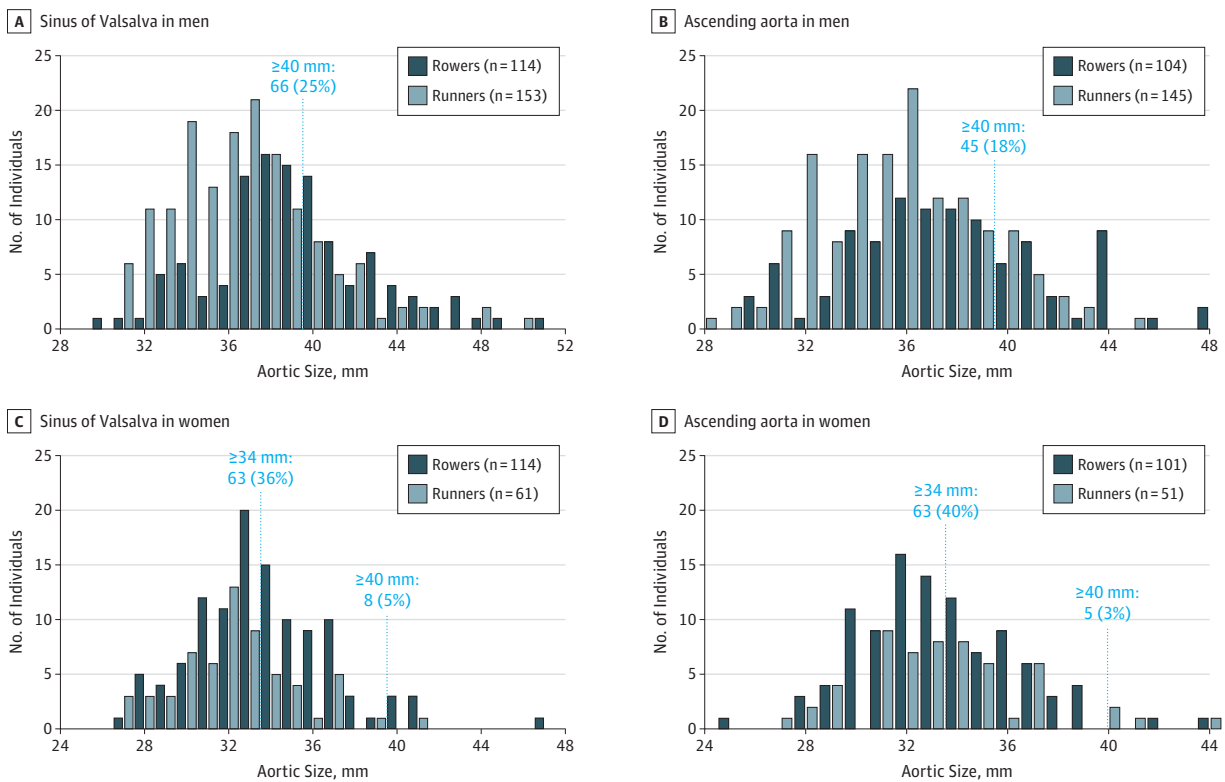
Distributions of aortic size at both the sinuses of Valsalva and the ascending aorta, measured leading edge–to–leading edge, are shown for men and women, with separate distributions presented for rowers and runners. Among men, 25% (66 of 267) measured 40 mm or larger at the sinuses of Valsalva and 18% (45 of 249) in the ascending aorta. Aortic sizes among rowers exhibited a rightward shift compared with that of runners (*P* < .01) in all cases except the ascending aorta in women, where the distribution was similar.

Table 2. Distribution of Aortic Dimensions[a]

