Enhanced Left Ventricular Performance in Endurance Trained Older Men

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Background The age-associated decline in aerobic exercise capacity is partially reversible by endurance exercise training. Moderate-intensity endurance exercise training increases aerobic exercise capacity mediated, in part, by improvement of stroke volume and left ventricular performance in older men. The present study was designed to characterize the nature of cardiovascular adaptations to strenuous endurance exercise of long duration and to delineate the mechanisms underlying increased stroke volume and cardiac output in highly trained older endurance athletes.

Methods and Results Nine male master athletes (MA: 64±2 years old, mean±SEM) and 9 older sedentary healthy men (controls: 63±1 year) were studied. Left ventricular systolic function was evaluated with the use of cardiac blood pool imaging and echocardiography. Maximal O2 uptake \((\dot{V}O_2max)\) was 50.4±1.7 mL·kg\(^{-1}\)·min\(^{-1}\) in the MA and 29.6±1.4 mL·kg\(^{-1}\)·min\(^{-1}\) \((P=.001)\) in controls. Systolic and mean blood pressures at rest and during exercise were not different in the two groups. Left ventricular systolic function at peak exercise was higher in the MA than in sedentary controls as evidenced by (1) a higher left ventricular functional reserve \((AEF: 5.6±2.5, P=.05)\), (2) a larger decrease in end-systolic volume during exercise \((\dot{V}O_2max)\): 56±4 mL at rest and 42±5 mL at peak exercise, \(P=.007\); controls: 43±2 mL at rest and 42±6 mL at peak exercise, \(P=.35\) with no differences in systolic blood pressure, (3) a higher left ventricular fractional shortening at peak exercise \((\dot{V}O_2max): 52±2.6\%, controls: 45±1\%, P=.046)\) at comparable values for end-systolic wall stress \((\text{MA: } 56±12 \text{ g/cm}^2; \text{controls: } 53±7 \text{ g/cm}^2, P=.50)\), and (4) a greater decrease in end-systolic diameter at peak exercise in the MA than in controls \((\dot{V}O_2max)\): −1.2±0.16 cm versus −0.57±0.13 cm, \(P=.014\) despite no significant differences between the changes in end-systolic wall stress during exercise \((\dot{V}O_2max)\): −15.5±7.5 g/cm\(^2\), controls: −11.0±9.0 g/cm\(^2\), \(P=.6\). MA had a larger end-diastolic volume at rest \((153±6 versus 132±4 \text{ mL}, P=.009)\) with a normal wall thickness-to–radius ratio \((0.34±0.02)\). Peak exercise stroke volume was higher \((P=.023)\) in the MA \((132±6 \text{ mL/min})\) than in the sedentary controls \((111±6 \text{ mL/min})\). Changes in stroke volume correlated strongly with changes in ejection fraction in the MA \((r=.80, P=.010)\) but not in sedentary controls \((r=.59, P=.097)\). Further, changes in stroke volume from rest to exercise correlated strongly with changes in end-diastolic volume in both MA \((r=.78, P=.013)\) and sedentary controls \((r=.73, P=.026)\), suggestive of reliance of stroke volume on end-diastolic volume and preload. However, for a given increase in end-diastolic volume, the rise in stroke volume during exercise was significantly larger in the MA than in controls, which, in the absence of differences in mean blood pressures, indicates that enhanced left ventricular systolic function independent of preload plays an additional role in maintaining a higher stroke volume at peak exercise in the highly trained older men.

Conclusions Cardiac adaptations in older endurance trained men are characterized by volume-overload left ventricular hypertrophy and enhancement of left ventricular systolic performance at peak exercise. These adaptive responses contribute to enhanced stroke volume at peak exercise in older endurance trained men. \((\text{Circulation, 1994;89:198-205.})\)

