A Meta-Analysis of Aortic Root Size in Elite Athletes

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***Background*—**The aorta is exposed to hemodynamic stress during exercise, but whether or not the aorta is larger in athletes is not clear. We performed a systematic literature review and meta-analysis to examine whethere athletes demonstrate increased aortic root dimensions compared with nonathlete controls.

***Methods and Results*—**We searched MEDLINE and Scopus from inception through August 12, 2012, for English-language studies reporting the aortic root size in elite athletes. Two investigators independently extracted athlete and study characteristics. A multivariate linear mixed model was used to conduct meta-regression analyses. We identified 71 studies reporting aortic root dimensions in 8564 unique athletes, but only 23 of these studies met our criteria by reporting aortic root dimensions at the aortic valve annulus or sinus of Valsalva in elite athletes (n=5580). Athletes were compared directly with controls (n=727) in 13 studies. On meta-regression, the weighted mean aortic root diameter measured at the sinuses of Valsalva was 3.2 mm (*P*=0.02) larger in athletes than in the nonathletic controls, whereas aortic root size at the aortic valve annulus was 1.6 mm (*P*=0.04) greater in athletes than in controls.

***Conclusions*—**Elite athletes have a small but significantly larger aortic root diameter at the sinuses of Valsalva and aortic valve annulus, but this difference is minor and clinically insignificant. Clinicians evaluating athletes should know that marked aortic root dilatation likely represents a pathological process and not a physiological adaptation to exercise. **(*Circulation*. 2013;127:791-798.)**

Key Words: aorta ■ exercise ■ remodeling

Athletic training induces changes in cardiac structure commonly described as the athlete's heart. These changes can include enlargement of all 4 cardiac chambers[1,2] and are considered benign physiological adaptations to the hemodynamic load associated with systemic training.[2] The cardiac adaptations to different forms of athletic conditioning tend to produce disparate morphological forms of the athlete's heart. Endurance training, such as distance running, mimics volume overload and produces increased cardiac chamber diameters and volumes, whereas strength training mimics pressure overload and is associated with increased left ventricular wall thickness. These differences are not a rigid, dichotomous classification but rather a spectrum,[3,4] and some studies show that the wall thickness changes attending strength training disappear after adjustment for body size.[5] It has been hypothesized that the hemodynamic load during exercise and particularly pressure overload during strength training may also lead to aortic remodeling.[6,7] The cardiac adaptations induced by athletic conditioning have been the subject of numerous studies, but investigations of the aorta in athletes have been limited, and it is not clear whether the hemodynamic overload during exercise training affects aortic root dimensions. Aortic dissection and rupture are occasional[8,9] but rare causes of sudden death in athletes,[10,11] and such events increase with increasing aortic diameter in nonathletes. Furthermore, bicuspid aortic valve (BAV) is the most frequent congenital cardiac anomaly, occurring in 1% to 2% of the entire population,[12] and is associated with aortic root dilatation and aortic dissection or rupture.[13] Because the effect of exercise training on aortic size and therefore the risk of aortic complications are unclear, we performed a systematic review of the medical literature and applied meta-analytic techniques to determine whether either endurance or strength training is associated with increased aortic dimensions.

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Methods

We followed the protocols for meta-analysis of observational studies in epidemiology.[14]

Data Source and Searches

We searched MEDLINE and Scopus from its inception through August 12, 2012, using the following search terms: *athlete*, *athletes*, *athletic*, *athletic performance*, *athletic training*, *sports person*, *sports persons*, *heart*, *hearts*, *aorta*, *aortic*, *aortic root*, *ventricle*, *ventricles*, and *atrium* (Appendix I in the online-only Data Supplement). In addition, we manually reviewed the references of included studies

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and of review articles and meta-analyses on the athlete's heart to identify additional articles not found by the initial search.

Study Selection

Studies had to meet the following criteria to be included: (1) explicitly stated that the evaluated athletes were elite competing at an international or national level (including National Collegiate Athletic Association); (2) reported absolute mean aortic root diameter measured at the aortic valve annulus or at the sinuses of Valsalva; (3) mean age of the study cohort was between 15 and 40 years; and (4) reported a measure of statistical variance (SD, SE, or confidence interval). Study arms that included nonelite athletes or children, reported populations that potentially overlapped with other studies, or did not report a measure of statistical variance for the aortic root data were excluded. One investigator performed article screening and selection. We first screened citations and then reviewed the full text of all titles and abstracts indicating that investigators evaluated the heart in athletes with echocardiography, computed tomography, or magnetic resonance imaging. For 26 studies, authors were contacted to request missing data because these articles did not specify where the aortic root was measured; sufficient responses were received for 20 of 26 studies.

