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The Athlete's Heart
A Meta-Analysis of Cardiac Structure and Function

Babette M. Pluim, MD; Aeilko H. Zwinderman, PhD;
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Background—It has been postulated that depending on the type of exercise performed, 2 different morphological forms of athlete's heart may be distinguished: a strength-trained heart and an endurance-trained heart. Individual studies have not tested this hypothesis satisfactorily.

Methods and Results—The hypothesis of divergent cardiac adaptations in endurance-trained and strength-trained athletes was tested by applying meta-analytical techniques with the assumption of a random study effects model incorporating all published echocardiographic data on structure and function of male athletes engaged in purely dynamic (running) or static (weight lifting, power lifting, bodybuilding, throwing, wrestling) sports and combined dynamic and static sports (cycling and rowing). The analysis encompassed 59 studies and 1451 athletes. The overall mean relative left ventricular wall thickness of control subjects (0.36 mm) was significantly smaller than that of endurance-trained athletes (0.39 mm, $P=0.001$), combined endurance- and strength-trained athletes (0.40 mm, $P=0.001$), or strength-trained athletes (0.44 mm, $P<0.001$). There was a significant difference between the 3 groups of athletes and control subjects with respect to left ventricular internal diameter ($P<0.001$), posterior wall thickness ($P<0.001$), and interventricular septum thickness ($P<0.001$). In addition, endurance-trained athletes and strength-trained athletes differed significantly with respect to mean relative wall thickness (0.39 versus 0.44, $P=0.006$) and interventricular septum thickness (10.5 versus 11.8 mm, $P=0.005$) and showed a trend toward a difference with respect to posterior wall thickness (10.3 versus 11.0 mm, $P=0.078$) and left ventricular internal diameter (53.7 versus 52.1 mm, $P=0.055$). With respect to cardiac function, there were no significant differences between athletes and control subjects in left ventricular ejection fraction, fractional shortening, and E/A ratio.

Conclusions—Results of this meta-analysis regarding athlete's heart confirm the hypothesis of divergent cardiac adaptations in dynamic and static sports. Overall, athlete's heart demonstrated normal systolic and diastolic cardiac functions. **(*Circulation*. 1999;100:336-344.)**

Key Words: exercise ■ hypertrophy ■ echocardiography ■ myocardium

Top-level training is often associated with morphological changes in the heart, including increases in left ventricular chamber size, wall thickness, and mass. The increase in left ventricular mass as a result of training is called "athlete's heart."[1] Morganroth et al[2] were the first to postulate that 2 different morphological forms of athlete's heart can be distinguished: a strength-trained heart and an endurance-trained heart. According to their theory, athletes involved in sports with a high dynamic component (eg, running) develop predominantly increased left ventricular chamber size with a proportional increase in wall thickness caused by volume overload associated with the high cardiac output of endurance training. Thus, endurance-trained athletes are presumed to demonstrate eccentric left ventricular hypertrophy, characterized by an unchanged relationship between left ventricular wall thickness and left ventricular radius (ie, ratio of wall thickness to radius). Athletes involved in mainly static or isometric exercise (eg, weightlifting) develop predominantly increased left ventricular wall thickness with unchanged left ventricular chamber size, which is caused by pressure overload accompanying the high systemic arterial pressure found in this type of exercise. Thus, strength-trained athletes are presumed to demonstrate concentric left ventricular hypertrophy, which is characterized by an increased ratio of wall thickness to radius.

Even though the morphology of athlete's heart and the impact of different sports on cardiac structure have been investigated recently by several authors,[3–6] they have not been able to resolve satisfactorily the question regarding the existence of 2 types of athlete's heart. We chose to focus on the basic forms of exercise, ie, dynamic exercise (long-distance running), static exercise (all sports involving the

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throwing and lifting of heavy objects), and combined dynamic and static exercise (cycling and rowing). The hypothesis of divergent cardiac adaptations in endurance- and strength-trained athletes was tested by applying meta-analytical techniques with the assumption of a random study effects model of published data of male athletes engaged in the sports mentioned above. Female athletes were excluded, because to the best of our knowledge no studies on the effect of strength training on the heart of female athletes are available. Cardiac systolic and diastolic functions were also studied to evaluate the relationship between geometry and function of athlete's heart.

Methods

Cardiac Structure

All available echocardiographic studies from the medical literature (from 1975 through 1998) on the anatomic structure of the heart in endurance-trained athletes (long-distance runners), strength-trained athletes (weight lifters, power lifters, bodybuilders, wrestlers, throwers), and athletes involved in combined forms of dynamic and static training (cyclists and rowers) were identified (Tables 1, 2, and 3). The outcome of the studies did not influence inclusion or rejection of data, and the following preset criteria for accepting data in our meta-analysis were applied: homogeneous groups of adult male athletes between 18 and 40 years of age. Nonuniform groups of athletes, women, mixed groups of men and women, children (<18 years) and veterans (>40 years) were excluded. Only original publications were considered; review papers were excluded. Original studies had to include assessment of left ventricular internal diameter and wall thickness. When left ventricular mass was not reported, it was calculated with the Penn-cube formula[7]: $LVM=1.04[(LVIDd+PWTd+IVSTd)^3-LVIDd]-13.6$ g, in which LVM indicates left ventricular mass; LVIDd, left ventricular end-diastolic internal diameter; PWTd, diastolic posterior wall thickness; and IVSTd, diastolic interventricular septum thickness. Relative left ventricular wall thickness was calculated as (PWTd+IVSTd)/LVIDd and expressed as a fraction. When the diastolic interventricular septal thickness was not reported, it was considered to be equal to the diastolic posterior wall thickness.

Cardiac Function

All available echocardiographic studies from the medical literature (from 1975 through 1998) on left ventricular ejection fraction, fractional shortening, and ratio of transmitral peak flow velocity during early left ventricular filling and peak flow velocity during atrial filling (E/A ratio) of endurance-trained athletes, strength-trained athletes, and athletes receiving combined forms of dynamic and static training were identified. The outcome of the studies did not influence inclusion or rejection of data, and the same set of criteria for accepting data as mentioned for cardiac structure assessment was applied. To investigate whether there was any relationship between cardiac geometry and left ventricular systolic and diastolic functions, left ventricular function was studied in the respective subgroups of endurance-trained athletes, combined endurance- and strength-trained athletes, and strength-trained athletes.

