Influence of age and gender on cardiac output-VO₂ relationships during submaximal cycle ergometry

DAVID N. PROCTOR, KENNETH C. BECK, PETER H. SHEN, TAMARA J. EICKHOFF, JOHN R. HALLIWILL, AND MICHAEL J. JOYNER
Department of Anesthesiology, Mayo Clinic, Rochester, Minnesota 55905

Proctor, David N., Kenneth C. Beck, Peter H. Shen, Tamara J. Eickhoff, John R. Halliwill, and Michael J. Joyner. Influence of age and gender on cardiac output-VO₂ relationships during submaximal cycle ergometry. J. Appl. Physiol. 84(2): 599–605, 1998.—It is presently unclear how gender, aging, and physical activity status interact to determine the magnitude of the rise in cardiac output (Qc) during dynamic exercise. To clarify this issue, the present study examined the Qc-VO₂ (Vo₂) relationship during graded leg cycle ergometry in 30 chronically endurance-trained subjects from four groups of n = 6 (8/group): younger men (20–30 yr), older men (56–72 yr), younger women (24–31 yr), and older women (51–72 yr). VO₂ (acetylene rebreathing), stroke volume (Qc/heart rate), and whole body VO₂ were measured at rest and during submaximal exercise intensities (40, 70, and ~90% of peak VO₂). Baseline resting levels of VO₂ were 0.6–1.2 l/min less in the older groups. However, the slopes of the Qc-VO₂ relationship across submaximal levels of cycling were similar among all four groups (5.4–5.9 l/l). The absolute Qc associated with a given VO₂ (1.0–2.0 l/min) was also similar among groups. Resting and exercise stroke volumes (ml/beat) were lower in women than in men but did not differ among age groups. However, older men and women showed a reduced ability, relative to their younger counterparts, to maintain stroke volume at exercise intensities above 70% of peak VO₂. This latter effect was most prominent in the oldest women. These findings suggest that neither age nor gender has a significant impact on the Qc-VO₂ relationships during submaximal cycle ergometry among chronically endurance-trained individuals.

CARDIAC OUTPUT (Qc) is a major determinant of systemic O₂ transport in humans. With aging, maximal Qc during exercise is reduced, and this reduction explains a given submaximal exercise intensity VO₂ uptake (Vo₂max; Refs. 9, 12, 17, 21, 24, and 25). In healthy older individuals at rest, Qc is usually lower compared with younger control subjects (26, 29). At a given submaximal exercise intensity [O₂ uptake (Vo₂)], Qc may (4, 18, 29, 30) or may not (2, 19, 25) decline with aging. However, the slope of the Qc-VO₂ relationship during graded dynamic exercise is generally considered to be well maintained with advancing age (3, 4, 14, 25, 26, 29).

Younger women reportedly achieve a higher absolute level of Qc at a given submaximal VO₂ than do younger men (2, 5, 15, 20). This gender-related difference has not been reported among sedentary older populations (2, 18). Moreover, recent studies by Spina and colleagues (27, 28) show that Qc at a given VO₂ is reduced in older women after endurance exercise training but is unchanged in older men or in younger groups with training. On the basis of these results, it is unclear how gender, aging, and physical activity status interact as determinants of this important physiological relationship. The equivocal nature of the data on this issue could be due, in part, to variation in Qc measurement techniques, exercise modes, and/or subject fitness levels among studies.

With this information as background, the present study was designed to evaluate whether the Qc-VO₂ relationships during graded leg cycle ergometry are different in chronically endurance-trained male and female subjects from two discrete age groups. Our general hypothesis was that the slope and/or absolute level of Qc at a given submaximal VO₂ would be reduced in endurance-trained older women compared with the other groups. Stroke volume responses were also studied because of recent evidence that stroke volume may not plateau during graded exercise in some highly endurance-trained younger (7) and older (24) men.