Data Extraction

Two investigators independently performed the data extraction, with discrepancies resolved by consensus. We classified the athletes into strength, endurance, and combined groups according to the intensity level of the static and dynamic components.[3] Heterogeneous groups of athletes of different sports classifications were categorized as mixed. In longitudinal exercise training studies, the aortic root diameter after the longest exercise exposure was used.

Data Synthesis and Analysis

Aortic dimensions were pooled with the use of meta-analytic methods. Random-effects meta-analyses and meta-regression analyses were conducted to determine how exercise and other important study characteristics influenced root dimensions. A multivariate linear mixed model was used to conduct meta-regression analyses. We conducted separate analyses for aortic dimensions measured at the aortic valve annulus and at the sinuses of Valsalva. Both random and fixed effects were used for meta-regression, which was weighted by the inverse of the variance of the aortic root diameter.[15] Fixed effects were assumed for study-level factors, including participant type (athlete/control), gender, and country of study origin. We also performed subgroup analysis of studies including only endurance- or strength-trained athletes when sample size permitted determination of the impact of these forms of exercise training on aortic root diameter.

We constructed a funnel plot of the SE versus the aortic root diameter to evaluate publication bias using StatsDirect version 2.7.9 (StatsDirect Ltd, Cheshire, UK). The funnel plot was examined visually and tested for asymmetry with Egger's test.[16] Heterogeneity across studies was assessed by calculating I^2 statistics, which measure the proportion of overall variation that is attributable to between-study heterogeneity rather than chance. I^2 statistic >50% was defined as significant.[17] Statistical analysis was performed with the use of SAS (PROC MIXED) version 9.2 (SAS Institute, Cary, NC), with statistical significance set at 0.05.

Results

Our systematic search identified 25|198 nonduplicate citations, and, from these, 850 full-text articles were identified for review (Figure 1). Of these, 827 were excluded for various reasons but most commonly because aortic diameter measurement was not reported. We identified 71 studies reporting absolute aortic root dimensions in 8564 unique athletes. However, we excluded 48 of these studies because they (1) included nonelite athletes in their study cohort (n=30); (2) did not specify the location of aortic root measurement (n=9); (3) measured the aortic root at locations other than the sinus of Valsalva or aortic valve annulus (n=8); or (4) included athletes with mean age >40 years (n=1). A final total of 23 studies met our inclusion criteria,[7,18–39] with athletes directly compared with controls in 13 studies.[7,18,20–23,27,29,33,35,36,38,39]

The identified studies included 19 cross-sectional and 4 longitudinal studies conducted in Europe (n=14), the United States (n=6), Africa (n=2), and Iran (n=1). Across the studies, aortic root dimensions were reported in 5580 unique elite athletes comprised of 1506 endurance-trained athletes, 425 strength-trained athletes, 213 combined endurance- and strength-trained athletes, and a heterogeneous group of 3436 athletes with mixed training. Our analysis included 727 controls. Sample sizes ranged from 11 to 1403 participants, and echocardiography was used to measure aortic root size in all studies. Aortic root was measured at the aortic valve annulus in 15 studies[7,18–20,23–25,27,28,30,31,34,36,38,39] and at the sinuses of Valsalva in 12 studies.[7,21–24,26,28,29,32,33,35,37] (Tables 1 and 2).

In the 13 studies that directly compared athletes with controls, there were variations in the degree of matching; 11 studies matched for age, and 3 studies explicitly stated that they matched for body size.[7,27,35] One study stated that the 2 arms were matched without further specification,[20] and 2 studies did not report whether the study arms were matched.[18,36] Of the 10 studies that did not explicitly state whether they matched for body size, 4 studies provided mean values for body surface area (BSA) and/or height in controls that were either greater than or not significantly different from the values in the athletes.[18,20,33,38] In 4 studies, mean values for BSA and/or height were significantly greater in athletes than in their controls,[21–23,29] and 2 studies did not statistically compare body size measurements.[36,39]

Most studies did not specify whether athletes with BAV were included, although 2 and 4 studies, respectively, explicitly included[32,33] or excluded[7,23,24,28] subjects with BAV. The incidence of athletes with BAV was 0.1% in both studies that included such athletes. Similarly, the majority of studies (21 of 23) did not state whether athletes with Marfan syndrome were included or excluded from the study cohort, and only 2 studies explicitly stated that they excluded patients with Marfan syndrome (1 athlete in each study, resulting in the incidence of Marfan syndrome of 0.1% to 2% in those 2 athletic cohorts).

