Arterial compliance of rowers: implications for combined aerobic and strength training on arterial elasticity

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The aorta and central arteries are not simply tubes or conduits; rather, they are highly complex components of the vascular tree that buffer oscillations in blood pressure and blood flow. Reductions in this cushioning function result in increased left ventricular afterload, increased myocardial oxygen demand, and decreased coronary blood flow and eventually lead to coronary ischemia (19, 22). Furthermore, because the vascular structure of the carotid sinus determines the deformation of and strain on the arterial baroreceptor endings during changes in arterial blood pressure, decreased arterial compliance is associated with impaired arterial baroreflex regulation of heart rate (17). Thus, through these mechanisms, stiffening of the central arteries exerts a combined effect on the heart, the arteries, and the autonomic nervous system in older humans.

Regular aerobic exercise and strength training are recommended for the prevention and treatment of cardiovascular disease and frailty associated with aging. Regular aerobic exercise is beneficial for reversing arterial stiffening in middle-aged and older adults (18, 26) and attenuates the age-related decline in carotid baroreflex sensitivity (BRS) (16). In contrast to the beneficial effects of aerobic exercise, resistance training in middle-aged adults is associated with lower, rather than higher, central arterial compliance (14). Therefore, regular aerobic exercise and resistance exercise seem to exert opposite effects on the elastic properties of the arterial wall. It is not known how the elastic properties of the arterial wall will behave when one performs endurance training and strength training simultaneously.

In this regard, rowing exercise is unique, as it includes components of aerobic endurance and muscular strength (23). Rowers require large muscle strength to accelerate the boat at the start of the race and high endurance capacity to maintain this speed during the race (24). Similarly, rowers perform a combination of endurance and strength training during their usual training regimen, as demonstrated by their large maximal aerobic capacity and muscle strength (13, 23, 28, 29). Because more time may be required for development of vascular wall adaptations, a cross-sectional study analyzing arterial compliance in rowers may shed light on this clinically important question.

Accordingly, the primary aim of this study was to determine whether central and peripheral arterial compliance is higher in middle-aged and older rowers than in age-matched sedentary controls. We hypothesized that habitual rowers would demonstrate greater central arterial compliance than sedentary controls. Moreover, we hypothesized that compliance of peripheral (more muscular) arteries would be similar between the two groups, because exercise training has been shown to have no impact on these vascular beds (14, 25, 26). Because a reduction in arterial BRS is one of the important sequelae of arterial stiffening (17), we also determined whether the hypothesized higher arterial compliance in rowers would be accompanied by greater BRS.

METHODS

Subjects. A total of 30 healthy middle-aged and older adults (37–71 yr) were studied. They were either rowers (11 men and 4 women) or age-matched sedentary controls (10 men and 5 women). All of the subjects were healthy, nonobese, nonsmoking, normotensive (<140/90 mmHg), normolipidemic, and free of overt cardiovascular and other chronic diseases as assessed by medical history question-
naire. None of the subjects were taking cardiovascular-acting medications, including hormone replacement therapy. Physical activity was documented by a modified Godin physical activity questionnaire (4). Rowers had been training 5.4 ± 1.2 (SD) times/wk, 73 ± 14 min/session for 5.7 ± 4.0 yr, and rowing was their primary form of regular exercise. Approximately 65% of their training sessions were devoted to high-intensity workouts, and 87 ± 8% of rowing was performed on water. Sedentary participants had not exercised for ≥12 mo. All procedures were approved by the Institutional Review Board at the University of Texas at Austin, and written informed consent was obtained from each individual before participation.

Procedures. All laboratory procedures were performed at rest under comfortable laboratory conditions. Subjects abstained from food, alcohol, and caffeine for ≥4 h before laboratory procedures. An overnight 12-h fast was required before the measurements of metabolic risk factors. Premenopausal women were tested during the early follicular phase of the menstrual cycle.

Body composition. Body composition was measured using dual-energy X-ray absorptiometry (Lunar DPX, GE Medical Systems, Fairfield, CT).

Dietary intake analysis. A 3-day diet record was obtained and analyzed by a registered dietitian. Carbohydrate, fat, protein, and alcohol intakes were presented as percentage of the total caloric intake.