METHODS

Subjects

Thirty endurance-trained men (8 younger, 8 older) and women (6 younger, 8 older) served as subjects in this cross-sectional study. Chronically endurance-trained subjects were studied rather than sedentary subjects to ensure that comparisons of cardiovascular responses between the age groups would not be confounded by differences in subject motivation, the normal decline in physical activity with aging, and to ensure that the older subjects could reach and sustain high exercise workloads. Subjects were notified of the study through an advertisement in a statewide running magazine and were enrolled so that approximately equal numbers of runners, cyclists, and cross-trained athletes (e.g., triathletes) would comprise each of the four groups. Older subjects were only admitted for study if they did not show any evidence of electrocardiogram or blood pressure abnormalities during a Bruce treadmill test. Four of the eight older women who were selected for this study had been taking physiological replacement doses of estrogen for a minimum of 1.5 yr.

In general, these four groups of subjects were successful in regional running/cycling competitions, but only one older female runner (72 yr) was an elite-caliber athlete. The treadmill VO₂max and physical characteristics of the four groups given in Table 1 reflect a highly trained, but noneleve, sample. All subjects gave written informed consent before the study, according to Mayo Clinic Institutional Review Board guidelines.

Rationale for Using Leg Cycle Ergometry

The Qc-VO₂ relationship was assessed during incremental upright leg cycling on a Monark cycle ergometer. Stationary cycling was chosen instead of treadmill exercise because power output (and thus VO₂) could be precisely controlled and multiple measurements of Qc and blood pressure could be
more easily obtained. Cycling is also frequently used by older endurance athletes for "cross-training" and injury/overtraining avoidance. The modes of training were similar among the four groups, with roughly equal numbers of runners (3–4), cyclists (2), and cross-trained athletes (2–3) in each group. Self-selected pedal rates averaged 70–75 revolutions/min (rpm; range 60–90 rpm) in all four groups. During all tests, subjects were required to remain seated and were not permitted to lean forward over the pedals.

Measurement of VO₂

Whole body VO₂ was measured by using a breath-by-breath mass spectrometry system previously validated against the meteorological balloon collection technique across a broad range of breathing frequencies (22). VO₂max was measured in subjects on a treadmill by using standard procedures (23). Peak VO₂ (VO₂peak) testing during cycle ergometry consisted of continuous incremental pedaling (2-min stages) to exhaustion (inability to maintain pedal cadence of ≥50 rpm). VO₂ during cycling did not typically reach a "plateau" (<150 ml/min after final minute of test) by using this protocol, except in three of the younger men who were cyclists/triathletes. Therefore, VO₂peak cycling tests were conducted twice (sessions 2 and 3 described in Test Protocols), with the average VO₂ measured during the final 30 s being used to define VO₂peak. The average of two VO₂peak values was used for subjects in whom the two values differed by <5%. In cases where larger differences were observed (~20% of all tests), the higher of the two VO₂peak Values was used. Power output (W) was closely regulated during these protocols by adjusting flywheel resistance and rpm. Heart rate (HR) was determined from electrocardiogram (10-beat average) tracings, with the highest value from the two tests being used to define peak HR.

Measurement of Qc

Qc was estimated by using acetylene rebreathing (31). Subjects rebreathed a mixture of 0.7% C₂H₂-40% O₂-10% He-balance N₂ from a 3- or 5-liter anesthesia bag. A three-way stopcock was manually opened before a normal inspiration, and subjects were asked to empty the bag with each inspiration. Verbal cues were used to maintain a consistent breathing pattern for 8–10 breaths. Gas concentrations were monitored at the mouth by using a respiratory mass spectrometer (Perkin-Elmer MGA 1100). A pneumotachograph flow signal was used to identify individual breaths. Digital displays of these signals were analyzed after each rebreathing effort by using a customized computer program that allowed for verification of the end-tidal He and C₂H₂ gas concentration values. End-inspiratory He data were automatically fit to the relationship He(t) = P 1e⁻¹(Ht – P2), where P1, P2, and k are parameters determined by minimizing the mean square error of the fitted curve to the data, and t is time. Time 0 for the acetylene curve was determined from where the He curve intercepted He(t) = 1.0 (32). In general, breaths 3–6 were selected for computation of Qc. Qc was estimated by using equations outlined by Triebwasser et al. (31), but we used blood solubility constant for acetylene of 0.74 ml·ml⁻¹·atm⁻¹ (8). Individual Qc measurements were separated by a minimum of 3 min to permit washout of C₂H₂, as confirmed by end-tidal monitoring. Qc measurements made on 2 separate days in 5 laboratory staff members were reproducible at rest (coefficient of variation = 6.2%; P = 0.11) and during submaximal loads of leg cycling (coefficient of variation = 7.8%; P = 0.20).