Key Words • aging • exercise • left ventricle

Maximal oxygen uptake decreases progressively at an average rate of 10% per decade after the age of 25.\(^1\) The decline is due to reductions in maximal cardiac output and arteriovenous \(O_2\) content difference.\(^6\) The age-related functional and structural changes in the heart and blood vessels that result in decreased chronotropic response, impaired cardiac function, and increased aortic impedance are responsible for diminished maximal cardiac output and stroke volume (SV) with advancing age.\(^9\) It is likely that physical inactivity and increased adiposity contribute to reduced cardiovascular function in older subjects because endurance exercise training can counteract the age-related decrease in maximal aerobic exercise capacity \((\dot{V}O_2max)\) and thus can partially prevent the progressive decline in \(\dot{V}O_2max\) in older subjects\(^14\)–\(^17\) up to a certain age. The higher values for \(\dot{V}O_2max\) seen in highly trained master athletes compared with sedentary individuals are the consequence of a larger cardiac output and SV and a greater extraction of \(O_2\) from the blood by the exercising skeletal muscles.\(^6\)\(^7\) We have recently reported that relatively short-term moderate- to high-intensity endurance exercise training in older sedentary men can induce cardiac adaptations characterized by a modest volume-overload left ventricular hypertrophy and improvement of left ventricular systolic function at peak exercise.\(^18\) However, the nature of cardiac adaptations in highly trained older men who have been performing regular vigorous endurance exercise for several years and whose \(\dot{V}O_2max\) values are considerably higher than levels seen in moderately trained men is unknown. Therefore, the present study was designed to characterize the cardiovascular adaptations to long-term high-intensity endurance exercise.
exercise training and to delineate the mechanisms responsible for larger cardiac output and SV in highly trained older men.

Methods

Subjects

Nine master athletes (aged 64±2 years, mean±SEM) and nine untrained men (aged 63±1 years) were studied after giving written voluntary informed consent. All subjects were evaluated clinically and underwent a graded maximal exercise test using the Bruce protocol.19 Only subjects free of clinical evidence of organic heart disease and with no significant exercise-induced ECG abnormalities participated further in the study. The study protocol was approved by The Human Studies Committee of Washington University.

Physical Activity Status

The master athletes were distance runners who were training regularly and participating in competitive endurance events on a regular basis. They were running 43±6 (range, 30 to 85) miles/wk and had been training regularly for 10±2 years (mean±SEM). The sedentary men had not performed any regular physical activity for several years.

Body Composition

Percent body fat was estimated by the skinfold thickness measurement with the use of a Lange caliper at the following sites: triceps, subscapular, pectoral, umbilical, suprailiac, and front thigh.

Measurement of Maximal (Treadmill) and Peak (Cycling) O2 Uptake

Maximal O2 uptake (V̇O2max) for the untrained men was determined during graded treadmill walking using a modified Balke protocol. V̇O2max for the master athletes was measured during graded treadmill running.14 The following criteria were used for determining a true V̇O2max (1) no further increase in V̇O2 despite an increase in exercise intensity, (2) a respiratory exchange ratio of 1.10 or greater, and (3) a heart rate within 10 beats of the age-predicted maximal heart rate.17,18 Peak V̇O2 during graded supine cycling was determined with the use of an electrically braked cycle ergometer (Engineering Dynamic Corp) during radionuclide studies. V̇O2 was measured using an open-circuit system in which subjects breathed through a Daniels valve, and expired gases were collected in neoprene meteorological balloons at 60-second intervals. O2 and CO2 fractions were analyzed with a mass spectrometer (Perkin-Elmer MGA 1100). Expired volumes were measured with a Tissot spirometer.20

Assessment of Left Ventricular Function at Rest and During Exercise

Radionuclide studies. Left ventricular performance was assessed by ECG-gated cardiac blood pool imaging with erythrocytes labeled with intravenous injection of 7.7 mCi of 99mTc given intravenously as described previously.18 The images were obtained with a standard field-of-view scintillation camera (Siemens LEM) equipped with a low-energy, medium-resolution, parallel-hole collimator. The subjects were imaged supine with the scintillation camera positioned in the left anterior oblique projection that gave the best separation of the ventricles (approximately 35°) with 15° caudal angulation to maximize separation of the left atrium and left ventricle. A computer system was interfaced to the scintillation camera. Data were collected in the frame mode (32 frames per RR interval) in a 64×64 pixel matrix and processed off-line with a minicomputer as previously described.21 Ejection fraction (EF) was calculated as (EDC−ESC)×100/EDC, where EDC and ESC are left ventricular end-diastolic and end-systolic counts, respectively, corrected for background activity.