	Men		Women		
Variable	Mean (SD)	95th Percentile	Mean (SD)	95th Percentile	P Value
Raw values, mm					
Aortic annulus	22.5 (2.2)	26.0	19.8 (1.6)	22.3	<.001
Sinus of Valsalva	37.8 (3.9)	44.7	33.2 (3.2)	38.7	<.001
Sinotubular junction	32.9 (3.6)	39.7	29.3 (2.5)	33.3	<.001
Ascending aorta	36.5 (3.7)	43.5	33.3 (3.3)	39.0	<.001
Abdominal aorta	20.7 (3.1)	26.0	19.5 (2.9)	24.0	<.001
Normalized by height, mm/m					
Aortic annulus	12.5. (1.1)	14.4	11.9 (1.0)	13.5	<.001
Sinus of Valsalva	21.0 (2.0)	25.0	19.9 (2.0)	23.4	<.001
Sinotubular junction	18.3 (1.9)	21.5	17.6 (1.5)	20.3	.001
Ascending aorta	20.3 (1.9)	23.3	20.0 (2.1)	23.3	.11
Abdominal aorta	11.5 (1.7)	14.4	11.7 (1.7)	14.7	.40
Normalized by body surface area, mm/m²					
Aortic annulus	11.4 (1.1)	13.4	11.7 (1.2)	13.9	.005
Sinus of Valsalva	19.1 (2.0)	22.8	19.6 (2.4)	24.2	.03
Sinotubular junction	16.7 (1.8)	19.6	17.4 (1.9)	21.6	.001
Ascending aorta	18.5 (1.9)	21.8	19.6 (2.5)	24.3	<.001
Abdominal aorta	10.5 (1.6)	13.1	11.4 (1.6)	14.0	<.001

[a] All measurements made using the leading edge–to–leading edge convention.

Figure 2. Actual vs Predicted Aortic Sizes by Sex and Sport
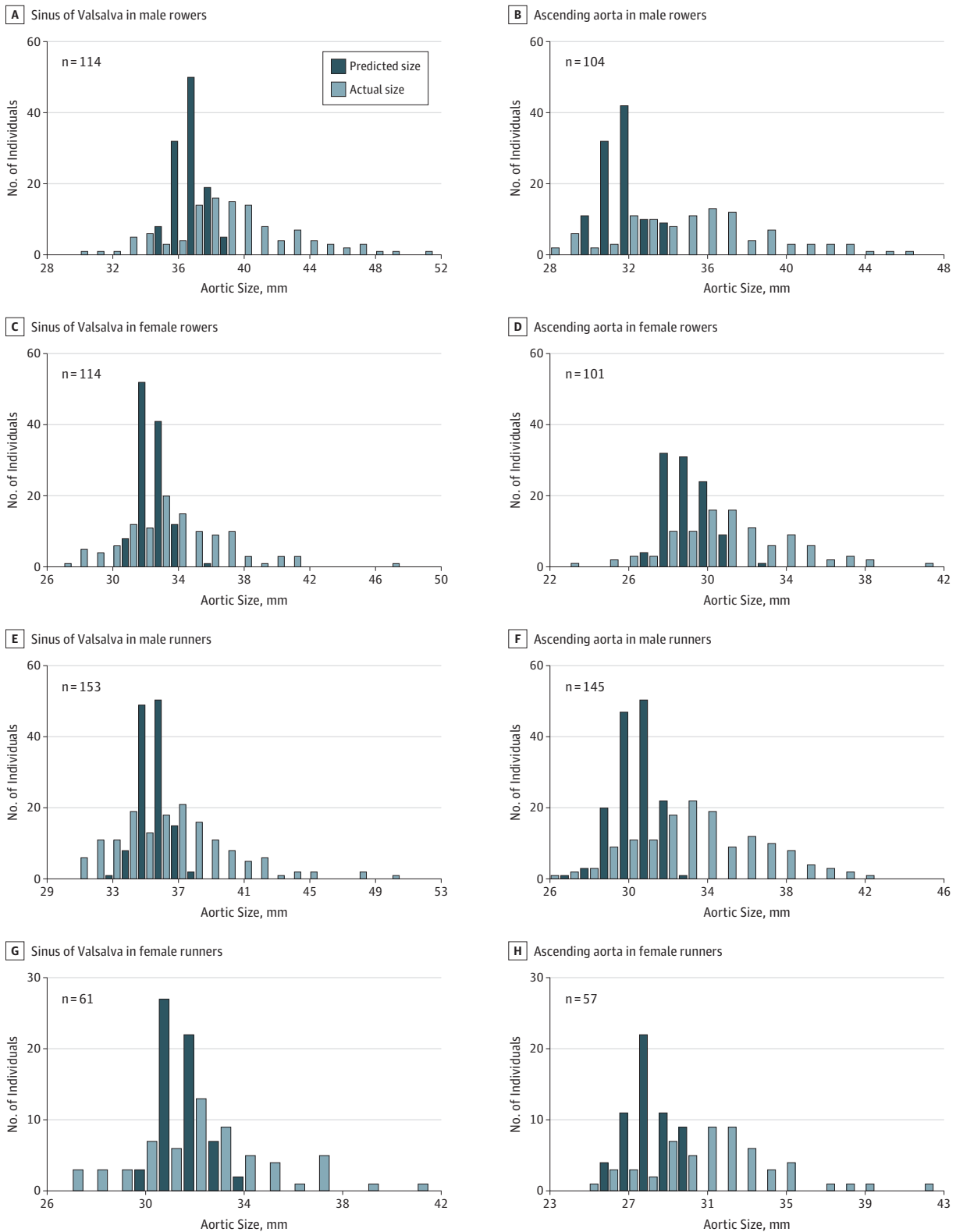
Measured aortic sizes are plotted by sport and sex against predicted sizes from existing population-level nomograms. Sinus of Valsalva dimensions are presented using leading edge–to–leading edge measurement, with predicted sizes from the body surface area–adjusted nomogram from Devereux et al.[19] Ascending aortic predicted dimensions are derived from the nomogram from Saura and colleagues,[18] who used a height-adjusted model using the inner edge–to–inner edge convention; dimensions are accordingly presented for inner edge–to–inner edge measurements for study individuals. In all cases, distribution of measured sizes exceeded that of predicted sizes (all $P < .05$).