Weighted mean aortic root dimensions in men generated by univariate subgroup analysis were 31.6 mm (95% confidence interval, 30.2–33.1) at the sinuses of Valsalva and 30.8 mm (95% confidence interval, 29.9–31.8) at the aortic valve annulus. Weighted mean aortic root dimension in elite female athletes at the sinuses of Valsalva was 25.1 mm (95% confidence interval, 22.9–27.3). Analysis of the aortic valve annulus dimensions in female athletes was not possible because of the paucity of studies for this group.

Meta-regression analysis demonstrated that pooled mean aortic root diameter at the sinuses of Valsalva was 3.2 mm (P=0.02) greater in athletes than in controls, whereas aortic root size at the aortic valve annulus was 1.6 mm (P=0.04) greater in athletes than in controls.

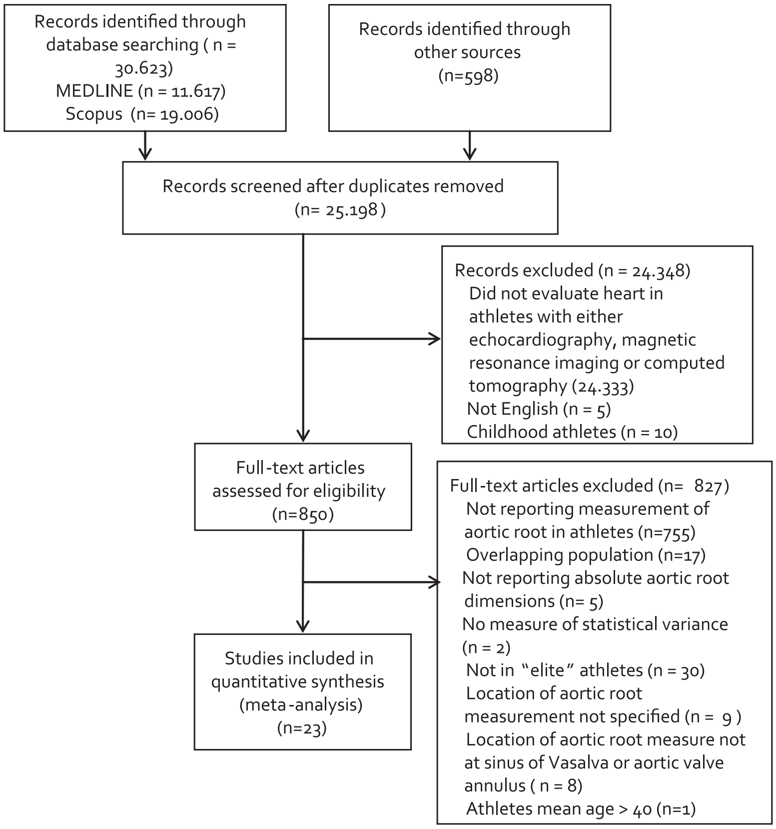

Figure 1. Results of the literature search and disposition of articles screened for inclusion. n indicates number of studies.

We assessed the influence of other study-level factors on aortic root dimensions, and men were found to have a 4.1-mm larger aortic root diameter at the aortic valve annulus than women (*P*=0.04). The aortic root at the sinuses of Valsalva in men was also 4.7 mm greater than in women, but this was not statistically significant (*P*=0.23). Study location did not have a statistically significant effect on aortic root diameters (Tables 3 and 4).

Subgroup analysis confined to the endurance-trained and strength-trained athletes demonstrated that the aortic valve annulus in endurance athletes was 2.2 mm greater than that in controls (*P*=0.03), whereas aortic valve annulus in strength-trained athletes was 1.5 mm greater than that in controls, which did not reach statistical significance (*P*=0.13). We attempted similar subgroup analyses for the aortic root dimensions at the sinuses of Valsalva, but the small number of available studies measuring the aortic root at this location precluded meaningful analysis.

There was significant statistical heterogeneity for pooling of both of the studies measuring the aortic valve annulus and sinuses of Valsalva (I^2=99% and I^2=99.5%, respectively). We produced separate funnel plots for studies measuring the aortic root at the aortic valve annulus and at the sinuses of Valsalva. There was no evidence of publication bias on the basis of either visual inspection of the funnel plot (Figure 2) or Egger's regression test (*P*=0.99) for the studies measuring the aortic root dimensions at the sinuses of Valsalva. The funnel plot for studies measuring the aortic valve annulus (Figure 3) suggested possible publication bias, but the Egger's regression test did not achieve statistical significance (*P*=0.77).