The left ventricular end-diastolic volume (LVEDV) was calculated by the standard geometric area-length method:22

\[ V = \frac{8}{3} A L \]

where V is volume, A is the area, and L is the long axis of the left ventricle. Spatial calibration factors for the X and Y axes of the digital images were generated with a phantom.23 The area and long axis of the left ventricle were determined with the end-diastolic region of interest generated during calculation of EF. The left ventricular end-systolic volume (LVESV) and SV were derived from EF and LVEDV. This scintigraphic method for volume measurements has been validated in our laboratory and correlates well with contrast ventriculography (r=.97).

After imaging at rest, subjects performed continuous graded supine cycle ergometer exercise to exhaustion. The pedaling rate was 65 to 70 rpm. The initial work rate for all subjects was 30 W. The work rate was increased every 3 minutes until exhaustion, defined as an inability to maintain pedaling rate above 50 rpm. All subjects performed three to four work rates.

Images were obtained during the last 2 minutes of each work rate in the same modified left anterior oblique projections used at rest. Heart rate was recorded each minute. During the final minute of each work rate, blood pressure was measured with a mercury sphygmanometer, and expired air was collected for the subsequent determination of VO2. Echocardiography. To facilitate the interpretation of differences in the ejection phase indexes of left ventricular function between the two groups and to obtain information concerning estimates of cardiac loading conditions during exercise, M-mode echocardiograms were recorded on eight master athletes and six sedentary older men at rest and during peak supine cycle ergometer exercise (Quinton Instruments). Of the eight master athletes, four were among those who had radionuclide studies and four were additional highly trained men whose level of training and VO2max were similar to those of the other master athletes (master athletes: VO2max 3.24±0.12 L/min versus 3.16±0.14 L/min, P=.7, and 50±2 mL·kg−1 min−1 versus 49.5±2 mL·kg−1 min−1, P=.8; sedentary controls: VO2max, 2.39±0.1 L/min versus 2.42±0.11 L/min, P=.8, and 30±1 mL·kg−1 min−1 versus 33±1 mL·kg−1 min−1, P=.1, in the radionuclide and echocardiographic studies, respectively). Inclusion of additional subjects was necessary because some of the original subjects were not available for echocardiographic studies. The interval between radionuclide and echocardiographic studies was 18 to 24 months. There were no changes in the physical activity status of the subjects during this interval as confirmed by VO2max data. End-diastolic and end-systolic diameters (EDD and ESD) and posterior wall thickness (PWT) were measured using the guidelines recommended by the American Society of Echocardiography.24 The left ventricular fractional shortening was calculated as previously described.18 Left ventricular end-diastolic wall stress was estimated with the use of the equation as described by Grossman et al.25 Peak systolic blood pressure was measured by standard cuff sphygmomanometry. We recognize the potential limitations of the standard “cuff” method and substitution of peak systolic for the end-systolic blood pressure in our data. However, measurement of peak systolic blood pressure during exercise is difficult with the use of noninvasive techniques. We are also cognizant that systolic blood pressure in the peripheral (brachial) artery may not be the same as the left ventricular systolic pressure. Therefore, the values for the left ventricular end-systolic wall stress should be regarded only as estimates in this study. To ensure acquisition of technically acceptable data, echocardiographic tracings were recorded at slightly lower exercise intensities than those used during radionuclide studies in both groups to minimize the effects of respiration and body motion.

Statistical Analysis

Data were analyzed with the use of the SAS program on the SUN computer system in the Division of Biostatistics at...
Anthropometric data were based nonparametrically. 

Table 1. Selected Anthropometric Data

<table>
<thead>
<tr>
<th></th>
<th>Weight, kg</th>
<th>Height, cm</th>
<th>BSA, m²</th>
<th>∑Skinfold Thickness, mm</th>
<th>Body Fat, %</th>
<th>FFM, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master athletes</td>
<td>63.8±2*</td>
<td>172.6±2†</td>
<td>1.76±0.03*</td>
<td>56.6±5.7*</td>
<td>11.0±0.6*</td>
<td>56.7±1.4†</td>
</tr>
<tr>
<td>Controls</td>
<td>81.3±3</td>
<td>180.5±1</td>
<td>2.01±0.03</td>
<td>118.2±9.4</td>
<td>19.2±1.7</td>
<td>66.6±2.3</td>
</tr>
</tbody>
</table>

BSA indicates body surface area; FFM, fat free mass. Values are mean±SEM. 