Table 3. Univariate Associations of Aortic Size With Medical, Athletic, and Echocardiographic Covariates

Characteristic	Sinus of Valsalva		Ascending Aorta	
	β (SE)	P Value	β (SE)	P Value
Age	0.09 (0.03)	.004	0.13 (0.03)	<.001
Sex	4.6 (0.4)	<.001	3.2 (0.4)	<.001
Height	0.2 (0.02)	<.001	0.17 (0.02)	<.001
Body surface area	10.9 (0.8)	<.001	8.6 (0.8)	<.001
Hypertension[a]	1.7 (0.6)	.005	2.2 (056)	<.001
Hyperlipidemia	0.3 (0.5)	.56	0.9 (0.5)	.06
Diabetes mellitus	−0.5 (1.5)	.75	1.0 (1.4)	.46
Smoking (current or former)	−0.80 (0.5)	.13	−0.5 (0.5)	.30
Atrial fibrillation	1.9 (1.1)	.09	1.4 (1.0)	.17
Coronary artery disease	0.6 (1.2)	.63	0.6 (1.1)	.62
Athletic experience				
Cumulative years training	0.05 (0.02)	.02	0.05 (0.02)	.01
Annual training volume	−0.007 (0.002)	.72	−0.003 (0.002)	.22
No. of marathons completed	−0.004 (0.007)	.60	−0.002 (0.006)	.68
Elite rower[b]	3.0 (1.0)	.002	2.3 (0.9)	.02
Elite runner[c]	4.4 (1.1)	<.001	1.2 (1.0)	.24
Exercise-induced cardiac remodeling				
LV mass index (area-length), g/m^2	0.08 (0.02)	<.001	0.1 (0.02)	<.001
LV end-diastolic volume index, mL/m^2	0.07 (0.01)	<.001	0.045 (0.01)	<.001

Abbreviation: LV, left ventricular.

[a] Self-reported hypertension or prescription of antihypertensive medication.

[b] Elite rower defined as prior international competition (participation in world championships or Olympics).

[c] Elite runner defined as completion of a marathon with a finishing time under 2 hours and 45 minutes.

associations between well-established markers of exercise-induced cardiac remodeling including LV mass and LV end-diastolic volume and aortic dimensions at both measured locations. In a fully adjusted multivariate model, significant factors associated with aortic size at the sinuses of Valsalva included sex, height, sport type (rowing), and elite competitor status. In contrast, correlates of aortic size in the ascending aorta included age, sex, height, and hypertension (eTable 4 in the Supplement).

Discussion

To our knowledge, this study presents the first detailed characterization of the prevalence of clinically relevant ascending aortic dilatation among aging competitive endurance athletes. Among a group of experienced competitive male and female rowers and runners with a low burden of both cardiovascular disease and traditional risk factors, we observed a prevalence of aortic dilatation, as defined by an aortic dimension of 40 mm or larger, of 21% (31% among men and 6% among women). These findings appeared particularly pronounced among rowers and elite competitors from both sports. Compared with validated age, sex, and body size–adjusted general population nomograms, the distributions of aortic dimensions at both the sinuses of Valsalva and the ascending aorta demonstrated a clear rightward shift among both men and women. Notably, when compared with guideline-endorsed z scores, almost 25% of study individuals had a z score of 2 or above, indicating an aortic size 2 SDs above the population mean. In aggregate, these findings suggest that long-term participation in competitive endurance sport may represent a

novel, clinically relevant risk factor for acquired ascending aorta dilatation.