Discussion

The purpose of this meta-analysis was to investigate whether elite athletes have increased aortic dimensions associated with their exercise training. Our meta-analysis of 5580 athletes and 727 controls suggests that athletes have larger aortic root diameters, especially at the sinuses of Valsalva. This effect is statistically significant but small because aortic diameters in athletes were only 3.2 mm on average greater than those in comparison subjects at the sinuses of Valsalva and 1.6 mm on average greater at the aortic valve annulus. The aortic root enlargement associated with exercise is 2-fold larger at the sinuses of Valsalva than at the aortic valve annulus. The aortic valve annulus is part of the fibrous skeleton of the heart and therefore may be less likely to remodel with exercise training.

Analysis of included study results with the use of a random-effects meta-analysis demonstrates that the 95% confidence limit of aortic size at the sinuses of Valsalva in elite athletes is only 33.and 27.3 mm for men and women, respectively. This further emphasizes that the effects of exercise training on aortic diameters are small and that marked enlargement suggests a pathological process. This is the first systematic review and meta-analysis to answer this important question and provides the most vigorous and reliable evidence to date of how systematic athletic training affects the aortic root in a large population of elite athletes. The difference in aortic size was most pronounced in elite endurance athletes compared with controls. The slightly larger aortic diameters in strength-trained athletes versus controls did not reach statistical significance. Our results suggest that mild aortic enlargement is a normal adaptation to exercise training, but our results also indicate that large increases in aortic size are unusual

Table 1. Subject Characteristics in Studies Measuring Aortic Root Dimensions at the Aortic Valve Annulus