Systolic and diastolic brachial arterial blood pressures were estimated by using a semiautomated cuff inflation system (model PE 3000, Narket Systems) and an amplified stethoscope. Mean arterial pressure was estimated, in the conventional manner, as pulse pressure/3 + diastolic pressure.

Body Composition

Percent body fat and leg muscle mass (bone-free lean tissue) were estimated by using dual-energy X-ray absorptiometry (Lunar, Madison, WI) as previously described by our laboratory (23). These measurements were found to be highly reproducible in 10 normal subjects (25–50 yr) studied twice during the course of the present study.

Test Protocols

Sessions 1 and 2: Peak exercise testing. In session 1, subjects underwent a dual-energy X-ray absorptiometry scan followed by a treadmill VO₂max test (23). During session 2, subjects were oriented to the cycle ergometer, and a VO₂peak test (described in Measurement of VO₂) was conducted.

Session 3: Submaximal cycle ergometer testing. During session 3, subjects completed submaximal bouts (5–6 min) of cycling at 40 and 70% (±2%) of VO₂peak. During minute 4 of these submaximal bouts, HR and a rating of perceived exertion (RPE) were collected. During the final minute, subjects practiced the acetylene rebreathing procedure. These procedures allowed us to accurately define the steady-state VO₂ and power outputs at these intensities and also provided
estimates of the rebreathing bag volumes that would be used for the test in session 4 (see below). VO_{2peak} tests were also repeated during session 3.

Session 4: Q˙c testing. During the final session, Q˙c measurements were made during seated rest and submaximal (40 and 70% of VO_{2peak}) and near-maximal (~90% of VO_{2peak}) exercise. Resting trials were conducted three to four times, with the two closest values used for averaging (19). During the 40 and 70% bouts, power output, HR, and RPE were closely monitored for 3 min (to achieve steady-state values obtained during session 3), followed by blood pressure and Q˙c measurements. After a 1- to 2-min recovery, this sequence was repeated to provide two measurements of Q˙c, blood pressure, and HR for averaging at each exercise intensity. If the two values for Q˙c differed by >10% for a given work intensity, the bout was repeated a third time. After at least a 15-min recovery from these submaximal bouts, subjects performed two graded cycling bouts (4–5 min each) that concluded with recovery from these submaximal bouts, subjects performed a third time. After at least a 15-min recovery, this sequence was repeated to provide two measurements of Q˙c, blood pressure, and HR for averaging at each exercise intensity. If the two values for Q˙c differed by >10% for a given work intensity, the bout was repeated a third time. After at least a 15-min recovery from these submaximal bouts, subjects performed two graded cycling bouts (4–5 min each) that concluded with recovery from these submaximal bouts, subjects performed a third time. After at least a 15-min recovery, this sequence was repeated to provide two measurements of Q˙c, blood pressure, and HR for averaging at each exercise intensity. If the two values for Q˙c differed by >10% for a given work intensity, the bout was repeated a third time. 

Statistics

Resting, peak exercise, and body composition variables were evaluated with two-way (age, gender) analysis of variance. The slope of the Q˙c-V˙O2 (l/min) relationship, which was defined by using baseline and 40 and 70% of V˙O2peak values, were compared among groups by using an SAS (general linear model procedure) slope-analysis procedure (6). Q˙c responses were also compared among groups at specific V˙O2 levels (e.g., 1.0 and 2.0 l/min) through the use of individual subject regression coefficients. Stroke volume (Q˙c/HR) and total peripheral resistance (TPR) changes across relative work intensities (e.g., difference between 40 and 70% of V˙O2peak) were also compared among groups by using delta values and two-way analysis of variance. Data are presented as means ± SE. Significance was accepted at P < 0.05.