*P=.001 (master athletes vs controls).  †P=.002 (master athletes vs controls).

Washington University. Student’s t tests were used to compare differences in variables at rest and at peak exercise between master athletes and sedentary groups. Because some of the volumetric data conformed to log normal distribution, the natural logarithm of these variables was used for the Student’s t test. Furthermore, because of substantial skewing of the data, we used Wilcoxon’s test for comparison of slopes reflecting changes during exercise in SV versus EDV and SV versus EF between the two groups. Regression analyses of the slopes defining changes in SV as a function of work rate and EDV were based nonparametrically on ranks of the computed regression slopes because of their nonnormal distribution. Analysis of covariance was also used to determine the independent contribution of pertinent hemodynamic variables to the changes in SV during exercise in the trained and untrained groups. Data are expressed as mean±SEM.

Results

Anthropometric Data

The sedentary men were significantly taller and heavier and had a larger body surface area than the master athletes (Table 1). The sum of skinfolds was 52% less in the master athletes than in the sedentary men. Estimated body fat was substantially less in the master athletes than in the sedentary men, but estimated fat free mass was more in the sedentary men than in the master athletes (Table 1).

Maximal and Peak Aerobic Exercise Capacity and Heart Rate

VO₂max, expressed as liters per minute or normalized for body weight or fat free mass, was considerably higher in the master athletes than in the older sedentary men (Table 2). Maximal heart rate was higher in the master athletes than in the sedentary controls, but the difference did not reach statistical significance (Table 2). However, the chronotropic reserve, defined as the difference between resting and maximal heart rate, was significantly greater in master athletes than in sedentary men (121±3 beats per minute versus 97±2 beats per minute, P=.01). Peak VO₂ during supine cycle ergometer exercise was 2.36±0.14 L/min and 2.03±0.06 L/min (P=.0001) in the master athletes and sedentary men, respectively (37±1.7 mL·kg⁻¹·min⁻¹ versus 25±0.6 mL·kg⁻¹·min⁻¹, P=.0001). The peak supine cycle ergometer power output was 169±3 W and 138±4 W for the master athletes and sedentary controls, respectively (P=.0001).

Hemodynamic Data

Resting heart rate was significantly slower in the master athletes than in the sedentary controls (50±2 beats per minute versus 71±3 beats per minute, P=.001). Peak heart rate during cycle ergometer exercise was 146±3 beats per minute in the master athletes and 151±5 beats per minute in the older sedentary men (P=.47). Mean blood pressure values both at rest and during peak exercise were similar in the two groups (Table 3). Systolic blood pressure at rest (137±5 versus 130±3 mm Hg) and during peak exercise (227±3 versus 216±7 mm Hg) also did not differ between the two groups. Cardiac output at rest was higher in the sedentary older men than in the master athletes (Table 3) because the sedentary men were taller and heavier with a larger body surface area (Table 1). Thus, neither cardiac index (CI) nor cardiac output normalized for fat free mass (Q/FFM) was significantly different between the two groups (CI: 2.8±0.10 L/min versus 3.1±0.20 L/min; Q/FFM: 87±3 mL/min versus 97±8 mL/min for master athletes and sedentary controls, respectively). Peak exercise cardiac output, however, was higher (16%) in the master athletes than in the sedentary older men (Table 3). This difference became more striking when cardiac output was normalized for body surface area (31% difference: 10.9±0.5 versus 8.3±0.4 L/min, P=.0001) or fat free mass (35% difference: 337±14 versus 249±12 mL/min, P=.001). Total peripheral resistance (TPR) at rest was significantly greater in the master athletes than in the sedentary controls. TPR declined to a greater extent (P=.001) during exercise in the trained group; as a result, there was no significant difference in TPR at peak exercise between the two groups (Table 3). Vasodilatory reserve, defined as the difference between rest and peak exercise TPR, was significantly greater in the master athletes than in the sedentary older men (1036±45 versus 574±93 dynes·s·cm⁻⁵, P=.001). This larger vasodilatory reserve was due to a greater increase in cardiac output in the