Handgrip strength. Handgrip strength was measured using an electrical handgrip dynamometer (model HDM-915, Lode Instruments, Groningen, The Netherlands).

Arterial blood pressure and heart rate at rest. Brachial and ankle blood pressure and heart rate were measured by an automated oscillometric device (model VP-2000, Colin Medical Instruments, San Antonio, TX) after ≥15 min of rest in the supine position (4). Ankle-brachial pressure index was calculated as ankle systolic blood pressure divided by brachial systolic blood pressure and was used to screen for peripheral artery disease.

Blood samples. A blood sample was collected from the antecubital vein after an overnight fast. Plasma concentrations of glucose, lipids, and lipoproteins were determined enzymatically using a Vitros DT60 analyzer (Ortho-Clinical Diagnostics, Raritan, NJ). Plasma norepinephrine concentrations were analyzed by enzyme immunoassay (Labor Diagnostika Nord, Nordhorn, Germany). Hematocrit was measured using a microcapillary reader (Damon/IEC Division, Needham, MA).

Arterial compliance. A combination of ultrasound imaging with simultaneous application of tonometrically obtained arterial pressures from the contralateral artery permitted noninvasive determinations of arterial compliance and β-stiffness index (14, 26). The common carotid artery was imaged using B-mode ultrasound (model HDI 5000CV, Philips, Bothel, WA) equipped with a high-resolution linear-array transducer. Ultrasound images were transferred to digital viewing software (Access Point 2000, Freeland, Westfield, IN). Diameters were measured from the intima of the far wall to the media-adventitia of the near wall. Pulsatile changes in the common carotid artery and common femoral artery diameters were analyzed I–2 cm proximal to the bifurcation. Blood pressure waveforms were obtained from the contralateral artery using arterialplanationometry (model TCB-500, Millar Instruments, Houston, TX) (14, 26) and analyzed by waveform browsing software (WinDaq 2000, Dataq Instruments, Akron, OH). To eliminate interinvestigator variability, one investigator analyzed all ultrasound images and blood pressure waveforms.

Cardiovagal BRS. Cardiovagal BRS was determined using the Valsalva maneuver (16, 17, 20). Briefly, subjects were seated in an upright position and familiarized with the procedure. Subjects performed a Valsalva maneuver and maintained an expiratory mouth pressure of 40 mmHg for 10 s. R-R interval (ECG) and blood pressure (Pilot 9200, Colin Medical, San Antonio, TX) were measured continuously. Subjects performed three Valsalva maneuvers ≥5 min apart to allow heart rate and blood pressure to return to baseline.

Data for cardiovagal BRS were recorded and analyzed by waveform browsing software (WinDaq 2000) during the phase IV overshoot. Systolic blood pressure values were linearly regressed against corresponding (lag 1) R-R intervals from the point where the R-R intervals began to lengthen to the point of maximal systolic blood pressure elevation (16, 17).

Carotid artery intima-media thickness. Carotid artery intima-media thickness was measured from images derived from an ultrasound machine equipped with a high-resolution linear-array transducer (model HDI-5000, Philips) (27). Images were analyzed by use of computerized software (QLab, Philips).

Statistics. One-way ANOVA and analysis of covariance were used for statistical analysis to determine significant group differences. Statistical significance was set a priori at P < 0.05 for all comparisons. Values are means ± SD, except in Figs. 1 and 2, where means ± SE are reported. Initially, univariate correlation and regression analysis were used to assess the strength of the relation between carotid arterial compliance and cardiovagal BRS. Partial correlation analysis and forward stepwise multiple regression analysis were then used to determine an independent association between cardiovagal BRS and arterial compliance.

RESULTS

There were no group differences in age, height, body mass, body mass index, body composition, or waist circumference (Table 1). As expected, physical activity scores assessed by the modified Godin questionnaire and handgrip strength were higher (both P < 0.02) in rowers than in sedentary controls. There were no group differences for total caloric intakes, percent carbohydrate, percent fat, percent alcohol, or sodium intakes. Daily protein intake was higher (P < 0.05) in rowers than in sedentary controls. Fasting plasma glucose, lipid, and lipoprotein concentrations were not different between groups. Plasma norepinephrine concentrations were higher (P < 0.05) in rowers than in sedentary controls. Heart rate at rest was
lower ($P < 0.05$) in rowers than in sedentary controls (Table 2). Brachial blood pressure, carotid blood pressure, carotid artery intima-media thickness, and ankle-brachial pressure index were not different between the groups.