RESULTS

Subjects (Table 1)

Older men and women had approximately the same body weights as their younger counterparts but were shorter and had ~10–15% less leg muscle. Gender differences in body size and composition were much larger. For example, leg muscle mass was ~30% lower in women than in the men of a given age. Hemoglobin concentration was also lower in women (1.2–1.4 g/dl less) than in men, but no age-related differences were observed. The age-associated reduction in treadmill V˙O2max averaged 22–26%, whether expressed as liters per minute or milliliters per kilogram body weight per minute (~6% decline per decade in ml·kg⁻¹·min⁻¹). Older subjects had trained twice as long (~20 yr) as the younger subjects had (~10 yr), but the average time spent training per week did not differ among groups (6.5 ± 1 h/wk). Running mileage averaged 20–30 miles/wk for both older groups and 30–50 miles/wk for the younger subjects.

Peak Cycle Ergometry (Table 2)

Peak respiratory exchange ratios and perceived exertion levels during the VO_{2peak} cycling tests averaged 1.13–1.23 and 18 RPE units, respectively, in all four subgroups, demonstrating that similar levels of maximal effort were achieved. The VO_{2peak} (ml·kg⁻¹·min⁻¹) achieved during cycle ergometry was 30–33% higher in men than in women and was significantly lower in the older groups. The VO_{2peak} values (ml·kg⁻¹·min⁻¹) during cycle ergometry were 9–13% lower than those observed during treadmill V˙O2max testing (Table 1). This difference between testing modes is larger than might be expected in subject groups with considerable cycling experience (see METHODS). However, cycle ergometer VO_{2peak} was probably limited by the requirement that subjects not lean forward or stand over the pedals during testing.

Hemodynamic Responses

The seated resting levels of Q˙c immediately before exercise testing were lower (P < 0.05) in the older groups (4.0 ± 0.6 and 3.9 ± 0.3 l/min for men and women, respectively) than in the younger groups (5.2 ± 0.5 and 4.5 ± 0.7 l/min for men and women, respectively). Figure 1 shows the Q˙c responses at rest and during graded cycle ergometry plotted as a function of absolute VO_{2} (l/min). The slope analysis indicated that the increases in Q˙c with increasing VO_{2} were similar (P = 0.73) in all four groups (range = 5.4–5.9 l/min). Additionally, there were no group differences (P > 0.05) in the absolute level of Q˙c when compared at specific VO_{2} levels (e.g., 1.0 or 2.0 l/min). These values averaged 8.3–9.2 and 13.8–14.8 l/min at 1.0 and 2.0 l/min, respectively.

Stroke volume (Fig. 2) increased from baseline to the first level of exercise (40% of VO_{2peak}) in all subjects, with larger increases occurring in the men than in the women (P = 0.01). Between 40 and 70% of VO_{2peak}, the stroke volume continued to increase in the men but not in the women (gender effect; P = 0.02). As exercise intensity increased to a near-maximal level (90% of VO_{2peak}), there was a significant age-related difference (P < 0.01) in the maintenance of stroke volume: in the younger men, stroke volume continued to increase slightly, whereas the older men as a group maintained it. The younger women also maintained stroke volume at this near-maximal intensity, whereas the older women did not. Within the older groups (men and women combined), there was a trend (P = 0.05) for a decline in stroke volume between these two highest work intensities (70–90% of VO_{2peak}). This response appeared to be related to age (r = −0.50), with the oldest subjects having the largest decrease.

Seated resting levels of systolic, diastolic, and mean arterial pressure were similar among groups (all P > 0.58; data not shown). Increases in mean arterial pressure from rest to 70% of VO_{2peak} (blood pressure not measured at 90% work intensity) were proportional to exercise intensity and did not differ among groups. TPR (mean arterial pressure/Q˙c) was higher at rest and
during exercise in the older groups and in women vs. men, but the exercise-induced reductions in TPR (% change from baseline) were similar (P > 0.05) among groups. The only consistent hemodynamic difference among groups was the lower absolute systolic blood pressure response of the younger women.