Table 2. Selected Data at Maximal Exercise

<table>
<thead>
<tr>
<th></th>
<th>VO₂max</th>
<th>VO₂max</th>
<th>VO₂max</th>
<th>HRmax, bpm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L/min</td>
<td>mL·kg⁻¹·min⁻¹</td>
<td>mL·kg·FFM⁻¹·min⁻¹</td>
<td>HRmax, bpm</td>
</tr>
<tr>
<td>Master athletes</td>
<td>3.24±0.12*</td>
<td>50.4±1.7*</td>
<td>57.1±1.6*</td>
<td>171±4</td>
</tr>
<tr>
<td>Controls</td>
<td>2.39±0.10</td>
<td>29.6±1.4</td>
<td>37.0±2.3</td>
<td>168±5</td>
</tr>
</tbody>
</table>

bpm indicates beats per minute; FFM, fat free mass; HRmax, maximal heart rate; and VO₂max, maximal O₂ consumption. Values are mean±SEM.

*P=.0001 (compared with controls).
### Table 3. Physiological Variables at Rest and During Peak Exercise

<table>
<thead>
<tr>
<th>Variable</th>
<th>Master Athletes</th>
<th>Controls</th>
<th>P*</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDV, mL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rest</td>
<td>153±6</td>
<td>133±4</td>
<td>.009</td>
</tr>
<tr>
<td>Exercise</td>
<td>173±5</td>
<td>153±8</td>
<td>.01</td>
</tr>
<tr>
<td>ESV, mL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rest</td>
<td>56±4</td>
<td>43±2</td>
<td>.032</td>
</tr>
<tr>
<td>Exercise</td>
<td>42±5</td>
<td>42±6</td>
<td>.5</td>
</tr>
<tr>
<td>EF, %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rest</td>
<td>63±2</td>
<td>67±1</td>
<td>.074</td>
</tr>
<tr>
<td>Exercise</td>
<td>76±3</td>
<td>73±3</td>
<td>.51</td>
</tr>
<tr>
<td>SV, mL/min</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Rest</td>
<td>97±2</td>
<td>90±3</td>
<td>.097</td>
</tr>
<tr>
<td>Exercise</td>
<td>132±6</td>
<td>111±6</td>
<td>.023</td>
</tr>
<tr>
<td>Q, L/min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rest</td>
<td>4.86±0.1</td>
<td>6.3±0.4</td>
<td>.001</td>
</tr>
<tr>
<td>Exercise</td>
<td>19.10±0.9</td>
<td>16.7±0.9</td>
<td>.05</td>
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<tr>
<td>HR, bpm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rest</td>
<td>51±4</td>
<td>71±3</td>
<td>.001</td>
</tr>
<tr>
<td>Exercise</td>
<td>146±3</td>
<td>151±5</td>
<td>.28</td>
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<tr>
<td>mBP, mm Hg</td>
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<td></td>
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</tr>
<tr>
<td>Rest</td>
<td>98±2</td>
<td>98±3</td>
<td>.95</td>
</tr>
<tr>
<td>Exercise</td>
<td>137±2</td>
<td>140±5</td>
<td>.58</td>
</tr>
<tr>
<td>TPR, dynes · cm⁻²</td>
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<td></td>
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<tr>
<td>Rest</td>
<td>1614±41</td>
<td>1262±74</td>
<td>.001</td>
</tr>
<tr>
<td>Exercise</td>
<td>580±30</td>
<td>674±50</td>
<td>.07</td>
</tr>
</tbody>
</table>

EDV indicates end-diastolic volume; EF, ejection fraction; ESV, end-systolic volume; HR, heart rate; bpm, beats per minute; mBP, mean blood pressure; Q, cardiac output; and SV, stroke volume. Values are mean±SEM.

*Master athletes vs controls (see the text for the significance of differences between rest and exercise variables).