Findings from this study fill an important gap in our understanding of how long-term participation in endurance sport affects the cardiovascular system. Responsiveness of the heart to exercise training was first suggested well over 100 years ago.[25,26] Subsequent longitudinal studies have established a causal relationship between exercise and structural, functional, and electrical myocardial adaptation,[27-29] with remodeling often leading to phenotypes that overlap with forms of myocardial pathology.[7,8,30] In contrast, prior work focused on aortic adaptations to exercise has suggested that aortic remodeling is comparatively minimal and rarely adequate to produce aortic dilatation of clinical relevance. Importantly, prior studies have leveraged national screening databases of high-caliber young athletes or meta-analytic approaches involving similarly aged cohorts and have not included middle-aged and older athletes.[10-14] One notable exception came recently from Gentry and colleagues,[31] who described an increased prevalence of aortic dilatation (≥40 mm) among 206 former National Football League athletes (30%, compared with 9% in a nonathletic reference group). However, this important data set emerged from a relatively unique population of men whose athletic experience was typically confined to early-life exposure to a sport associated with static-predominant exercise physiology, frequent weight gain, and blood pressure increases.[32] In contrast, we now present data documenting an elevated prevalence of aortic dilatation among both men and women who train and compete in endurance sports late into life.

The current paradigm of athletic cardiovascular remodeling presents the aorta as a relatively static organ, in contrast to the highly adaptable nature of myocardium. How-

ever, prior literature provides suggestive clues that the aorta may indeed have its own degree of plasticity. As noted above, a meta-analysis showed a small but statistically significant difference in aortic size between young athletes and controls,[9] and associations have been established between training duration and aortic size.[10] In addition, there is evidence of differences in aortic function, specifically aortic stiffness and aortic distensibility, between trained and untrained individuals,[33-35] and training interventions have been associated with improvements in distensibility and compliance.[36,37] Our findings expand the evidence of aortic remodeling and suggest that the aorta responds to the hemodynamic stress of endurance sport with a temporal trajectory that is slower than that of the myocardium.

The physiology underlying endurance sport varies considerably across disciplines, and we therefore set an a priori hypothesis that aortic dimensions would differ among rowers and runners. Long-distance running is classified as a predominantly dynamic sport characterized by sustained increases in cardiac output and concomitant volume load on the heart and the blood vessels with minimal pressure stress.[38] In contrast, rowing involves a combination of dynamic and static physiology in which the volume challenge imparted by high cardiac output is coupled with repetitive surges in arterial blood pressure, a pressure load on the left side of the heart and great vessels that occur during the catch or initiation of each stroke.[39] Correspondingly, these 2 sports have been associated with different patterns of LV remodeling.[27] Data from the present study suggest a similar element of sport specificity within the aorta. Although BSA and height adjustment substantially attenuated intersport differences in raw aortic dimensions, rowing remained independently associated with dilatation at the sinuses of Valsalva in adjusted models. While speculative, these findings suggest that the pressure stress uniquely present in rowing may represent an important hemodynamic driver of aortic dilatation, particularly at the level of the aortic sinuses.

There are potentially important clinical implications of our findings and an urgent call for future work. It is possible that mild to moderate dilatation of the ascending aorta among long-term exercisers may represent a previously unrecognized and benign adaptation to sport, similar to exercise-induced eccentric LV hypertrophy.[40] Alternatively, aortic dilatation in the setting of long-term endurance training may represent a novel form of acquired overuse pathology with attendant implications on morbidity and mortality. Our a priori decision to exclude athletes with bicuspid aortic valves, a step that parallels available population nomograms[18-20] and that was made to maximally isolate the effect of long-term exercise, suggests that our rates of clinically relevant aortic dilatation rep-

resent conservative estimates for the overall population of masters-level athletes. While aortic rupture is a rare cause of sudden death among young competitive athletes, the prevalence of aortic events among long-term aging endurance athletes remains unknown. Future studies aimed at defining the natural history of aortic dilatation in this population with an emphasis on clinical outcomes, including the incidence of acute aortic syndromes and elective aortic surgical intervention, will be required to resolve this fundamental uncertainty. In the absence of such data, clinical implications of our findings remain uncertain and will require individualized assessment.