**DISCUSSION**

The primary new finding of this study is that the slope of the Qc-V̇O₂ relationship, as well as the Qc associated with a given V̇O₂, does not significantly differ between younger and older chronically endurance-trained women. The Qc-V̇O₂ relationships in these women were similar to those seen in younger and older endurance-trained men in this and in previous studies by using graded leg cycle ergometry (1, 4, 10, 16, 17, 19, 25, 29). These findings suggest that neither aging nor gender per se significantly modifies the Qc response to submaximal dynamic exercise among chronically endurance-trained individuals. An additional new finding is that chronically endurance-trained older women showed a reduced ability, relative to their younger counterparts and to their male cohorts, to maintain stroke volume at near-maximal intensities of leg cycling. Because we obtained these measurements in chronically endurance-trained individuals. An additional new finding is that chronically endurance-trained older women showed a reduced ability, relative to their younger counterparts and to their male cohorts, to maintain stroke volume at near-maximal intensities of leg cycling. Because we obtained these measurements in chronically endurance-trained younger and older men and women in a single investigation, these findings are unlikely to be confounded by variations in Qc measurement techniques, protocols, physical activity, or subject motivational factors.

**Slope of Qc-V̇O₂ Relationship**

In the 1960’s, Strandell (29) and Julius et al. (13) used cardiac catheterization and the direct Fick method to measure exercise Qc, and they established that the slope of the Qc-V̇O₂ relationship was not altered by aging in healthy men. This has been consistently demonstrated by several investigators since that time by using a variety of gas-rebreathing techniques (4, 9, 17, 18). Reported slopes range from -4.6 to >6.0 l/l among studies but do not normally differ as a function of fitness level or mode of exercise testing (4, 16, 30). The Qc-V̇O₂ relationship in the younger and older men in the present study conforms to this pattern quite closely (i.e., 5.4–5.6 l/l). However, we are unaware of any studies that have closely examined this relationship as a function of age in trained women. Our data indicate that values in the chronically endurance-trained younger and older women also fall within the commonly reported 5–6 l/l range.

The slope of the Qc-V̇O₂ relationship for each group (Fig. 1) was evaluated by using seated resting and submaximal levels of steady-state exercise (40 and 70% of V̇O₂peak). We also studied our subjects at ~90% of V̇O₂peak, a non-steady-state workload even for endurance-trained subjects (33). When the Qc values obtained at 90% of V̇O₂peak were included in the regressions, the overall slopes were reduced slightly in each group (i.e., <5%) but remained similar among groups and ranged from 5.0 to 5.5 l/l. This indicates that our use of three data points (baseline and 40 and 70% of V̇O₂peak) for the

![Fig. 1. Cardiac output (Qc)-O2 uptake (V̇O2) relationship during graded leg cycle ergometry in endurance-trained younger and older men and women. Data represent 8 subjects/group except for younger women (n = 6). Regression lines represent mean responses for a given group derived from individual subject regression coefficients. Regression lines were derived from resting and 40 and 70% of peak V̇O₂ (V̇O₂peak) responses. Slope analysis of submaximal Qc-V̇O₂ relationship indicated no significant differences (P = 0.73) among groups.](attachment:image.png)