Author, Year of Study	Study Group	n	Sex	Training Regimen*	Duration of Training, y*	Age, y*	Height, cm*	BSA, m²*	AoD, mm*
Babaee Bigi,2007[7]	ST athletes;sport type NR	100	M	NR	NR	22 (4)	181 (7)	NR	25.1 (2.9)
	Control subjects	128	M			22 (3)	183 (9)	NR	21.8 (2.4)
Bossone,2004[18]	ET athletes;ice hockey	26	M	≥10 h/wk†	12.3 (3.9)	20 (2)	NR	NR	32 (3)
	Control subjects	14	M			19 (1)	NR	NR	30 (2)
Calderón,2010[19]	CT athletes;sprinting	34	M	NR	≥10†	23 (2)	178 (10)	NR	30.5 (2.3)
	ET athletes;running	42	M	NR	≥10†	25 (3)	181 (8)	NR	31 (1.5)
Carlsson,2011[20]	ET athletes;skiing	10	M	NR	>10†	28 (5)	180 (4)	1.9 (0.1)	30.4 (3.2)
	Control subjects	10	M			28 (7)	181 (6)	2.0 (0.1)	28.4 (4.4)
D'Andrea,2010[24]	ET athletes;long- and middle-distance swimming and running, soccer, basketball	370	M/F	15–20 h/wk†	>4†	28 (10)	NR	1.84 (0.5)	21 (6)
	ST athletes;bodybuilding, weight lifting, martial arts, windsurfing	245	M/F	15–20 h/wk†	>4†	29 (10)	NR	1.89 (0.6)	25 (4)
D'Andrea,2012[23]	Control subjects	240	M/F			28 (11)	NR	1.84 (0.6)	21 (6)
Deligiannis,1992[25]	ST athletes;weight lifting	15	M	11.5 (2.5) h/wk	6.2 (2.1)	23 (5)	174 (5)	NR	28.2 (3.6)
	ST athletes;weight lifting	15	M	11.8 (3.1) h/wk	6.4 (2.2)	23 (5)	173 (5)	NR	30.3 (4.1)
Dzudie,2007[27]	ET athletes;handball	21	M	11 (2) h/wk	10 (3)	25 (3)	178 (7)	1.95 (0.2)	29.6 (3.6)
	Control subjects	21	M			25 (3)	178 (7)	1.96 (0.2)	30.3 (2.8)
Galanti,2010[28]	ET athletes;soccer	196	NR	NR	NR	25 (5)	179 (6)	1.93 (0.1)	26.1 (4.6)
Lamont,1980[30]	ET athletes;swimming	11	F	15–20 h/wk†	5.3 (5)	21 (4)	170 (5)	1.7 (0.1)	28 (2)
Lewis,1989[31]	MT athletes;8 sports	265	M/F	NR	NR	19 (NR)	NR	NR	31 (3)
Rawlins,2010[34]	MT athletes;sport type NR	240	F	13.7 (3.4) h/wk	NR	21 (5)	171 (8)	1.78 (0.2)	27.2 (2.9)
	MT athletes;sport type NR	200	F	14.4 (6.1) h/wk	NR	20 (4)	170 (8)	1.73 (0.2)	26.4 (3.5)
Spataro,1985[36]	ET athletes;long-distance running	17	M	NR	NR	26 (4)	NR	1.8 (0.1)	30.7 (1.9)
	ET athletes;volleyball	16	M	NR	NR	23 (4)	NR	2.1 (0.1)	30.0 (2.7)
	ET athletes;soccer	50	M	NR	NR	24 (5)	NR	1.8 (0.1)	30.0 (3.0)
	ET athletes;basketball	22	M	NR	NR	25 (3)	NR	2.3 (0.2)	34.0 (3.2)
	ET athletes;fencing	18	M	NR	NR	26 (4)	NR	1.9 (0.1)	31.0 (2.1)
	ST athletes;bobsleigh racers	15	M	NR	NR	24 (3)	NR	2.0 (0.1)	31.0 (1.8)
	ST athletes;bodybuilding	14	M	NR	NR	22 (4)	NR	2.0 (0.2)	31.6 (3.1)
	ST athletes;weight lifting	21	M	NR	NR	26 (6)	NR	2.2 (0.3)	32.1 (2.3)
	CT athletes;road cycling	30	M	NR	NR	20 (2)	NR	1.9 (0.1)	31.9 (2.0)
	CT athletes;rowing	30	M	NR	NR	21 (3)	NR	2.0 (0.9)	32.8 (2.8)
	CT athletes;track cycling	14	M	NR	NR	20 (1)	NR	2.0 (0.1)	31.6 (2.8)
	CT athletes;canoeing	13	M	NR	NR	20 (2)	NR	1.9 (0.8)	31.3 (2.9)
	CT athletes;jump sprinting	11	M	NR	NR	24 (5)	NR	1.8 (0.1)	29.9 (2.2)
	Control subjects	50	M			23 (4)	NR	1.7 (0.2)	29.3 (0.3)
Whyte,1999[38]	CT athletes;triathletes	18	M	26.5 (2.1) h/wk	5.6 (1)	29 (6)	179 (7)	1.91 (0.1)	28.8 (5.1)
	CT athletes;pentathletes	11	M	28.5 (3.2) h/wk	7.4 (1.2)	27 (5)	182 (7)	1.93 (0.1)	33.5 (2.1)
	Control subjects	13	M			29 (3)	179 (5)	1.9 (0.2)	31.1 (1.9)
Wieling,1981[39]	CT athletes;oarsmen	14	M	10–14 h/wk	≥2 seasons†	23 (2)	187 (5)	2.1 (0.1)	31.2 (2)
	Control subjects	17	M			22 (4)	184 (8)	1.93 (0.2)	29.9 (2.8)

AoD indicates aortic root diameter at aortic valve annulus; BSA, body surface area; CT, combined endurance- and strength-trained; ET, endurance-trained; F, female; M, male; MT, mixed-trained; n, number of participants; NR, not reported; and ST, strength-trained.

*Mean (SD) unless otherwise specified.

†Range.

in athletes and are therefore consistent with a pathological process, perhaps exacerbated by exercise training.

Most studies included in our meta-analysis did not focus on aortic dimensions in athletes, and we had to extract aortic dimensions from their results. One study that evaluated mean aortic root dimensions and the prevalence of aortic root dilatation in 2317 Italian athletes[40] was not included in our meta-analysis. We did not include this large study because we sought to include only athletes defined as elite or at the national level by the authors, and this Italian study included

Table 2. Subject Characteristics in Studies Measuring Aortic Root Dimensions at the Sinuses of Valsalva