Statistical Analysis

The means of the posterior wall thickness, interventricular septum thickness, left ventricular internal diameter, ejection fraction, fractional shortening, and E/A ratio in the individual studies were analyzed by use of a meta-analysis model with a random study effect as described by Dersimonian and Laird.[8] The different groups of athletes were also compared by use of this model. A value of $P \leq 0.05$ was considered statistically significant.

Results

Cardiac Structure

In Table 4, results of echocardiographic data regarding cardiac structure in endurance-trained athletes, strength-trained athletes, combined endurance- and strength-trained athletes, and control subjects are summarized. There were 31 studies of endurance-trained athletes,[2,9–38] 23 studies of combined endurance- and strength-trained athletes,[16,19,24,26,39–57] and 24 studies of strength-trained athletes* included in the meta-analysis. The analysis involved a total of 413 endurance-trained athletes, 494 combined endurance- and strength-trained athletes, 544 strength-trained athletes, and 813 control subjects.

Mean Relative Wall Thickness

The overall mean relative left ventricular wall thickness of control subjects (0.36 mm) was significantly smaller than that of endurance-trained athletes (0.39 mm, $P=0.001$), combined endurance- and strength-trained athletes (0.40 mm, $P=0.001$), or strength-trained athletes (0.44 mm, $P<0.001$). Also, the mean relative wall thickness of endurance-trained athletes was significantly lower than that of strength-trained athletes (0.39 versus 0.44 mm, $P=0.006$). There was no significant difference in mean relative wall thickness between endurance- and combined endurance- and strength-trained athletes ($P=0.04$).

Left Ventricular Internal Diameter

There was a significant difference between the 3 groups of athletes and control subjects with respect to left ventricular internal diameter ($P<0.001$). The endurance-trained athletes and strength-trained athletes showed a trend toward a significant difference with respect to left ventricular internal diameter ($P=0.055$).

Interventricular Septum Thickness

In 6 studies, interventricular septum thickness was not mentioned and was considered to be equal to the posterior septum thickness.[11,15,17,22,27,51] There was a significant difference with respect to interventricular septum thickness between control subjects and endurance-trained athletes (8.8 versus 10.5 mm, $P<0.001$) and between endurance-trained athletes and strength-trained athletes (10.5 versus 11.8 mm, $P=0.005$) but not between endurance-trained athletes and combined endurance-trained and strength-trained athletes ($P=0.042$).

Posterior Wall Thickness

There was a significant difference in posterior wall thickness between control subjects and endurance-trained athletes (8.8 versus 10.3 mm, $P<0.001$) but not between endurance-trained athletes and combined endurance- and strength-trained athletes (10.3 versus 11.0 mm, $P=0.064$) or between endurance-trained athletes and strength-trained athletes (10.3 versus 11.0 mm, $P=0.078$).

Left Ventricular Mass

The overall mean left ventricular mass of the control subjects (174 g) was significantly less than the overall mean left ventricular mass of the endurance-trained athletes (249 g, $P<0.001$), combined endurance- and strength-trained athletes (288 g, $P<0.001$), or strength-trained athletes (267 g,

*References 2, 14, 21, 24, 28–31, 35–37, 44, 45, 48, and 58–67.

TABLE 1. Subject Characteristics: Endurance-Trained Athletes (Runners)

Reference	Study Group	Training	Training, y	$\dot{V}O_2$max	n	Age, y	LVM, g
2	Control subjects				16	19±1	211±8
	Long-distance runners	NR	>3		15	19±1	302±9
9	Control subjects			43±1	26	29 (22–38)	213±9
	Long-distance runners	100 km/wk	9	69±2	20	28 (20–39)	263±13
10	Control subjects			54	10	22	135
	Distance runners	NR	NR	77	20	26	189
11	Control subjects				20	Matched	123
	Marathon runners	120±25 km/wk	Several		12	39±10	212
12	Control subjects			47±7	12	29±4	176±21
	Long-distance runners	108 km/wk	7	74±6	12	26±7	262±39
13	Control subjects			NR	13	24±7	147±21
	Marathon runners	150 km/wk	9.4±4.7	NR	12	29±4	264±44
14	Control subjects			44±3	10	25±1	120±18
	Long-distance runners	126±11 km/wk	6.4±1.2	53±3	12	28±2	198±24
15	Control subjects			41±6	10	27±5	224±18
	Marathon runners	97±11 km/wk	7±1	73±5	8	29±7	316±22
16	Control subjects			NR	17	24	163±50
	Long-distance runners	NR	9	64±10	16	28	278±80
17	Control subjects			NR	14	20±1	177
	Competitive runners	Several hours per day	>6	NR	31	20±1	307
18	Control subjects			35±5	12	56±8	216±24
	Long-distance runners	67–200 km/wk	>20	56±8	9	54±11	274±27
19	Control subjects			49±2	12	26±2	147
	Long-distance runners	64–150 km/wk	7	60±2	12	26±2	215
20	Control subjects				13	24±7	163
	Ultraendurance runners	100–250 km/wk	Several		13	38±8	291
21	Control subjects			NR	10	28±3	216±41
	Long-distance runners	110 km/wk	5.3±1.4	NR	10	20±1	312±59
22	Control subjects			48±8	12	30±4	163±28
	Long-distance runners	>64 km/wk	6.4±3.2	69±1	11	31±6	232±52
23	Control subjects			41±5	26	36±6	153±34
	Marathon runners	119±47 km/wk	Several	65±7	39	37±9	167±32
24	Control subjects			NR	50	23±4	163±17
	Long-distance runners	NR	NR	NR	17	26±4	301±28
25	Control subjects			NR	15	31±6	128±36
	Amateur runners	20 km/wk	0.5	NR	15	31±5	214±54
26	Control subjects			NR	16	27±2	168
	Long-distance runners	NR	Many	NR	5	23±1	225
27				NR			
	Marathon runners	NR	10±2	NR	13	30±2	174
28	Control subjects			NR	33	22±6	168±55
	Long-distance runners	140 km/wk	NR	NR	11	21±2	230±50
29				NR			
	Long-distance runners	7±4 km/wk	8±4	NR	57	30±9	243±45
30	Control subjects			NR	31	NR	191
	World-class runners	NR	Several	NR	4	NR	219
31	Control subjects			44±2	10	24±1	202±6