**Table 2. Peak responses during leg cycle ergometry**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Younger</th>
<th>Older</th>
<th>Gender Effect</th>
<th>Age Effect</th>
<th>Power output, W</th>
<th>Respiratory exchange ratio</th>
<th>V̇O₂, l/min</th>
<th>ml·kg⁻¹·min⁻¹</th>
<th>Ventilation, l/min</th>
<th>Heart rate, beats/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>367 ± 22</td>
<td>247 ± 16</td>
<td></td>
<td></td>
<td>1.23 ± 0.02</td>
<td>1.21 ± 0.04</td>
<td>4.0 ± 0.2</td>
<td>56.5 ± 1.8</td>
<td>162 ± 8</td>
<td>184 ± 3</td>
</tr>
<tr>
<td></td>
<td>250 ± 15</td>
<td>164 ± 8</td>
<td></td>
<td></td>
<td>1.19 ± 0.02</td>
<td>1.15 ± 0.05</td>
<td>2.7 ± 0.2</td>
<td>45.6 ± 2.2</td>
<td>115 ± 3</td>
<td>180 ± 3</td>
</tr>
<tr>
<td></td>
<td>602</td>
<td>562</td>
<td></td>
<td></td>
<td>5.0</td>
<td></td>
<td>3.0 ± 0.1</td>
<td>39.9 ± 1.4</td>
<td>135 ± 9</td>
<td>162 ± 6</td>
</tr>
<tr>
<td></td>
<td>905</td>
<td>850</td>
<td></td>
<td></td>
<td>6.0</td>
<td></td>
<td>2.0 ± 0.1</td>
<td>35.1 ± 1.6</td>
<td>98 ± 4</td>
<td>162 ± 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.2</td>
<td></td>
<td>1.8 ± 0.1</td>
<td>1.6 ± 0.1</td>
<td>1.4 ± 0.1</td>
<td>1.4 ± 0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td></td>
<td>1.0 ± 0.1</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.01</td>
<td></td>
<td>0.02</td>
<td>0.04</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 8 subjects/group except for younger women (n = 6). P values are defined as in Table 1.
computation of the slope of the $Q_c$-$V_{O2}$ relationship was equally effective in defining the rise in $Q_c$ during graded exercise for each of the four subject groups.

Absolute Values of $Q_c$ at a Given $V_{O2}$

Computing the "intercept" of the $Q_c$-$V_{O2}$ relationship has been the standard approach by which investigators have compared absolute $Q_c$ responses among different age, gender, and fitness subgroups (4, 17, 18, 30). However, we reasoned that comparisons of $Q_c$ among our age and gender subgroups would be most informative if examined at similar physiologically relevant exercise intensities (i.e., 1.0 and 2.0 l/min) rather than extrapolating to the $V_{O2} = 0$ intercept. Our analysis indicated that the absolute values of $Q_c$ at $V_{O2}$ values of 1.0 and 2.0 l/min did not differ among any of the groups that we studied. Similar findings (similar $Q_c$ at a specific submaximal $V_{O2}$) have been reported in younger and older endurance-trained men during upright cycle ergometry (17, 25). By contrast, age-associated reductions in $Q_c$ at submaximal work intensities are often seen when treadmill testing is used (9, 18, 21, 24) and/or older, less fit subjects are studied (4, 29, 30). These equivocal findings might result from intersubject differences in efficiency during weight-bearing vs. non-weight-bearing exercise and/or to the higher absolute stroke volumes attained by most subjects at a given $V_{O2}$ during treadmill compared with cycle ergometer exercise (10).

It has been reported that young women have a higher absolute level of $Q_c$ at a given submaximal $V_{O2}$ than do young men, possibly due to the lower hemoglobin concentration in women (2, 5, 20). However, Zwieren et al. (34) found no gender-related difference in submaximal $Q_c$ during leg cycling when they compared young men and women carefully equated in training background and with similar $V_{O2max}$ values normalized to lean body mass. Our results are consistent with those of Zwieren et al. and extend this observation to older endurance-trained groups. Collectively, these findings suggest that when differences in physical activity and cardiopulmonary performance capacity (i.e., $V_{O2max}/kg$ lean body mass) are controlled, gender differences in the absolute $Q_c$ responses to submaximal exercise are abolished.

A primary hypothesis of this study was that the $Q_c$ responses of endurance-trained older women would be lower at a given $V_{O2}$ compared with other endurance-trained subject groups. This was based on recent studies by Spina and colleagues (27, 28), who reported endurance-training-induced reductions in $Q_c$ at a given $V_{O2}$ in older women but not in other groups. Our data do not support this hypothesis. These apparently conflicting findings may be explained by the fact that the older women we studied had been training for ~20 yr (i.e., during the period before and after menopause), whereas the studies of Spina and colleagues were conducted in women who had trained for much shorter periods (~1 yr), after a decline in circulating estrogen had presumably already occurred.