Carotid arterial compliance was higher ($P < 0.001$) and β-stiffness index was lower ($P < 0.001$) in rowers than in sedentary controls (Fig. 1). Because of the significant group difference in heart rate at rest, analysis of covariance was performed with heart rate as the covariate. The group difference in carotid arterial compliance remained statistically significant ($P = 0.01$). Femoral arterial compliance and β-stiffness index were not different between rowers and sedentary controls. Cardiovagal BRS was greater ($P < 0.01$) in rowers than in sedentary controls (Fig. 2) and was positively associated with carotid arterial compliance ($r = 0.54$, $P < 0.005$). Stepwise regression analysis revealed that, among the variables correlated with cardiovagal BRS (arterial compliance, diastolic blood pressure, and heart rate), carotid arterial compliance was the strongest independent physiological correlate of cardiovagal BRS, inasmuch as it explained 36% of the variance ($P < 0.01$). Additionally, when the influence of other variables (e.g., diastolic blood pressure and heart rate) was accounted for using a partial correlation analysis, the relation between cardiovagal BRS and carotid arterial compliance remained significant ($r = 0.45$, $P < 0.05$).

### DISCUSSION

The primary findings of the study are as follows: 1) Central arterial compliance was higher and β-stiffness index was lower in habitual rowers than in age-matched sedentary controls who were matched for age, body mass, metabolic risk factors, blood pressure, and heart rate.

### Table 2. Selected physiological variables at rest

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sedentary</th>
<th>Rowers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate, beats/min</td>
<td>63±7</td>
<td>53±11*</td>
</tr>
<tr>
<td>Brachial systolic BP, mmHg</td>
<td>122±10</td>
<td>122±10</td>
</tr>
<tr>
<td>Brachial diastolic BP, mmHg</td>
<td>75±13</td>
<td>75±10</td>
</tr>
<tr>
<td>Brachial mean BP, mmHg</td>
<td>93±9</td>
<td>92±10</td>
</tr>
<tr>
<td>Brachial pulse pressure, mmHg</td>
<td>47±6</td>
<td>49±5</td>
</tr>
<tr>
<td>Carotid systolic BP, mmHg</td>
<td>105±9</td>
<td>103±8</td>
</tr>
<tr>
<td>Carotid pulse pressure, mmHg</td>
<td>35±6</td>
<td>35±5</td>
</tr>
<tr>
<td>Carotid IMT, mm</td>
<td>0.59±0.06</td>
<td>0.61±0.08</td>
</tr>
<tr>
<td>ABI</td>
<td>1.10±0.07</td>
<td>1.08±0.07</td>
</tr>
</tbody>
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Values are means ± SD; $n = 15$. BP, blood pressure; IMT, intima-media thickness; ABI, ankle-brachial pressure index. *$P < 0.05$ vs. sedentary.
pressure, and sodium intake. 2) Measures of peripheral arterial stiffness were not different between the groups. 3) Cardiovascular BRS was higher in rowers than in sedentary controls and was positively related to carotid arterial compliance. These results indicate that regular rowing exercise in middle-aged and older adults is associated with favorable effects on the elastic properties of the central arteries.

Because vascular adaptations may be a long-term process requiring a prolonged follow-up or intervention periods to induce appreciable changes, we used a cross-sectional study design. To minimize the weaknesses of this study design and to isolate the influence of rowing as much as possible, both groups were carefully matched for age, body composition, blood lipids, plasma glucose, blood pressure, and dietary sodium intake. Additionally, to isolate the effect of rowing, we excluded individuals for whom rowing was not their primary form of exercise. Rower were also excluded if more than two training days per week were exclusively nonrowing exercise, such as running, cycling, or weightlifting. Many rowers were competitive and followed similar training schedules. The majority (>65%) of their training sessions were devoted to high-intensity workouts. We found that central arterial compliance was higher and β-stiffness index was lower in habitual rowers. Therefore, the results of the present study suggest that chronic rowing exercise is associated with a greater central arterial compliance.