TABLE 1. Continued

Reference	Study Group	Training	Training, y	$\dot{V}_{O_2}$max	n	Age, y	LVM, g
	Elite endurance runners	70 km/wk	>4	75±1	10	24±2	283±10
32	Control subjects			NR	44	32±5	129
	Marathon runners	90±10 km/wk	>2	NR	23	33±6	217
33	Control subjects			49±7	26	22	178±50
	Long-distance runners	80 km/wk	>2	67±5	15	20	214±37
34				NR			
	Endurance trained	3–6 h/wk	>3	NR	9	38±10	271
35	Control subjects			36±4	10	27±4	249
	Long-distance runners	NR	9±1	58±5	10	26±2	154
36	Runners	80–110 km/wk	>2	NR	8	21 (18–30)	237±76
37	Control subjects				9	31±7	165±23
	Runners	60 km/wk	NR	NR	13	38±9	289±51
38	Control subjects			NR	15	26±3	167±37
	Runners	11±2 km/wk	12±4	NR	32	26±3	263±28

LVM indicates left ventricular mass; NR, not reported.
Values in parentheses are ranges; others are mean±SD.

$P<0.001$). Left ventricular mass did not differ significantly between the 3 groups of athletes.

Cardiac Function

In Table 4, results of echocardiographic data from 50 studies on cardiac function in endurance-trained athletes, strength-trained athletes, combined endurance- and strength-trained athletes, and control subjects are summarized.† There were no significant differences between the athletes and the control subjects with respect to left ventricular ejection fraction, fractional shortening, and E/A ratio.

Discussion

Cardiac Structure

The results of this meta-analysis of athlete's heart demonstrated slightly divergent cardiac adaptations in dynamic and static sports, with an intermediate form of hypertrophy for those sports with combined high static and dynamic components. The development of an endurance-trained heart (eccentric hypertrophy) and a strength-trained heart (concentric hypertrophy) is not to be considered an absolute and dichotomous concept. Endurance-trained runners, who are thought to develop pure eccentric left ventricular hypertrophy, demonstrated a more pronounced increase in wall thickness than expected, in addition to an increase in left ventricular end-diastolic diameter. This resulted in an unexpected increase in relative wall thickness. The strength-trained weight lifters, power lifters, bodybuilders, throwers, and wrestlers, who are considered to develop pure concentric left ventricular hypertrophy, demonstrated an increase in both absolute and relative wall thickness and a significant increase in left ventricular diameter. Consequently, the geometric pattern of athlete's heart is more complicated than expected. Endurance-trained athletes showed a significant increase in left ventricular relative wall thickness ratio instead of a proportional increase in left ventricular wall thickness and internal diameter with a normal relative wall thickness; strength-trained athletes showed an increase in left ventricular diameter in addition to an increase in left ventricular wall thickness. The combined endurance- and strength-trained cyclists and rowers showed a significant increase in relative wall thickness and the highest increase in left ventricular internal diameter. This observation is largely in accordance with the results reported by Spirito et al,[3] who performed the largest study on athlete's heart on 947 elite athletes representing 27 different sports. They ranked sports according to the impact on left ventricular diastolic cavity dimension and left ventricular wall thickness. Rowing was ranked first according to the calculated effect on left ventricular wall thickness (with cycling second), and cycling was ranked first according to the calculated effect on left ventricular internal dimension (with rowing seventh). The authors convincingly demonstrated that sports differ greatly with regard to their impact on left ventricular dimensions and that in general athletes training in sports associated with large diastolic cavity dimensions also have relatively high values of wall thickness.

Endurance-Trained Athletes

Adaptation of the heart to endurance training with an increase in both diameter and wall thickness is useful if we take into account heart rate and blood pressure responses during intense exercise. The cardiac output of trained endurance athletes may increase from 5 to 6 L/min at rest to up to 40 L/min during maximal exercise.[73] The heart adapts to this volume load with an increase in internal diameter. Blood pressure also increases during endurance exercise, although to a lesser extent than during strength training. Blood pressure readings of 175/69 mm Hg during treadmill running were recorded by Palatini et al.[74] In other words, pure volume load during endurance training does not exist; during long-distance running, the heart has to adapt to both a volume and a pressure load, whereby the endurance-trained heart shows

†References 9–14, 17–23, 25, 26, 28, 30–32, 34, 35, 37–42, 44–46, 49–53, and 58–72.

TABLE 2. Subject Characteristics: Combined Endurance- and Strength-Trained Athletes (Cyclists and Rowers)