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**Left Ventricular Systolic Function**

SV at rest did not differ between the two groups (Table 3 and Fig 1). However, when normalized for body surface area, resting SV was significantly higher in the master athletes (55±1.0 ml/min/m² versus 45±1.5 ml/min/m², P=.001). Peak exercise SV was considerably larger in the master athletes than in the older sedentary men (Table 3 and Fig 1). Left ventricular EF at rest was not significantly different between the two groups. At peak exercise, left ventricular EF was slightly higher in the master athletes but the difference did not attain the statistical significance (Table 3). Left ventricular exercise (functional) reserve, defined as the change in EF (ΔEF) from rest to exercise, was higher in the master athletes than in the sedentary controls (12.4±2 versus 5.6±3, P=.05). At comparable increments in EDV during submaximal exercise, the increases in EF were larger in the master athletes than in the sedentary men (Fig 2) with no significant differences in either systolic or mean blood pressure.

LVEDV at rest was larger (15%) in the master athletes than in controls, consistent with volume-overload hypertrophy (Table 3 and Fig 1). This difference...
was considerably greater (25%) when EDV was indexed for body surface area (83±4 mL versus 66.5±2 mL, P=.001). EDV was increased at peak exercise to a similar extent in both groups (master athletes, 20.2±5 mL; controls, 20.1±6.3 mL; Table 3 and Fig 1). ESV at rest was larger in the master athletes than controls (Table 3 and Fig 1). ESV decreased significantly (P=.007) at peak exercise in the master athletes but not in the sedentary subjects (P=.35) (Table 3 and Fig 1). Systolic blood pressure increased similarly during exercise in the two groups. Master athletes had a higher fractional shortening (FS) at peak exercise and also exhibited a larger increase in FS from rest to exercise than did controls (ΔFS: 18.4±2% versus 6.7±2%, P=.004) despite similar values for the estimated end-systolic wall stress (58±12 g/cm² versus 53±7 g/cm²) in both groups (Fig 3A). End-systolic diameter decreased to a greater extent in the master athletes than in the older sedentary men (−1.2±0.16 cm versus −0.6±0.13 cm, P=.014) even though the reductions in the estimated end-systolic wall stress during exercise (master athletes, −15.5±7.5 g/cm²; control, −11±9 g/cm²; P=.60) did not differ between the two groups (Fig 3B). EDD and PWT normalized for body surface area were significantly larger in the master athletes than in the sedentary controls (EDDI: 29±1 mm/m² versus 25±1 mm/m², P=.03; PWTI: 5±0.2 mm/m² versus 4±0.1 mm/m², P=.036, Fig 5). Left ventricular wall thickness-to-radius ratio did not differ between the two groups (master athletes, 0.34±0.02; controls, 0.35±0.01, Fig 5) consistent with the pattern of volume-overload left ventricular hypertrophy.

Wilcoxon analysis showed that the rate of increase in SV as a function of relative work rate during incremental exercise was marginally greater in the master athletes than in controls (0.37±0.05 mL versus 0.24±0.05 mL, P=.052). After regression analysis adjusted for the baseline differences in the hemodynamic variables that can influence SV, ie, EF, mean blood pressure, and EDV, the rate of increase in SV as a function of increase in power output was substantially greater (P=.026) in the master athletes than in the sedentary older men. The regression slopes defining the rate of change in EDV as a function of work rate, however, were almost identical in the two groups (0.21±0.04 mL versus 0.24±0.08 mL for master athletes and controls, respectively). There was a strong correlation between changes from rest to exercise in SV (ΔSV) and both the changes in EDV (r=.78, P=.013) and EF (r=.80, P=.01) in the master athletes. Sedentary controls exhibited only a strong correlation between ΔSV and ΔEDV (r=.73, P=.026) but not between ΔSV and ΔEF (r=.59, P=.097). Analysis of covariance showed that after adjusting for the associated changes in EDV, the increase in SV from rest to peak exercise was significantly greater in the master athletes than in the sedentary men. Although each
group showed a significant association between SV and EDV, we found that for a given increase in EDV there was a greater rise in SV. Therefore, the slope of the relation between EDV and SV was steeper in the master athletes than in controls (1.64±0.22 versus 1.05±0.16, P=.046; Fig 4). In contrast, for any given change in EF, the changes in SV were not significantly different between the two groups. Thus, the differences observed in the change in SV from rest to exercise between the two groups could not be accounted for by alterations in EDV but instead by changes in EF. When analysis of covariance was used to examine differences in SV between the two groups at peak exercise, similar results were observed. For any given peak value for EDV, peak exercise SV was larger (P=.003) in the master athletes than in the older sedentary men. In contrast, for any given EF, there were no significant differences in peak exercise SV between the two groups. Therefore, the differences detected in SV at peak exercise between the two groups could be explained by changes in EF but not by changes in EDV.