Stroke Volume (Absolute Responses)

Resting and exercise stroke volumes (ml/beat) were lower in women than in men in both age groups. Although stroke volumes during exercise tended to be lower in the older groups (Fig. 2), these differences were not significant. This is in apparent contrast to the age-related reductions in exercise stroke volume seen by Ogawa et al. (21) during treadmill testing in similar age groups of endurance-trained subjects. One possible explanation for the lack of age-related change in our study is that the older subjects in the present study were relatively better trained than the older subjects studied by Ogawa et al. However, it is likely that the older athletes from both studies had trained hard enough and for a long enough period of time (i.e., ~20 yr) to reach and maintain their $V_{O2max}$ at or near its upper limit (11). More likely explanations for the differing results between studies include differences between treadmill running and stationary cycling and the fact that our older men were taller and heavier than many of the older athletes studied previously (9, 21, 24).

Stroke Volume (Graded Responses)

Stroke volume normally increases up to exercise intensities of 40–60% of $V_{O2max}$ in sedentary young subjects and then plateaus or falls slightly (1, 3, 10, 26). Endurance training has been shown to attenuate the normal reduction in stroke volume seen at heavy and near-maximal exercise intensities (27, 28). In the present study, there was some evidence that the younger men had not reached a plateau by the ~90% $V_{O2peak}$ workload during leg cycling. Similar findings have been reported recently in highly trained younger male cyclists (7) and in some older men (24) by using the same
generally maintained their level of stroke volume at younger women and older men in the present study.

The stroke-volume response of the older women deserves special mention. At near-maximal intensities of cycling (90% of V\text{\textsubscript{O2peak}}), the older women showed an impaired ability, relative to the younger women, to maintain their stroke volume. This impaired response absolute difference in stroke volume (\delta) between 70 and 90% of V\text{\textsubscript{O2peak}}) was less evident in the four women who were 51–59 yr old and receiving estrogen replacement than in the oldest women (61–72 yr, n = 4) who were not. As a result of recent attention focused on the possible effects of estrogen on exercise stroke volume in older women (27, 28), this observation deserves further attention in future studies. Several of the oldest men who were 51–59 yr old and receiving estrogen replacement had a modest decline in stroke volume at 90% of V\text{\textsubscript{O2peak}}. When the stroke volume responses of the older women and men were evaluated together, there was a tendency for stroke volume to fall in the oldest subjects at workloads between 70 and 90% of V\text{\textsubscript{O2peak}} (r = −0.50, P = 0.05).

In summary, the findings of this study demonstrate that the slope of the \text{Qc-VO2} relationship and the absolute \text{Qc} associated with a given \text{VO2} during submaximal leg cycling are well maintained with age in chronically endurance-trained older women and men. Because hemoglobin concentrations were similar among age groups, these results suggest that aging does not alter the linkage between systemic \text{O2} transport and utilization during dynamic exercise in chronically trained older athletes of either gender. However, there was evidence of an impaired ability of the older subjects, relative to their younger counterparts, to maintain stroke volume at high absolute \text{VO2} levels (i.e., 70–90% of V\text{\textsubscript{O2peak}}). This effect was most prominent in the oldest women. The influence of estrogen replacement on cardiac function in the older female athlete is deserving of further investigation.

We are grateful to the women and men who participated as subjects. We also thank Darrel Loeffler, Ethan Ebersold, and Lori Lawler for technical assistance and Janet Beckman for secretarial assistance.

This study was supported by the Mayo Foundation, Mayo Research Training in Anesthesiology Grant GM-08288, National Institutes of Health Grants M01-RR00585 and HL-46493 (M. J. Joyner), and the Glen L. and Lyra M. Ebling Cardiology Research Endowment.

Address for reprint requests: D. N. Proctor, Anesthesia Research, Mayo Clinic, 200 First St. SW, Rochester, MN 55905.

Received 19 February 1997; accepted in final form 8 September 1997.

REFERENCES


26. \textsc{Seals, D. R.} Influence of aging on autonomic-circulatory control at rest and during exercise in humans. In: Perspectives in