Limitations

We acknowledge several limitations of this study. First, our data are cross-sectional and thus can neither establish causality between exercise and aortic dilatation nor permit conclusions about the natural history and clinical risk profile of aortic dilatation among long-term competitive athletes. Second, we compared our data with the imperfect reference of population nomograms. However, these data sets contain the best available normative aortic size values and represent the clinical standard for differentiating normal from abnormal. Third, our characterization of exercise exposure was confined to the measures that we felt we could assess with adequate accuracy. Thus, we lack data defining exercise training intensity and blood pressure response to exercise, both of which may represent mechanistic underpinnings of our findings. Fourth, the individuals performing the echocardiographic measurements were not blinded to participant sport status, allowing for the possible introduction of bias. Fifth, we studied experienced well-trained athletes participating in 2 common endurance sports, thereby limiting generalizability to more recreational exercisers and to athletes participating in other endurance disciplines.

Conclusions

In conclusion, we present data characterizing ascending aortic dimensions among aging competitive endurance athletes with the principal finding of a marked increase in the prevalence of aortic dilatation based on established population nomograms. This finding was consistent between men and women and across athletes participating in 2 of the most common endurance sports. Thus, it appears that the aorta is an exercise-responsive plastic organ that remodels in the setting of long-term exercise. Further longitudinal study will be required to establish definitive clinical correlates of these findings.

exercise on cardiovascular structure and function and compensation for his role as team cardiologist from US Soccer, US Rowing, the New England Patriots, the Boston Bruins, the New England Revolution, and Harvard University. No other disclosures were reported.

REFERENCES

1. Davies RR, Goldstein LJ, Coady MA, et al. Yearly rupture or dissection rates for thoracic aortic aneurysms: simple prediction based on size. *Ann Thorac Surg*. 2002;73(1):17-27. doi:10.1016/S0003-4975(01)03236-2

2. Hiratzka LF, Bakris GL, Beckman JA, et al; American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines; American Association for Thoracic Surgery; American College of Radiology; American Stroke Association; Society of Cardiovascular Anesthesiologists; Society for Cardiovascular Angiography and Interventions; Society of Interventional Radiology; Society of Thoracic Surgeons; Society for Vascular Medicine. 2010 ACCF/AHA/AATS/ACR/ASA/SCA/SCAI/SIR/STS/SVM guidelines for the diagnosis and management of patients with thoracic aortic disease: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines, American Association for Thoracic Surgery, American College of Radiology, American Stroke Association, Society of Cardiovascular Anesthesiologists, Society for Cardiovascular Angiography and Interventions, Society of Interventional Radiology, Society of Thoracic Surgeons, and Society for Vascular Medicine. *Circulation*. 2010;121(13):e266-e369.

3. Hagan PG, Nienaber CA, Isselbacher EM, et al. The International Registry of Acute Aortic Dissection (IRAD): new insights into an old disease. *JAMA*. 2000;283(7):897-903. doi:10.1001/jama.283.7.897

4. Erbel R, Aboyans V, Boileau C, et al; ESC Committee for Practice Guidelines; The Task Force for the Diagnosis and Treatment of Aortic Diseases of the European Society of Cardiology (ESC). 2014 ESC Guidelines on the diagnosis and treatment of aortic diseases: document covering acute and chronic aortic diseases of the thoracic and abdominal aorta of the adult. *Eur Heart J*. 2014;35 (41):2873-2926. doi:10.1093/eurheartj/ehu281

5. Isselbacher EM. Thoracic and abdominal aortic aneurysms. *Circulation*. 2005;111(6):816-828. doi:10.1161/01.CIR.0000154569.08857.7A

6. Turkbey EB, Jain A, Johnson C, et al. Determinants and normal values of ascending aortic diameter by age, gender, and race/ethnicity in the Multi-Ethnic Study of Atherosclerosis (MESA). *J Magn Reson Imaging*. 2014;39(2):360-368. doi:10.1002/jmri.24183

7. Sharma S, Maron BJ, Whyte G, Firoozi S, Elliott PM, McKenna WJ. Physiologic limits of left ventricular hypertrophy in elite junior athletes: relevance to differential diagnosis of athlete's heart and hypertrophic cardiomyopathy. *J Am Coll Cardiol*. 2002;40(8):1431-1436. doi:10.1016/S0735-1097(02)02270-2

