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Cardiovascular responses to rowing

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ABSTRACT

ROSIELLO, R. A., D. A. MAHLER, and J. L. WARD. Cardiovascular responses to rowing. *Med. Sci. Sports Exerc.*, Vol. 19, No. 3, pp. 239–245, 1987. The purpose of this investigation was to evaluate the cardiovascular responses to rowing. In the first part of the study, heart rate (HR) and cardiac output (Q) were measured at rest and at three steady-state exercise levels on the variable-resistance rowing ergometer in 10 female and 11 male subjects. $\dot{Q}$ was determined non-invasively by the equilibration method of CO_2 re-breathing, and stroke volume (SV) was calculated. Subjects varied in rowing ability from healthy, inexperienced rowers to competitive athletes. The linear relationships between $\dot{Q}$ and oxygen consumption for the women ($r = 0.57$; $P < 0.001$; slope = 5.2 ± 1.1) (mean ± SD) and the men ($r = 0.58$; $P < 0.001$; slope = 6.1 ± 1.4) were similar to published values for other types of upright exercises. For both men and women, SV increased from rest to the first level of exercise, and then reached a plateau at or before the second exercise intensity. Between the second and third levels of exercise, SV decreased significantly in the female subjects (107 ± 18 vs 94 ± 16 ml; $P < 0.05$), but not in the male subjects (128 ±1 1 vs 126 ± 15 ml; P = not statistically significant). In the second part of the study, HR, $\dot{Q}$, and SV were compared on the cycle and rowing ergometers on successive days in eight additional subjects. At similar levels of oxygen consumption and $\dot{Q}$, HR was significantly higher, and SV was significantly lower during rowing exercise than with cycle exercise. These results demonstrate that the cardiovascular responses to rowing are different from upright cycle exercise. There was a greater reliance upon the increase in HR than the SV response to increase $\dot{Q}$ during rowing than during cycling.

CARDIAC OUTPUT, CO_2 RE-BREATHING, STROKE VOLUME, ROWING ERGOMETER, CYCLE ERGOMETER

During progressive incremental exercise, heart rate (HR) and cardiac output ($\dot{Q}$) increase linearly while stroke volume (SV) usually reaches a plateau at approximately 40% of maximal oxygen consumption ($\dot{V}O_{2max}$) (2, 3, 8). However, different absolute values for these cardiovascular variables have been observed depending on the specific physical activity (5–7, 9, 12, 17, 21, 23). For example, $\dot{V}O_{2max}$ and peak $\dot{Q}$ are significantly higher with exhaustive exercise on the treadmill than on the cycle ergometer in the same individuals (12, 17, 21). These differences in exercise responses may be due, at least in part, to the specific biomechanics of the particular type of exercise.

The sport of rowing involves rhythmic contractions of both upper and lower extremities, as well as the back muscles, to propel the boat forward. Comparison of $\dot{V}O_{2max}$ values during exercise on the cycle and rowing ergometers has shown conflicting results (7, 19). However, in a recent study, $\dot{V}O_{2max}$ was found to be significantly higher on the cycle ergometer than on the rowing ergometer in collegiate rowers, but was the same in untrained subjects (1). Furthermore, HR was higher at similar levels of oxygen consumption ($\dot{V}O_2$) during rowing than with cycling (1). These findings suggest that the cardiovascular responses to rowing may be different than cycling and raise the question whether the cardiovascular system might potentially limit rowing performance.

The purpose of this study was two-fold; i) to describe the cardiovascular responses to rowing; and ii) to compare $\dot{Q}$, HR, and SV during rowing and cycling. These two objectives allowed us to evaluate the hypothesis that cardiovascular variables during rowing were quantitatively different than upright cycling. We measured $\dot{Q}$ non-invasively by the CO_2 re-breathing method to investigate this question.

METHODS

Subjects. A total of 21 subjects (11 male and 10 female) participated in the first part of the study (Table 1). All subjects were in good health and had no history of cardiorespiratory disease. Pulmonary function tests and a 12-lead electrocardiogram were normal in all participants. Many, but not all, of the subjects exercised daily and varied in rowing ability from no experience to competitive athletes.

Eight male subjects participated in the second part of the study, which compared the cardiovascular responses between cycle and rowing exercises (Table 1). Individuals were selected based on a $\dot{V}O_{2max}$ on both the cycle and rowing ergometers greater than 3.5 $l \cdot min^{-1}$, and $\dot{V}O_2$ at the anaerobic threshold, measured non-invasively by ventilatory changes (24), greater than 2.5 $l \cdot min^{-1}$. These criteria were established so that three different levels of sub-maximal steady-state exercise could be maintained for 10 to 12 min to measure $\dot{Q}$.

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TABLE 1. Anthropometric data on subjects.

	Part 1		Part 2
	Female	Male	Male
No. of subjects	10	11	8
Age (yr)	23 ± 4	26 ± 3	28 ± 5
Height (cm)	169 ± 5	179 ± 7	181 ± 6
Weight (kg)	63 ± 4	73 ± 7	77 ± 5
BSA (m^2)	1.71 ± 0.08	1.90 ± 0.13	1.95 ± 0.06

Values are mean ± SD. BSA = body surface area.