Reference	Study Group	Training	Training, y	$\dot{V}O_2$max	n	Age, y	LVM, g
39	Control subjects			NR	20	30 (20–39)	132±25
	Professional cyclists	100–700 km/wk	10±6	NR	31	30 (20–39)	187±19
40	Control subjects			NR	17	22±4	236
	Junior rowers	6–12 h/wk	0.6	NR	9	20±2	303
	Senior rowers	10–14 h/wk	>1	NR	14	23±2	160
41	Control subjects			43±7	11	26±2	197±38
	Professional cyclists	Professional	NR	67±6	14	25±2	388±53
42	Control subjects			43±2	12	24±2	192
	Cyclists	600 km/wk	8 (4–10)	61±2	12	24±1	352
16	Control subjects			NR	17	24	163±50
	Competitive cyclists	NR	7	64±10	15	26	337±70
19	Control subjects			44±2	12	24±2	168
	Competitive cyclists	200–900 km/wk	8	64±2	12	23±1	286
44	Control subjects			NR	8	22±4	185±24
	National-level cyclists	Several hours	NR	NR	12	22±4	314±74
24	Control subjects			NR	50	23±4	163±17
	Top-level road cycling	NR	NR	NR	30	20±2	355±30
45	Control subjects			NR	9	21±6	127±37
	Cyclists	3 h/wk	0.4	NR	13	17±4	164±39
26	Control subjects			NR	16	27±2	168
	Road-racing cyclists	NR	NR	NR	15	23±1	234
46	Control subjects			50±7	16	23±4	169±30
	Competitive cyclists	534 km/wk	7	72±6	16	22±5	311±60
47	Olympic cyclists	14–20 h/wk	NR	72±3	8	24±4	262±20
48	Control subjects			NR	10	24±5	219±15
	Competitive cyclists	Professional	NR	NR	14	22±3	418±31
43	Competitive cyclists	Professional	NR	NR	23	29±2	284±36
49	Top-level rowers	30 h/wk	NR	NR	15	22±6	315±27
50	Control subjects			NR	16	21–30	171±33
	Professional cyclists	>40 h/wk	7	NR	16	21–30	354±47
51	Olympic rowers	12 Sessions	NR	NR	6	24±4	315±19
52	Control subjects			NR	21	26±4	203±28
	Professional cyclists	600–800 km/wk	>5	NR	26	26±3	324±41
53	Control subjects			NR	26	28±8	159±20
	Professional cyclists	Professional	8	NR	69	27±4	287±47
54	Professional cyclists	750 km/wk	>10	NR	40	26±3	273±65
55	Professional cyclists	580 km/wk	>3	74±3	40	26±3	274±36
56	Control subjects			NR	32	22±4	214±48
	Rowers	National/regional	NR	NR	64	21±4	256±45
57	Rowers	NR	NR	55.6±8	8	23±6	208±46

LVM indicates left ventricular mass; NR, not reported.
Values in parentheses are ranges; others are mean±SD.

an increase in both left ventricular internal diameter and left ventricular wall thickness.

Strength-Trained Athletes

Adaptation of the heart to strength training with a slight increase in left ventricular internal diameter and a large increase in left ventricular wall thickness can be explained on the basis of blood pressure response and cardiac output during weight lifting.[75–78] During heavy-resistance exercise, arterial blood pressure shows a large increase, amounting to values to 480/350 mm Hg.[75] However, heart rate and cardiac output do not remain unchanged but show an increase during strength training. MacDougall et al[75] demonstrated that heart rate during weight lifting ranged

TABLE 3. Subject Characteristics: Strength-Trained Athletes (Weight Lifters, Power Lifters, Bodybuilders, Wrestlers, Throwers)

Reference	Study Group	Training, h/wk	Training, y	$\dot{V}_{O_2}$max	n	Age, y	LVM, g
2	Control subjects			NR	16	19±1	211±8
	Wrestlers	Daily	>3	NR	12	20±1	330±16
14	Control subjects			33±2	14	27±1	149±18
	Olympic/power weight lifters	Several	8±2	39±2	17	27±2	184±25
58	National-level weight lifters	15–20	>2	NR	13	19–39	285
44	Control subjects			NR	8	22±4	185±24
	Wrestlers/weight lifters/throwers	NR	NR	NR	18	20±4	259±61
21	Control subjects			NR	10	28±3	216±41
	Wrestlers	10	6±2	NR	10	19±1	326±46
60	Control subjects			NR	22	22±6	167±26
	National power lifters	Daily	>4	NR	11	24±3	380±57
61	Control subjects			NR	15	22 (19–40)	174
	Bodybuilders	8	4±2	NR	15	22 (19–40)	262
24	Control subjects			NR	50	23±4	163±17
	Olympic weight lifters	Several	Many	NR	21	26±6	302±27
45	Control subjects			NR	9	21±6	126±37
	Weight lifters	3	0,4	NR	6	22±4	148±20
62	Control subjects			NR	10	25 (17–39)	165±28
	Weight lifters	>8	>2	NR	16	28 (18–38)	241±70
63	Control subjects			NR	7	23±4	225±51
	Weight lifters	7±2	4±2	NR	12	26±5	242±43
59	Control subjects			NR	10	17±1	216±41
	National junior wrestlers	Daily	9±2	NR	17	18±1	326±46
28	Control subjects			NR	33	22±6	168±55
	Power lifters	NR	>4	NR	11	24±3	373±125
64	Control subjects			NR	10	19±1	197±31
	Throwers	9±2	3±1	NR	10	20±3	216±40
29	Bodybuilders	8±1	8±5	NR	46	27±6	265±55
30	Control subjects			50±7	31	NR	191
	Olympic throwers	Several	Many	38±11	4	NR	430
65	Bodybuilders	10±2	8±4	39±3	7	26±5	214±29
31	Control subjects			44±2	10	24±1	202±6
	Weight lifters	12–20	>3	45±2	10	24±1	261±9
48	Control subjects			NR	10	24±5	219±15
	Weight lifters	NR	NR	NR	10	25±6	354±25
66	Bodybuilders	6±1	>3	NR	11	26±7	135±21
67	Control subjects			NR	26	27±8	167±20
	Weight lifters, bodybuilders, wrestlers, throwers	9–18	>3	NR	100	26±5	194±37
35	Control subjects			36±4	10	27±4	154
	Weight lifters	NR	9±4	42±5	10	26±3	307
36	Weight lifters	>10	>2		16	21 (18–30)	268±94
37	Control subjects				9	31±7	165±23
	Weight lifters	Several	>4		8	30±10	280±66

LVM indicates left ventricular mass; NR, not reported.
Values in parentheses are ranges; others are mean±SD.