Because of the contrasting effects of endurance and resistance training on the elastic properties of arteries, it is of particular interest to determine how the arteries adapt to a combination of these training modes. To gain insight into this issue, we studied a group of highly trained rowers. Rowing is unique for examination of training adaptations, because it includes the components of endurance training and resistance training (13, 23). Rowers exhibit markedly enlarged left ventricular dimensions as well as left ventricular wall thickness (13, 21). This is thought to be due to a combination of extreme volume load (as seen in endurance training) and extreme pressure overload (as seen in resistance training) during rowing (21). Rowing uses the upper and lower body and utilizes both limbs simultaneously to generate powerful force, causing large fluctuations in blood pressure and pulse pressure (2, 23). As shown in the present study, in regard to the impact of the overall rowing training on the vasculature, the endurance-training component appears to outweigh the resistance-training component, producing a higher arterial compliance in rowers. These results suggest that stiffening of the large arteries may be avoided if endurance training is incorporated into an exercise program that has a strength-training component. Intervention studies are necessary to draw more definite conclusions on this issue.

Endurance training does not influence the compliance of peripheral arteries (25, 26). Similarly, peripheral arterial compliance is not different between sedentary and resistance-trained individuals (14). Consistent with these observations, we found that femoral arterial compliance was not different between groups. A lack of association between exercise training and peripheral arterial compliance is attributed to the fact that the arterial wall components of the femoral artery, which, in contrast to the central elastic arteries, do not act to buffer large fluctuations in blood pressure and blood flow.

The sympathetic nervous system exerts a tonic restraint on the compliance of the common carotid artery (11), and the removal of that restraint produces an immediate increase in its compliance (11). We measured plasma concentrations of norepinephrine, a rough index of sympathetic nervous system activity, in an attempt to gain insight into the physiological mechanisms underlying the effects of rowing training on arterial compliance. Although carotid arterial compliance was greater in rowers than in sedentary controls, plasma norepinephrine levels were also higher in rowers. These results are not consistent with the idea that decreased sympathetic vasoconstrictor activity is responsible for the greater arterial compliance in rowers. A more likely explanation for the greater arterial compliance in rowers is increased nitric oxide bioavailability. Arterial compliance is modulated significantly by endothelial function (7), and regular aerobic exercise improves this important function (5). Other possibilities include increases in vasa vasorum flow (1), decreases in collagen cross-linking (8), and/or decreases in local endothelin-1 action (12). Given that the influence of exercise training manifests only in the central elastic arteries, where beat-by-beat arterial distension is greater, there may be an interaction between these physiological mechanisms and mechanical factors that are inherent in the central arterial wall.

The vascular structure of the carotid sinus determines the deformation of the arterial baroreceptor endings during changes in arterial pressure. A compliant artery acts to augment stimulus transduction and affect responsiveness of baroreceptors. Endurance training is associated with enhanced cardiovagal BRS (17). However, it is unclear whether resistance training has the same effect (3, 9). Given the lower arterial compliance in strength-trained individuals and the close association between arterial compliance and arterial BRS, it is reasonable to hypothesize that strength training is associated with lower cardiovagal BRS. The higher cardiovagal BRS in rowers was positively and independently associated with carotid arterial compliance. Thus regular rowing exercise appears to enhance arterial BRS, arguably via its effects on arterial compliance. Alternatively, rowing exercise itself causes large blood pressure changes that mimic the Valsalva maneuver at the catch of the stroke (23). Therefore, in contrast to sedentary individuals, rowers may have developed a greater capacity to adjust disturbances in blood pressure because of frequent exposure to this stimulus.

In addition to the use of a cross-sectional study design, the present study has other important limitations. Because of the risks associated with the testing and a lack of specific testing procedure, we did not measure maximal aerobic capacity and muscle strength to confirm that rowers were endurance trained as well as strength trained. As alternatives, we used the Godin physical activity questionnaire and handgrip strength. Even though these are indirect measures, the magnitude of the differences in these results between the sedentary controls and rowers clearly shows that rowers in the present study demonstrated greater aerobic fitness and muscular strength.

In conclusion, habitual rowers demonstrate a greater central arterial compliance and higher cardiovagal BRS than sedentary controls who are matched for many potentially confounding factors. Our findings suggest that concurrently performed endurance training may negate the stiffening effects of resistance training on arterial compliance.
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GRANTS

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