8. Pelliccia A, Maron BJ, Spataro A, Proschan MA, Spirito P. The upper limit of physiologic cardiac hypertrophy in highly trained elite athletes. *N Engl J Med*. 1991;324(5):295-301. doi:10.1056/NEJM199101313240504

9. Iskandar A, Thompson PD. A meta-analysis of aortic root size in elite athletes. *Circulation*. 2013; 127(7):791-798. doi:10.1161/CIRCULATIONAHA.112.000974

10. D'Andrea A, Cocchia R, Riegler L, et al. Aortic root dimensions in elite athletes. *Am J Cardiol*. 2010;105(11):1629-1634. doi:10.1016/j.amjcard.2010.01.028

11. Kinoshita N, Mimura J, Obayashi C, Katsukawa F, Onishi S, Yamazaki H. Aortic root dilatation among young competitive athletes: echocardiographic screening of 1929 athletes between 15 and 34 years of age. *Am Heart J*. 2000;139(4):723-728. doi:10.1016/S0002-8703(00)90055-3

12. Gati S, Malhotra A, Sedgwick C, et al. Prevalence and progression of aortic root dilatation in highly trained young athletes. *Heart*. 2019;105(12):920-925. doi:10.1136/heartjnl-2018-314288

13. Boraita A, Heras ME, Morales F, et al. Reference values of aortic root in male and female white elite athletes according to sport. *Circ Cardiovasc Imaging*. 2016;9(10):e005292. doi:10.1161/CIRCIMAGING.116.005292

14. Pelliccia A, Di Paolo FM, De Blasiis E, et al Prevalence and clinical significance of aortic root dilation in highly trained competitive athletes. *Circulation*. 2010;122(7):698-706. doi:10.1161/CIRCULATIONAHA.109.901074

15. Engel DJ, Schwartz A, Homma S. Athletic cardiac remodeling in US professional basketball players. *JAMA Cardiol*. 2016;1(1):80-87. doi:10.1001/jamacardio.2015.0252

16. Lincoln A, Vogel R, Tucker A, Dunn R, Castle L, Kovacs R. Abstract 16812: aortic size in National Football League scouting combine participants. *Circulation*. 2013;128(suppl 22):A16812-A16812.

17. Shapero K, Deluca J, Contursi M, et al. Cardiovascular risk and disease among masters endurance athletes: insights from the Boston MASTER (Masters Athletes Survey To Evaluate Risk) initiative. *Sports Med Open*. 2016;2:29. doi:10.1186/s40798-016-0053-0

18. Saura D, Dulgheru R, Caballero L, et al. Two-dimensional transthoracic echocardiographic normal reference ranges for proximal aorta dimensions: results from the EACVI NORRE study. *Eur Heart J Cardiovasc Imaging*. 2017;18(2):167-179. doi:10.1093/ehjci/jew053

19. Devereux RB, de Simone G, Arnett DK, et al. Normal limits in relation to age, body size and gender of two-dimensional echocardiographic aortic root dimensions in persons ≥15 years of age. *Am J Cardiol*. 2012;110(8):1189-1194. doi:10.1016/j.amjcard.2012.05.063

20. Campens L, Demulier L, De Groote K, et al. Reference values for echocardiographic assessment of the diameter of the aortic root and ascending aorta spanning all age categories. *Am J Cardiol*. 2014;114(6):914-920. doi:10.1016/j.amjcard.2014.06.024

21. Mitchell C, Rahko PS, Blauwet LA, et al. Guidelines for performing a comprehensive transthoracic echocardiographic examination in adults: recommendations from the American

Society of Echocardiography. *J Am Soc Echocardiogr*. 2019;32(1):1-64. doi:10.1016/j.echo.2018.06.004

22. Lang RM, Badano LP, Mor-Avi V, et al 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*. 2015;28(1):1-39.e14. doi:10.1016/j.echo.2014.10.003

23. Braverman AC, Harris KM, Kovacs RJ, Maron BJ; American Heart Association Electrocardiography and Arrhythmias Committee of Council on Clinical Cardiology, Council on Cardiovascular Disease in Young, Council on Cardiovascular and Stroke Nursing, Council on Functional Genomics and Translational Biology, and American College of Cardiology. Eligibility and disqualification recommendations for competitive athletes with cardiovascular abnormalities: task force 7: aortic diseases, including Marfan syndrome: a scientific statement from the American Heart Association and American College of Cardiology. *Circulation*. 2015;132(22):e303-e309. doi:10.1161/CIR.0000000000000243