TABLE 4. Cardiac Structure and Function in Endurance-Trained Athletes, Combined Endurance and Strength-Trained Athletes, Strength-Trained Athletes, and Control Subjects

	Endurance-Trained Athletes	Combined Endurance- and Strength-Trained Athletes	Strength-Trained Athletes	Control Subjects	*P**
RWT	0.389 (0.374–0.404) (n=413)	0.398 (0.374–0.421) (n=494)	0.442 (0.403–0.480) (n=544)	0.356 (0.343–0.369) (n=813)	<0.001
LVIDd, mm	53.7 (52.8–54.6) (n=413)	56.2 (55.2–57.1) (n=494)	52.1 (50.6–53.6) (n=544)	49.6 (48.9–50.2) (n=813)	<0.001
PWTd, mm	10.3 (10.0–10.6) (n=413)	11.0 (10.3–11.6) (n=494)	11.0 (10.2–11.7) (n=544)	8.8 (8.5–9.0) (n=813)	<0.001
IVSTd, mm	10.5 (10.1–10.9) (n=413)	11.3 (10.6–12.0) (n=494)	11.8 (10.9–12.7) (n=544)	8.8 (8.6–9.1) (n=813)	<0.001
LVM, g	249 (233–264) (n=413)	288 (260–316) (n=494)	267 (234–300) (n=544)	174 (165–183) (n=813)	<0.001
LVEF, %	68.8 (65.1–72.6) (n=177)	66.1 (62.9–69.3) (n=127)	66.3 (60.7–71.9) (n=73)	67.2 (64.5–69.8) (n=296)	0.68
LVFS, %	34.4 (32.6–36.1) (n=204)	34.7 (32.7–36.8) (n=293)	35.7 (33.7–37.7) (n=276)	34.4 (33.5–35.2) (n=491)	0.50
E/A ratio	2.20 (1.49–2.91) (n=93)	1.89 (1.46–2.31) (n=126)	2.11 (1.22–2.99) (n=44)	1.84 (1.64–2.05) (n=132)	0.41

RWT indicates relative wall thickness; LVIDd, left ventricular end-diastolic internal diameter; PWTd, diastolic posterior wall thickness; IVSTd, diastolic interventricular septum thickness; LVM, left ventricular mass; LVEF, left ventricular ejection fraction; and LVFS, left ventricular fractional shortening. Values in parentheses are 95% confidence intervals and n indicates number of studies for which the respective variable for the subsequent group of athletes was reported.

*Mixed-model ANOVA.

from 102 bpm between sets to peak values of 170 bpm during actual lifting. Accordingly, pure pressure load during strength training does not exist.

Combined Endurance- and Strength-Trained Athletes

Rowing and cycling represent typical strength and endurance sports involving combined dynamic and static exercise of large groups of muscles. Top-level cyclists can perform with a near-maximal heart rate for long periods of time, sometimes up to 6 hours. Systolic and mean arterial blood pressures also are increased during cycling; Systolic blood pressure readings of >200 mm Hg can be found during maximal exercise testing on the bicycle ergometer.[78,79] During rowing, heart rate increases to near-maximal values of ≈190 bpm, with peak systolic blood pressure waves of ≈200 mm Hg.[80] The combination of both extreme volume load and extreme pressure load may explain why the largest increases in left ventricular internal dimension and left ventricular wall thickness are found in cyclists and rowers.

Cardiac Function

Left ventricular systolic function is generally assessed by measuring the extent and velocity of fiber shortening, ejection fraction, and velocity of circumferential fiber shortening.[81] Our meta-analysis shows that in the group of athletes studied, overall systolic function as judged by fractional fiber shortening or ejection fraction is similar to that of sedentary control subjects. We therefore conclude that there is no relation between cardiac geometry and left ventricular systolic function in athlete's heart. However, the parameters used in these studies reflect chamber mechanics rather than myocardial mechanics. Studies of myocardial contractile function in the hypertrophied left ventricle resulting from hypertension suggest that intrinsic myocardial performance may be depressed, even when left ventricular ejection fraction remains normal.[82] However, the presumed innocent nature of the athlete's heart does not allow the performance of more invasive studies in athletes.

Left ventricular diastolic function is commonly assessed by studying the pattern of ventricular filling through the mitral valve.[83] The generally used diastolic function parameter is the E/A ratio. Our meta-analysis demonstrated a normal or slightly enhanced diastolic function in athletes compared with sedentary control subjects. These results should be interpreted with some caution because the E/A ratio not only is related to left ventricular compliance but also is influenced by other factors such as heart rate, preload, and afterload. A slower heart rate may reduce the atrial contribution to left ventricular filling by lengthening diastole. Generally, a normal or slightly enhanced diastolic function in athletes may be considered as a positive finding because in hypertensive patients the increase in left ventricular mass and wall thickness is associated with diastolic filling abnormalities.[84–86]

Potential Study Limitations

Previous reviews only included those studies that used control subjects matched for body size.[87,88] However, in studies of relative wall thickness, it is not mandatory to adjust for body size because body size parameters appear in both the numerator and denominator of the calculation, implying that relative wall thickness is dimensionless. Also body size parameters do not influence left ventricular systolic or diastolic function. It was therefore possible to include studies with control subjects of different body sizes or those without control subjects; thus, the greater number of observations lead to increased statistical power. Body size, however, does influence the diameter and wall thickness of the left ventricle,

and we can therefore not exclude the possibility that part of the differences in heart size may be ascribed to the larger body size of the athletes. Athletes ≥40 years of age and children were excluded from the analysis of cardiac structure and function to eliminate other factors besides training, such as hypertension or age-related increases in wall thickness, which may be responsible for any differences in cardiac mass or geometry.

It would have been interesting to study divergent cardiac adaptations of athlete's heart in women. However, to the best of our knowledge, no literature is available regarding the effects of strength training on the heart of female athletes.

Conclusions

The present meta-analysis on the anatomic structure and function of the heart in endurance-trained athletes, strength-trained athletes, and combined endurance- and strength-trained athletes confirms the hypothesis of the existence of an endurance-trained and a strength-trained heart. Divergent cardiac adaptations do occur in athletes performing dynamic and static sports. However, the classification as an endurance-trained heart or a strength-trained heart is not an absolute and dichotomous concept but rather a relative concept. In every form of endurance training, blood pressure increases (pressure load), in addition to the increase in cardiac output (volume load), just as in every form of strength training, heart rate, cardiac output, and blood pressure increase.