Author, Year	Study Group	n	Sex	Training Regimen†	Duration of Training, y*	Age, y*	Height, cm*	BSA, m²*	AoD, mm*
Babaee Bigi,2007[7]	ST athletes;sport type NR	100	M	NR	NR	22 (4)	181 (7)	NR	38.2 (4.1)
	Control subjects	128	M			22 (3)	183 (9)	NR	31.6 (3.2)
Caselli,2011[21]	MT athletes;27 sports	429	M/F	NR	≥3†	26 (5)	NR	2.0 (0.2)	31.0 (3.8)
	Control subjects	98	M/F			27 (5)	NR	1.8 (0.2)	28.7 (3.3)
Crouse,1992[22]	ET athletes;basketball	15	F	NR	NR	20 (1)	178 (6)	1.9 (0.1)	25.7 (3.3)
	Control subjects	20	F			20 (2)	165 (5)	1.6 (0.1)	21.7 (2.4)
D'Andrea,2010[24]	ET athletes;long- and middle-distance swimming and running, soccer, basketball	370	M/F	15–20 h/wk	>4†	28 (10)	NR	1.84 (0.5)	31 (6)
	ST athletes;bodybuilding, weight lifting, martial arts, windsurfing	245	M/F	15–20h/wk	>4†	29 (10)	NR	1.89 (0.6)	36 (5)
D'Andrea,2012[23]	Control subjects	240	M/F			28 (11)	NR	1.84 (0.6)	32(3)
Di Paolo,2012[26]	ET athletes;soccer	154	M	≥12 h/wk	≥3†	16 (1)	NR	1.80 (0.1)	30 (3.9)
Galanti,2010[28]	ET athletes;soccer	196	NR	NR	NR	25 (5)	179 (6)	1.93 (0.1)	31.0 (5.8)
Krol,2011[29]	CT athletes;cycling and speed skating	38	M/F	NR	NR	25 (3)	186 (10)	2.1 (0.2)	33 (4)
	Control subjects	41	M/F			24 (4)	177 (9)	1.9 (0.2)	29 (2)
Magalski,2011[32]	MT athletes;14 sports	457	M	NR	NR	18–21†	185 (8)	2.2 (0.3)	29 (3)
	MT athletes;14 sports	507	F	NR	NR	18–21†	170 (8)	1.7 (0.2)	25 (3)
Pelliccia,1996[33]	MT athletes;27 sports	600	F	NR	9	21 (5)	167 (8)	1.64 (0.2)	27.6 (2.5)
	MT athletes;25 sports	738	M	NR	3–20†	23 (5)	180 (8)	1.94 (0.2)	30.3 (2)
	Control subjects	65	F			24 (6)	167 (7)	1.62 (0.1)	27 (1.8)
Rubal,1981[35]	ET athletes;softball	9	F	32--42 km/wk	≥1†	19–23†	NR	NR	22 (1)
	Control subjects	10	F			19–24†	NR	NR	23 (1)
Thünenkötter,2009[37]	ET athletes;World Cup soccer	529	M	NR	NR	NR	NR	NR	31 (3)

AoD indicates aortic root diameter at aortic valve annulus; BSA, body surface area; CT, combined endurance- and strength-trained; ET, endurance-trained; F, female; M, male; MT, mixed-trained; n, number of participants; NR, not reported; and ST, strength-trained.
*Mean (SD) unless otherwise specified.
†Range.

Table 3. Results of Base Case and Subgroup Analyses of Aortic Root in Athletes Compared With Controls at the Aortic Valve Annulus

Study-Level Factor	No. of Subjects	Meta-Regression Analysis: Adjusted Difference at Aortic Valve Annulus, mm (95% CI)
Base case analysis		
Participant type		
Athlete	2104	1.6 (0.2 to 3.0)*
Control	493	Reference
Gender		
Male	830	4.1 (0.4 to 7.8)*
Mixed/NA	1316	−2.6 (−7.3 to 2.1)
Female	451	Reference
Study location		
Non-US	2281	−1.5 (−4.0 to 1.0)
US	316	Reference
Subgroup analysis		
Training type		
Endurance athletes	799	2.2 (0.4 to 4.0)*
Strength athletes	425	1.6 (−0.4 to 3.5)
Control subjects	463	Reference

CI indicates confidence interval; NA, not available.
*P<0.05.

athletes competing at the regional level and therefore did not satisfy our inclusion criteria. This study[40] also included some elite athletes who were also included in a study that we included.[33] We could not include both studies because this would result in double counting of some elite athletes, and therefore we elected to include the study[33] examining only elite athletes. Nevertheless, 17 of the 2317 Italian athletes had aortic dilatation, defined as aortic root dimensions ≥99th percentile in the study population (>40 mm in men and >34 mm in women). Fifteen of these 17 athletes demonstrated increases in aortic root dimensions over 8±5 years of follow-up, suggesting, as do our results, that aortic dilatation in athletes represents a pathological process and not a physiological adaptation to exercise.[40]