Comparison of Physiological Variables During Radionuclide and Echocardiographic Studies

The differences in the peak values for O2 uptake and heart rate between the radionuclide and echocardiographic studies were not statistically significant. Peak VO2 was 2.36±0.14 L/min versus 2.10±0.06 L/min (P=.11) in the master athletes and 2.03±0.06 L/min versus 1.8±0.14 L/min (P=.10) in the sedentary older men during radionuclide and echocardiographic studies, respectively. Peak heart rate in the master athletes was 146±3 beats per minute during radionuclide studies and 122±4 beats per minute (P=.08) during echocardiographic studies. In the sedentary older men, peak heart rate was 151±5 beats per minute and 139±3 beats per minute (P=.10) during radionuclide and echocardiographic studies, respectively. Values for peak exercise systolic blood pressure during radionuclide studies were higher significantly in the master athletes (P=.001) and marginally (P=.056) in the sedentary controls than those attained during echocardiographic studies (master athletes: 227±3 mm Hg versus 197±3 mm Hg; sedentary controls: 216±7 mm Hg versus 193±7 mm Hg). Because resting systolic blood pressure in the master athletes was greater during radionuclide studies than during echocardiographic studies (137±5 mm Hg versus 120±4 mm Hg, P=.01), the higher values for peak exercise systolic blood pressure were due to the higher resting values.

Discussion

The findings of the present study indicate that highly trained older endurance athletes exhibit significant adaptations in the heart that can account, in part, for amelioration of impaired left ventricular systolic function commonly associated with advancing age and physical inactivity.26 Cardiac adaptations in these master athletes are manifested by left ventricular enlargement with normal values for wall thickness-to-radius ratio typical of volume-overload left ventricular hypertrophy consistent with previous reports27,28 and enhancement of left ventricular systolic performance during exercise as evidenced by (1) a significant decrease in ESV during exercise in the master athletes despite similar increases in systolic blood pressure in the trained and untrained men,29 (2) a larger left ventricular exercise reserve, (3) a greater rise in EF in the master athletes at comparable increases in EDV during exercise in the trained and untrained men, and (4) a larger increase in FS along with a greater decrease in ESD at comparable reductions in estimated end-systolic wall stress.30,31 Furthermore, in the absence of differences in mean blood pressure, the greater rise in SV for any given increase in EDV provides evidence for enhanced left ventricular systolic function independent of preload in the master athletes. These adaptive responses contribute to a larger SV at peak exercise, which is responsible for a higher cardiac output in these highly trained master
endurance athletes because the differences in peak heart rate between the two groups were negligible. We have found similar adaptations in previously sedentary older men in response to endurance exercise training.\textsuperscript{18} However, these adaptations appear to be more conspicuous in the master athletes than in older moderately trained men as evidenced by a 24\% higher $V_{O_{2max}}$ in the master athletes compared with the values in the older moderately trained men that we have reported recently.\textsuperscript{18} Differences in the magnitude of cardiac adaptations are likely to account, in part, for the higher $V_{O_{2max}}$ in the master athletes because EDV, SV, and cardiac output at peak exercise, when normalized for body surface area, all were larger in the master athletes who have been training strenuously for several years than in the moderately trained older men.\textsuperscript{18}