References

1. Pellicia A, Maron BJ. Outer limits of the athlete's heart: the effect of gender and relevance to the differential diagnosis with primary cardiac diseases. *Cardiol Clin*. 1997;15:381–396.
2. Morganroth J, Maron BJ, Henry WL, Epstein SE. Comparative left ventricular dimensions in trained athletes. *Ann Intern Med*. 1975;82: 521–524.
3. Spirito P, Pellicia A, Proschan MA, Granata M, Spataro A, Bellone P, Caselli G, Biffi A, Vecchio C, Maron BJ. Morphology of the "athlete's heart" assessed by echocardiography in 947 elite athletes representing 27 sports. *Am J Cardiol*. 1994;74:802–806.
4. Pellicia A, Maron BJ, Spataro A, Proschan MA, Spirito P. The upper limit of physiologic hypertrophy in highly trained elite athletes. *N Engl J Med*. 1991;324:295–301.
5. Fagard RH. Impact of different sports and training on cardiac structure and function. *Cardiol Clin*. 1997;15:397–412.
6. Fagard RH. Athlete's heart: a meta-analysis of the echocardiographic experience. *Int J Sports Med*. 1996;17:140–144.
7. Devereux RB, Reichek N. Echocardiographic determination of left ventricular mass in man. *Circulation*. 1977;55:613–618.
8. Dersimonian R, Laird N. Meta-analysis in clinical trials. *Control Clin Trials*. 1986;7:177–188.
9. Gilbert CA, Nutter DO, Felner JM, Perkins JV, Heymsfield SB, Schlant RC. Echocardiographic study of cardiac dimensions and function in the endurance-trained athlete. *Am J Cardiol*. 1977;40:528–533.
10. Underwood RH, Schwade JL. Noninvasive analysis of cardiac function of elite distance runners: echocardiography, vectorcardiography, and cardiac intervals. *Ann N Y Acad Sci*. 1977;301:297–309.
11. Zoneraich S, Rhee JJ, Zoneraich O, Jordan D, Appel J. Assessment of cardiac function in marathon runners by graphic noninvasive techniques. *Ann N Y Acad Sci*. 1977;301:900–917.
12. Parker BM, Londeree BR, Cupp GV, Dubiel JP. The noninvasive cardiac evaluation of long-distance runners. *Chest*. 1978;73:376–381.
13. Ikäheimo MJ, Palatsi IJ, Takkunen JT. Noninvasive evaluation of the athletic heart: sprinters versus endurance runners. *Am J Cardiol*. 1979; 44:24–29.
14. Longhurst JC, Kelly AR, Gonyea WJ. Echocardiographic left ventricular masses in distance runners and weight-lifters. *J Appl Physiol*. 1980;48: 154–162.
15. Paulsen W, Boughner DR, Ko P, Cunningham DA, Persaud JA. Left ventricular function in marathon runners: echocardiographic assessment. *J Appl Physiol*. 1981;51:881–886.
16. Snoeckx LHEH, Abeling HFM, Lambregts JAC, Schmitz JJF, Verstappen FTJ, Reneman RS. Cardiac dimensions in athletes in relation to variations in their training program. *Eur J Appl Physiol*. 1983;52:20–28.
17. Sugishita Y, Koseki S, Matsuda M, Yamaguchi T, Ito I. Myocardial mechanics of athletic hearts in comparison with diseased hearts. *Am Heart J*. 1983;105:273–280.
18. Child JS, Barnard RJ, Taw RL. Cardiac hypertrophy and function in master endurance runners and sprinters. *J Appl Physiol*. 1984;57: 176–181.
19. Fagard R, Aubert A, Staessen J, Vanden Eynde E, Vanhees L, Amery A. Cardiac structure and function in cyclists and runners. *Br Heart J*. 1984; 52:124–129.
20. Niemelä KO, Palatsi IJ, Ikäheimo MJ, Takkunen JT, Vuori JJ. Evidence of impaired left ventricular performance after an uninterrupted competitive 24-hour run. *Circulation*. 1984;3:350–356.
21. Cohen JL, Segal KR. Left ventricular hypertrophy in athletes: an exercise-echocardiographic study. *Med Sci Sports Exerc*. 1985;17: 695–700.
22. Granger CB, Karimeddini MK, Smith VE, Shapiro HR, Katz AM, Riba AL. Rapid ventricular filling in left ventricular hypertrophy, 1: physiologic hypertrophy. *J Am Coll Cardiol*. 1985;5:862–868.
23. Hagan RD, Laird WP, Gettman LR. The problems of per-surface area and per-weight standardization indices in the determination of cardiac hypertrophy in endurance-trained athletes. *J Cardiopulm Rehabil*. 1985;5: 554–560.
24. Spataro A, Pellicia A, Caselli G, Amici E, Venerando A. Echocardiographic standards in top-class athletes. *J Sports Cardiol*. 1985;2:17–27.
25. Finkelhor RS, Hanak LJ, Bahler RC. Left ventricular filling in endurance-trained subjects. *J Am Coll Cardiol*. 1986;8:289–293.
26. Pavlik G, Bachl N, Wollein W, Längfy G, Prokop L. Resting echocardiographic parameters after cessation of regular endurance training. *Int J Sports Med*. 1986;7:226–231.
27. Perrault H, Péronnet F, Lebeau R, Nadeau RA. Echocardiographic assessment of left ventricular performance before and after marathon running. *Am Heart J*. 1986;112:1026–1031.
28. Colan SD, Sanders SP, Borow KM. Physiologic hypertrophy: effects on left ventricular systolic mechanics in athletes. *J Am Coll Cardiol*. 1987; 9:776–783.
29. Roy A, Doyon M, Dumesnil JG, Jobin J, Landry F. Endurance vs strength training: comparison of cardiac structures using normal predicted values. *J Appl Physiol*. 1988;64:2552–2557.
30. Fisher AG, Adams TD, Yanowitz FG, Ridges JD, Orsmond G, Nelson AG. Noninvasive evaluation of world class athletes engaged in different modes of training. *Am J Cardiol*. 1989;63:337–341.
31. MacFarlane N, Northridge DB, Wright AR, Grant S, Dargie HJ. A comparative study of left ventricular structure and function in elite athletes. *Br J Sports Med*. 1991;25:45–48.
32. Störk TV, Möckel M, Eichstädt H, Müller RM, Hochrein H. Noninvasive assessment by pulsed Doppler ultrasound of left ventricular filling behavior in long distance runners during marathon race. *Am J Cardiol*. 1991;68:1237–1241.
33. Osborne G, Wolfe LA, Burggraf GW, Norman R. Relationships between cardiac dimensions, anthropometric characteristics and maximal aerobic power (V_{O_2} max) in young men. *Int J Sports Med*. 1992;13:219–224.
34. Dickhuth HH, Rocker K, Heitkamp HC. Echocardiographic findings in endurance athletes with hypertrophic non-obstructive cardiomyopathy (HNCM) compared to non-athletes with HNCM and physiological hypertrophy (athlete's heart). *Int J Sports Med*. 1994;15:273–277.
35. Deligiannis A, Kouidi E, Milonas A. Effect of submaximal dynamic exercise on left ventricular function in endurance- and power-trained athletes. *Med Sci Res*. 1995;23:225–227.
36. Yeater R, Reed C, Ullrich I, Morise A, Borsch M. Resistance trained athletes using or not using anabolic steroids compared to runners: effects on cardiorespiratory variables, body composition, and plasma lipids. *Br J Sports Med*. 1996;30:11–14.
37. Abinader EG, Sharif D, Sagiv M, Goldhammer E. The effects of isometric stress on left ventricular filling in athletes with isometric or isotonic training compared to hypertensive and normal controls. *Eur Heart J*. 1996;17:457–461.
38. Karjalainen J, Mäntysaari M, Viitasalo M, Kujala U. Left ventricular mass, geometry, and filling in endurance athletes: association with exercise blood pressure. *J Appl Physiol*. 1997;82:531–537.