24. Lancellotti P, Badano LP, Lang RM, et al. Normal Reference Ranges for Echocardiography: rationale, study design, and methodology (NORRE Study). *Eur Heart J Cardiovasc Imaging*. 2013;14(4):303-308. doi:10.1093/ehjci/jet008

25. Darling EA. The effects of training: a study of the Harvard University crews. *Boston Med Surg J*. 1899;141(10):229-233. doi:10.1056/NEJM189909071411001

26. Henschen S. Skidlauf und skidwettlauf: eine medizinische sportstudie. *Mitt Med Klin Upsala*. 1899;2:15-18.

27. Wasfy MM, Weiner RB, Wang F, et al. Endurance exercise-induced cardiac remodeling: not all sports are created equal. *J Am Soc Echocardiogr*. 2015;28(12):1434-1440. doi:10.1016/j.echo.2015.08.002

28. Arbab-Zadeh A, Perhonen M, Howden E, et al. Cardiac remodeling in response to 1 year of intensive endurance training. *Circulation*. 2014;130 (24):2152-2161. doi:10.1161/CIRCULATIONAHA.114.010775

29. Baggish AL, Wang F, Weiner RB, et al Training-specific changes in cardiac structure and function: a prospective and longitudinal assessment of competitive athletes. *J Appl Physiol (1985)*. 2008;104(4):1121-1128. doi:10.1152/japplphysiol.01170.2007

30. Sharma S, Elliott PM, Whyte G, et al. Utility of metabolic exercise testing in distinguishing hypertrophic cardiomyopathy from physiologic left ventricular hypertrophy in athletes. *J Am Coll Cardiol*. 2000;36(3):864-870. doi:10.1016/S0735-1097(00)00816-0

31. Gentry JL 3rd, Carruthers D, Joshi PH, et al. Ascending aortic dimensions in former National Football League athletes. *Circ Cardiovasc Imaging*. 2017;10(11). doi:10.1161/CIRCIMAGING.117.006852

32. Weiner RB, Wang F, Isaacs SK, et al. Blood pressure and left ventricular hypertrophy during American-style football participation. *Circulation*. 2013;128(5):524-531. doi:10.1161/CIRCULATIONAHA.113.003522

33. D'Andrea A, Cocchia R, Riegler L, et al. Aortic stiffness and distensibility in top-level athletes.

J Am Soc Echocardiogr. 2012;25(5):561-567. doi:10.1016/j.echo.2011.12.021

34. Erol MK, Yilmaz M, Oztasyonar Y, Sevimli S, Senocak H. Aortic distensibility is increasing in elite athletes. *Am J Cardiol*. 2002;89(8):1002-1004. doi:10.1016/S0002-9149(02)02260-9

35. Kasikcioglu E, Oflaz H, Akhan H, et al. Left ventricular remodeling and aortic distensibility in elite power athletes. *Heart Vessels*. 2004;19(4):183-188. doi:10.1007/s00380-004-0765-9

36. Dupont AC, Poussel M, Hossu G, et al. Aortic compliance variation in long male distance triathletes: a new insight into the athlete's artery? *J Sci Med Sport*. 2017;20(6):539-542. doi:10.1016/j.jsams.2016.10.009

37. Otsuki T, Maeda S, Iemitsu M, et al. Relationship between arterial stiffness and athletic training programs in young adult men. *Am J Hypertens*. 2007;20(9):967-973. doi:10.1016/j.amjhyper.2007.05.001

38. Levine BD, Baggish AL, Kovacs RJ, Link MS, Maron MS, Mitchell JH. Eligibility and disqualification recommendations for competitive athletes with cardiovascular abnormalities: task force 1: classification of sports: dynamic, static, and impact: a scientific statement from the American Heart Association and American College of Cardiology. *J Am Coll Cardiol*. 2015;66(21):2350-2355. doi:10.1016/j.jacc.2015.09.033

39. Clifford PS, Hanel B, Secher NH. Arterial blood pressure response to rowing. *Med Sci Sports Exerc*. 1994;26(6):715-719. doi:10.1249/00005768-199406000-00010

40. Baggish AL, Wood MJ. Athlete's heart and cardiovascular care of the athlete: scientific and clinical update. *Circulation*. 2011;123(23):2723-2735. doi:10.1161/CIRCULATIONAHA.110.981571