The results of our meta-analysis cannot directly address the upper limits of normal root size in athletes, nor can they define the level of aortic dilation that would be considered pathological. We suggest that clinicians evaluating athletes make clinical decisions using the nomogram for aortic root size for the general population because the effect of elite training is small and clinically nonsignificant. Commonly used nomograms of aortic root dimensions versus BSA, including that adapted by the American Society of Echocardiography,[41,42] assume a linear correlation between aortic root and BSA, but a study of 92 men and 90 women with heights >95th percentile demonstrated that

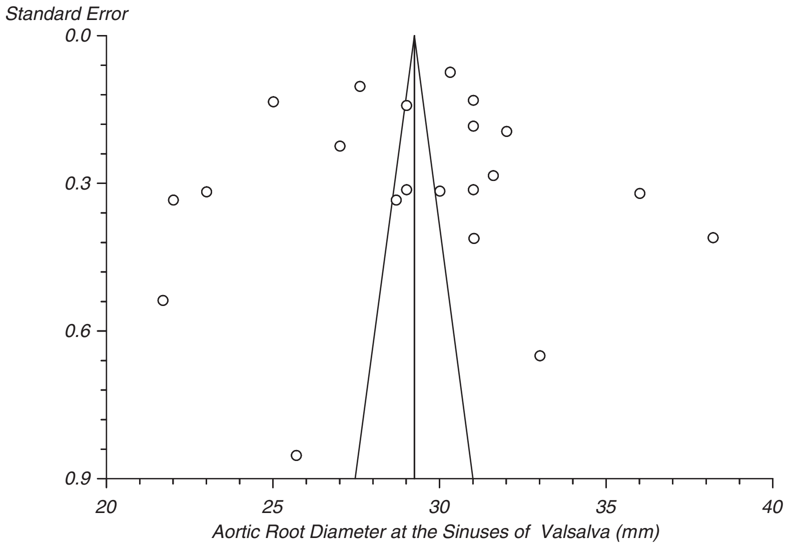

Figure 2. Funnel plot for studies measuring aortic root at the sinus of Valsalva.

aortic root diameter at the sinuses of Valsalva plateaued with increased BSA.[43] Similarly, a nonlinear relationship with a plateau between aortic root dimensions and BSA was observed in a study of 1929 Japanese athletes, of whom 415 (>20%) participated in either basketball or volleyball and had anthropometric measures significantly greater than those of the other athletes.[44] This nonlinear relationship between anthropometric and aortic measurements, which suggests a plateauing of aortic dimensions with increasing height and BSA, further emphasizes the importance of not dismissing markedly enlarged aortas in large athletes as a result of athletic training or body size alone.

BAV is a risk factor for aortic dilatation, although athletic training does not appear to accelerate the increase in aortic size in athletes with BAV.[28] Yearly echocardiograms performed in 88 athletes with BAV for 5 years demonstrated that the proximal ascending aorta increased by 0.98 mm/y.[28] This rate of increases is comparable to that observed in nonathletes with BAV, which ranges among studies from ≈0.2 to 1.9 mm/y.[45] Nevertheless, additional studies focusing solely on aortic root dimension changes in athletes with BAV are needed to evaluate the effect of exercise training on this subgroup of athletes.

Aortic dilatation ≥40 mm in athletes is rare, with a reported prevalence among athletes ranging from 0.26% to 1.2%.[24,40,44] Aortic dissection, aortic rupture, and death may be the first manifestation of aortic dilatation. The risk of these complications increases with aortic size. Aortic events are rare causes of sudden death among athletes, and when they occur, they are often associated with syndromes known to increase the risk of aortic events such as Marfan syndrome. The results of our meta-analysis indicate that any aortic root enlargement that occurs with exercise training is small and that large increases in aortic size are not produced by exercise training alone. The observation that exercise training may increase aortic dimension, however, suggests that the risks and benefits of exercise should be weighed carefully in individuals with conditions predisposing to aortic dilatation.

There are limitations to the present study. Nearly all studies identified were cross-sectional, and we cannot exclude the remote possibility that aortic size in athletes is innately larger than in sedentary subjects even before exercise training. The majority of the studies were conducted in Europe, and only a few studies reported race-specific data, and therefore we