39. Nishimura T, Yamada Y, Kawai C. Echocardiographic evaluation of long-term effects of exercise on left ventricular hypertrophy and function in professional bicyclists. *Circulation*. 1980;61:832–840.
40. Wieling W, Borghos EAM, Hollander AP, Danner SA, Dunning AJ. Echocardiographic dimensions and maximal oxygen uptake in oarsmen during training. *Br Heart J*. 1981;46:190–195.
41. Bekaert I, Pannier JL, Van de Weghe C, Van Durme JP, Clement DL, Pannier R. Non-invasive evaluation of cardiac function in professional cyclists. *Br Heart J*. 1981;45:213–218.
42. Fagard R, Aubert A, Lysens R, Staessen J, Vanhees L, Amery A. Non-invasive assessment of seasonal variations in cardiac structure and function in cyclists. *Circulation*. 1983;67:896–900.
43. Abergel E, Cohen A, Vaur L, Khellaf F, Menard J, Chatellier G. Accuracy and reproducibility of left ventricular mass measurement by subcostal M-mode echocardiography in hypertensive patients and professional bicyclists. *Am J Cardiol*. 1993;72:620–624.
44. Agati L, Fedele F, Gagliardi MG, Sciomer S, Penco M. A super-normal behavior of echocardiographic diastolic data in athletes despite left ventricular hypertrophy. *J Sports Cardiol*. 1985;2:10–16.
45. Luisiani L, Ronsisvalle G, Bonamone A, Visona A, Castellani V, Macchia C, Pagnan A. Echocardiographic evaluation of the dimensions and systolic properties of the left ventricle in freshman athletes during physical training. *Eur Heart J*. 1986;7:196–203.
46. Fagard R, Van den Broeke C, Bielen E, Vanhees L, Amery A. Assessment of stiffness of the hypertrophied left ventricle of bicyclists using left ventricular inflow Doppler velocimetry. *J Am Coll Cardiol*. 1987;9:1250–1254.
47. Lo YSA, Chin MK. Echocardiographic left ventricular hypertrophy in Chinese endurance athletes. *Br J Sports Med*. 1990;24:274–276.
48. Lattanzi F, Spirito P, Picano E, Mazzarisi A, Landini L, Distante A, Vecchio C, L'Abbate A. Quantitative assessment of ultrasonic myocardial reflectivity in hypertrophic cardiomyopathy. *J Am Coll Cardiol*. 1992;17:1085–1090.
49. Cavallaro V, Petretta M, Betocchi S, Salvatore C, Morgano G, Bianchi V, Breglio R, Bonaduce D. Effects of sustained training on left ventricular structure and function in top level rowers. *Eur Heart J*. 1993;14:898–903.
50. Galanti G, Comeglio M, Vinci M, Cappelli B, Vono MC, Bamoshmoosh M. Echocardiographic Doppler evaluation of left ventricular diastolic function in athletes' hypertrophied hearts. *J Vasc Dis*. 1993;44:341–346.
51. Maron BJ, Pellicia A, Spataro A, Granata M. Reduction in left ventricular wall thickness after deconditioning in highly trained Olympic athletes. *Br Heart J*. 1993;69:125–128.
52. Missault L, Duprez D, Jordaens L, De Bruyzere M, Bonny K, Adang L, Clement D. Cardiac anatomy and diastolic filling in professional road cyclists. *Eur J Appl Physiol*. 1993;66:405–408.
53. Miki T, Yokota Y, Seo T, Yokoyama M. Echocardiographic findings in 104 professional cyclists with follow-up study. *Am Heart J*. 1994;127:898–905.
54. Cubero GI, Reguero JJR, Terrados N, Gonzalez V, Barriales R, Cortina A. Aldosterone levels and cardiac hypertrophy in professional cyclists. *Int J Sports Med*. 1995;16:475–477.
55. Reguero JJR, Cubero GI, De la Iglesia JL, Terrados N, Gonzalez V, Cortina R, Cortina A. Prevalence and upper limit of cardiac hypertrophy in professional cyclists. *Eur J Appl Physiol*. 1995;70:375–378.
56. Urhausen A, Monz T, Kindermann W. Sports-specific adaptation of left ventricular mass in athlete's heart. *Int J Sports Med*. 1996;17:145–151.
57. Haykowsky M, Chan S, Bhambhani Y, Syrotuik D, Quinney H, Bell G. Effects of combined endurance and strength training on left ventricular morphology in male and female rowers. *Can J Cardiol*. 1998;14:387–391.
58. Menapace FJ, Hammer WJ, Ritzer TF, Kessler KM, Warner HF, Spann JF, Bove AA. Left ventricular size in competitive weight lifters: an echocardiographic study. *Med Sci Sports Exerc*. 1982;14:72–75.
59. Cohen CR, Allen HD, Spain J, Marx GR, Wolfe RW, Harvey JS. Cardiac structure and function of elite high school wrestlers. *Sports Med*. 1987;141:576–581.
60. Colan SD, Sanders SP, MacPherson D, Borow KM. Left ventricular diastolic function in elite athletes with physiologic cardiac hypertrophy. *J Am Coll Cardiol*. 1985;6:545–549.
61. Salke RC, Rowland TW, Burke EJ. Left ventricular size and function in body builders using anabolic steroids. *Med Sci Sports Exerc*. 1985;17:701–704.