Our results suggest that the primary mechanisms contributing to a larger SV at peak exercise in our master athletes compared with sedentary older men are larger EDV due to physiological volume-overload hypertrophy, the use of the Frank-Starling effect, and enhanced left ventricular systolic function. The strong correlation between changes in SV and alterations in left ventricular EDV in both groups indicates that SV during exercise is dependent on modulations in preload regardless of the physical activity status, similar to our previous observations in young subjects.\textsuperscript{32} Therefore, a larger EDV in the trained state would be expected to result in a higher SV. However, our data suggest that changes in preload alone are not sufficient to account entirely for the larger SV in master athletes during exercise. In view of a larger increase in SV in response to a given increase in EDV, a higher FS, and a greater reduction of ESD at comparable decreases in end-systolic wall stress at peak exercise, it is likely that enhanced inotropic state plays an additional role in larger SV and cardiac output in the highly trained older endurance athletes. The mechanisms underlying the training-associated increase in left ventricular contractile function are unknown. One possibility is an increased sensitivity to catecholamines, which diminishes with advancing age.\textsuperscript{9} Stratton et al.\textsuperscript{33} however, have reported that cardiovascular responses to isoproterenol were unaffected by endurance exercise training in older men. It is possible that a considerably higher training stimulus than that used by Stratton et al\textsuperscript{33} is required to attain cardiac adaptations and augmented responses to $\beta$-adrenergic stimulation. In a recent study, Schulman et al.\textsuperscript{34} found that left ventricular filling dynamics and systolic function at rest and during upright exercise did not differ between older endurance trained men and their sedentary peers. The differences between their results and our findings are probably due to the type of exercise used in these studies. We used supine exercise, whereas Schulman et al.\textsuperscript{34} used upright exercise. However, additional factors such as biological differences between the subjects as reflected in absence of cardiac enlargement in the trained subjects reported by Schulman et al can also account for these disparate observations.

The enhanced left ventricular systolic performance in the master athletes observed at peak exercise echocardiography is unlikely to be the consequence of the slightly lower peak $V_{O_{2}}$ values during these studies than those during radionuclide studies because (1) peak $V_{O_{2}}$ values during echocardiographic studies were close to those during radionuclide studies (89\%) and the differences between the two studies were not statistically significant and (2) endurance trained older subjects do not generally exhibit any decline in left ventricular systolic performance at peak supine exercise.\textsuperscript{18} Therefore, attainment of a higher FS and a greater decrease in ESD in the master athletes than in the sedentary controls is consistent with enhancement of left ventricular systolic performance at peak exercise in highly trained older endurance athletes. Because of the cross-sectional nature of our study, we cannot exclude the possibility that genetic influences may be responsible, at least in part, for the differences in cardiac performance between master athletes and sedentary older men. We do not believe, however, that genetic influences can entirely explain the differences in hemodynamic responses to exercise between the two groups because longitudinal studies have demonstrated development of qualitatively similar adaptations in previously sedentary older men.\textsuperscript{18} The use of supine cycle ergometer exercise to assess left ventricular function does not provide data on the true maximal exercise response that can usually be achieved with treadmill exercise. The variables used for evaluation of contractile function should be interpreted with caution because we used the standard sphygmomanometer for measurement of blood pressure, which may not necessarily reflect precise changes in central aortic or left ventricular systolic pressure. Further, accurate assessment of changes in left ventricular end-systolic wall stress requires knowledge of end-systolic instead of peak systolic pressure in the ascending aorta or left ventricular cavity, which is virtually impossible to measure during exercise by means of noninvasive techniques. Nevertheless, despite these limitations, our data taken together provide evidence suggestive of enhanced left ventricular systolic performance in highly trained master athletes.

Our findings suggest that volume-overload left ventricular hypertrophy with moderate cardiac enlargement in older endurance trained athletes is a benign and physiological phenomenon because it is associated with enhanced left ventricular function during exercise and excellent prognosis.\textsuperscript{14} Our results also indicate that larger SV and cardiac output play a significant role in maintaining a higher peak $V_{O_{2}}$ and $V_{O_{2max}}$ in older endurance athletes. The higher SV at peak exercise observed in these highly trained older men appears to result not only from physiological volume-overload hypertrophy and the Frank-Starling effect but also from improvement in left ventricular systolic performance independent of preload.

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**References**


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