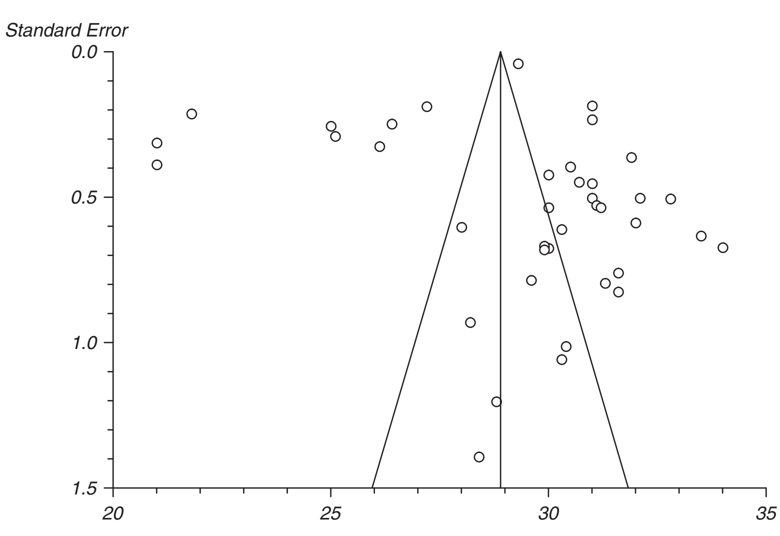

Figure 3. Funnel plot for studies measuring aortic root at the aortic valve annulus.

Table 4. Results of Aortic Root Analyses in Athletes Compared With Controls at the Sinuses of Valsalva

Study-Level Factor	No. of Subjects	Meta-Regression Analysis: Adjusted Difference at Aortic Valve Annulus, mm (95% CI)
Base case analysis		
Participant type		
Athlete	3487	3.2 (0.5 to 5.9)*
Control	602	Reference
Gender		
Male	2106	4.7 (−2.8 to 12.2)
Mixed/NA	1657	2.6 (−4.8 to 9.9)
Female	1226	Reference
Study location		
Non-US	3442	4.9 (−2.3 to 12.1)
US	1547	Reference
Subgroup analysis	Not done because of insufficient number of endurance- or strength- trained only athletes	

CI indicates confidence interval; NA, not available.
*P<0.05.

were unable to examine possible racial or ethnic effects on the results. Most studies did not report whether athletes with Marfan syndrome were excluded from the study cohort. The incidence of classic Marfan syndrome in the general population is ≈2 to 3 per 10|000 individuals, but the incidence is likely increased in certain sports in which height is advantageous, such as volleyball and basketball.[46] We therefore cannot exclude that athletes with Marfan syndrome were included, which theoretically could result in greater aortic root dimensions and cause overestimation of any exercise effect, but we consider this possibility unlikely. There was significant statistical heterogeneity among the included studies, which we attempted to control using multivariate meta-regression analysis.[15] This permits pooling of studies for additional power while adjusting for differences in multiple study-level characteristics, but it is likely that we were unable to adjust for all important sources of heterogeneity and that some confounding factors remain. Our literature review was limited to English-language studies, which can introduce selection bias. We sought to avoid possible misunderstandings and data inaccuracies by not using translated articles, and we suspect that the possibility of selection bias is reduced by the large number of studies available in English.

Few studies carefully matched athletes and controls for anthropometric parameters that affect aortic size such as BSA and height.[7,40–42,44,47] We therefore cannot exclude the possibility that part of the difference in aortic root size may be due to the larger body size of athletes. Despite these limitations, the difference in aortic root diameter between athletes and controls in our analysis was small, suggesting that any training-related increases in aortic size are clinically nonsignificant.

Conclusions

We conclude that elite athletic training is associated with a small but significantly larger aortic root diameter, especially at the sinuses of Valsalva. The magnitude of this increase is clinically nonsignificant, and marked increases in aortic root measurements in athletes should not be attributed to athlete's heart.

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Disclosures

None.

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CLINICAL PERSPECTIVE

The aorta is exposed to hemodynamic stress during exercise, but whether or not the aorta is larger in athletes is not clear. We performed a systematic literature review and meta-analysis to examine whether athletes demonstrate increased aortic root dimensions compared with nonathlete controls. We identified 23 studies reporting aortic root dimensions at the aortic valve annulus or sinus of Valsalva in 5580 unique elite athletes. Athletes were compared directly with controls (n=727) in 13 studies. On meta-regression, the weighted mean aortic root diameter measured at the sinuses of Valsalva was 3.2 mm (P=0.02) larger in athletes than in the nonathletic controls, whereas aortic root size at the aortic valve annulus was 1.6 mm (P=0.04) greater in athletes than in controls. Our analysis shows that elite athletes have a small but significantly larger aortic root diameter at the sinuses of Valsalva and aortic valve annulus, but this difference is minor and clinically insignificant. Clinicians evaluating athletes should know that marked aortic root dilatation likely represents a pathological process and not a physiological adaptation to exercise.