62. Pearson AC, Schiff M, Mrosek D, Labovitz AJ, Williams GA. Left ventricular diastolic function in weight lifters. *Am J Cardiol*. 1986;58:1254–1259.
63. Brown SP, Thompson WR. Standardization indices of cardiac hypertrophy in weight lifters. *J Sport Sci*. 1987;5:147–153.
64. Van den Broeke C, Fagard R. Left ventricular structure and function, assessed by imaging and Doppler echocardiography, in athletes engaged in throwing events. *Int J Sports Med*. 1988;9:407–411.
65. Urhausen A, Kindermann W. One- and two-dimensional echocardiography in body builders and endurance-trained subjects. *Int J Sports Med*. 1989;10:139–144.
66. Thompson PD, Sadaniantz A, Cullilane EM, Bodziony KS, Catlin DH, Torek-Both G, Douglas PS. Left ventricular function is not impaired in weight-lifters who use anabolic steroids. *J Am Coll Cardiol*. 1992;19:278–282.
67. Pellicia A, Spataro A, Caselli G, Maron BJ. Absence of left ventricular wall thickening in athletes engaged in intense power training. *Am J Cardiol*. 1993;72:1048–1054.
68. Dickhuth HH, Simon G, Kindermann W, Wildberg A, Keul J. Echokardiographische Untersuchungen bei Sportlern verschiedener Sportarten und Untrainierten. *Z Kardiol*. 1979;68:449–453.
69. Mumford M, Prakash R. Electrocardiographic and echocardiographic characteristics of long distance runners. *Am J Sports Med*. 1981;9:23–28.
70. Shapiro LM, Moore RB, Logan-Sinclair RB, Gibson DG. Relation of regional echo amplitude to left ventricular function and the electrocardiogram in left ventricular hypertrophy. *Br Heart J*. 1984;52:99–105.
71. Fedele F, Agati L, Penco M, Sciomer S, Gagliardi MG, Di Renzi P. 2D exercise echocardiography in athletes. *J Sports Card*. 1985;2:1–9.
72. Fisman EZ, Embon P, Pines A, Tenenbaum A, Drory Y, Shapiro I, Motro M. Comparison of left ventricular function using isometric exercise Doppler echocardiography in competitive runners and weight-lifters versus sedentary individuals. *Am J Cardiol*. 1997;79:355–359.
73. Ekblom B, Hermansen I. Cardiac output in athletes. *J Appl Physiol*. 1968;25:619–625.
74. Palatini P, Mos L, Di Marco A, Mormino P, Munari L, Del Torre M, Valle F, Pessina AC, Dal Palu C. Intra-arterial blood pressure recording during sports activities. *J Hypertens*. 1987;5:479–481.
75. McDougall JD, Tuxen D, Sale DG, Moroz JR, Sutton JR. Arterial blood pressure response to heavy resistance exercise. *Am J Physiol*. 1985;58:785–790.
76. MacDougall JD, McKelvie RS, Moroz DE, Sale DG, McCartney N, Buick F. Factors affecting blood pressure during heavy weight lifting and static contractions. *J Appl Physiol*. 1992;73:1590–1597.
77. Perez-Gonzalez JF. Factors determining the blood pressure responses to isometric exercise. *Circ Res*. 1981;48:76–86.
78. Vitcenda M, Hanson P, Folts J, Besozzi M. Impairment of left ventricular function during maximal isometric dead lifting. *J Appl Physiol*. 1990;69:2062–2066.
79. Mitchell JH, Haskell WL, Raven PB. Classification of sports. *J Am Coll Cardiol*. 1994;24:864–866.
80. Clifford PS, Hanel B, Secher NH. Arterial blood pressure response to rowing. *Med Sci Sports Exerc*. 1994;26:715–719.
81. Shimizu G, Hirota Y, Kita Y, Kawamura K, Saito T, Gaasch WH. Left ventricular midwall mechanics in systemic arterial hypertension. *Circulation*. 1991;83:1676–1684.
82. Palmon L, Reichek N, Yeon SB, Clark NR, Browson D, Hoffman E, Axel L. Intramyocardial shortening in hypertensive left ventricular hypertrophy with normal pump function. *Circulation*. 1994;89:122–131.
83. Nishimura RA, Housmans PR, Hatle LK, Tajik AJ. Assessment of diastolic function of the heart: background and current applications of Doppler echocardiography, part 1: physiologic and pathophysiologic features. *Mayo Clin Proc*. 1989;64:71–81.
84. Smith VE, White WB, Karimeddini MK. Echocardiographic assessment of left ventricular diastolic performance in hypertensive subjects. *Hypertension*. 1987;9:81–84.
85. Fouad FM, Slominski JM, Tarazi RC. Left ventricular diastolic function in hypertension: relation to left ventricular mass and systolic function. *J Am Coll Cardiol*. 1984;3:1500–1506.
86. Massie BM. Myocardial hypertrophy and cardiac failure: a complex interrelationship. *Am J Med*. 1983;72:67–74.
87. Maron BJ. Structural features of the athlete heart as defined by echocardiography. *J Am Coll Cardiol*. 1986;7:190–203.
88. Fagard RH. Impact of different sports and training on cardiac structure and function. *Cardiol Clin*. 1997;15:397–412.