Testing. Part 1 consisted of two consecutive days of testing in the Cardiopulmonary Laboratory of our institution. On the first day, subjects performed a progressive, incremental exercise test to exhaustion on the variable-resistance rowing ergometer (Concept II, Morrisville, VT). This system incorporates a chain and pulley with an air-resistance flywheel and sliding seat. The ergometer provides variable resistance based on the number of revolutions of the flywheel. Participants who were unfamiliar with the mechanics of the rowing stroke received instruction and were required to practice on the rowing ergometer 1 to 2 d prior to actual testing. Subjects were evaluated at the same time of the day for the two tests.

Before beginning the exercise tests, subjects sat comfortably on the ergometer for 5 min and breathed ambient air through a Hans-Rudolph two-way valve. Minute ventilation ($\dot{V}_E$), $\dot{V}O_2$, and CO_2 production ($\dot{V}CO_2$) were measured ever 30 s using the Metabolic Measurement Cart (Sensormedics, Schiller Park, IL). Expired volume was calibrated for 10 l with a 1-l syringe at different flow rates, and the gas analyzers were calibrated with known gas concentrations as determined by Scholander analysis. This system has been regularly evaluated by collection of expired gas in bags and analyzed by the Scholander method (18). HR and rhythm were monitored by surface electrodes attached to the anterior chest.

The exercise protocol consisted of 1-min increments based on the speed of the flywheel of the rowing ergometer. With the "catch" and throughout the "drive" phase of the rowing stroke, the speedometer needle increases, depending on the effort expended by the rower; with the "recovery," the needle falls to its lowest level. Each rower was instructed to keep the lowest level of the needle at the selected speed. The initial speed was 26 $km \cdot h^{-1}$ (16 mph). After the first minute, the speed was increased by 3 $km \cdot h^{-1}$ each minute until exhaustion, which occurred at 9 to 10 min of rowing exercise.

Power production during rowing was calculated for each subject by recording the time required to row 0.5 km at each level of exercise. Based on the power curve derived by measuring force on a strain gauge for a given change in length of the chain per time, the following formula for power output was derived (10):

$$\text{Power (w)} = \frac{3.5 \times 10^8}{s^3}$$

where s = time in seconds to complete 1.6 km. The time to row 0.5 km was corrected for a distance of 1.6 km. The highest value represented peak power production.

$\dot{V}O_{2max}$ was identified for each subject when $\dot{V}O_2$ reached a plateau as power production increased. Maximal values for HR (HR_{max}), $\dot{V}_E$, and $\dot{V}CO_2$ were measured at the corresponding exercise intensity at which $\dot{V}O_{2max}$ occurred.

On the following day, HR, $\dot{V}_E$, $\dot{V}O_2$, and $\dot{V}CO_2$ were measured at rest and at three sub-maximal levels of steady-state exercise on the rowing ergometer. In addition, $\dot{Q}$ was determined at rest and during exercise by CO_2 re-breathing, an indirect Fick method, using the Metabolic Measurement Cart (15, 25). After 4 min of quiet breathing at rest or sub-maximal exercise, $\dot{V}CO_2$, end-tidal CO_2 tension, and mixed venous CO_2 tension ($P_{\bar{v}}CO_2$) were measured sequentially. $\dot{V}CO_2$ was measured every 30 s and was averaged over 3 min. End-tidal CO_2 tension was averaged over 30 s and then used to calculate arterial CO_2 tension (13). $P_{\bar{v}}CO_2$ was estimated over 4 min using the equilibration method of Collier with the subject breathing 9.8% CO_2 in oxygen at rest and 12.1, 13.2, and 15.5% CO_2 in oxygen at the rowing speeds of 26, 32, and 38 $km \cdot h^{-1}$, respectively. Three measurements of $P_{\bar{v}}CO_2$ were made in each subject with 1 min allowed between re-breathing periods for elimination of CO_2, and the average $P_{\bar{v}}CO_2$ was used for calculations. Criteria for satisfactory equilibration during re-breathing were an equilibrium of partial pressure CO_2 tension obtained within 15 s of the start of re-breathing (usually within three breaths) and a "plateau" where partial pressure CO_2 tension did not vary by more than ±1 mm Hg. Mixed venous and arterial CO_2 contents were calculated from $P_{\bar{v}}CO_2$ and arterial CO_2 tension, respectively, using the standard, oxygenated CO_2 dissociative curve with McHardy's equation (13). Values for SV at rest and during exercise were calculated by dividing the respective $\dot{Q}$ by the corresponding HR.

In part 2 of the investigation, eight subjects were studied over 4 d. Progressive incremental exercise tests were performed on a cycle ergometer (Monark-Crescent AB, Varberg, Sweden) and the variable-resistance rowing ergometer on two successive days. The order of testing was alternated with each consecutive subject. Exercise on the cycle ergometer started at 25 W and then increased by increments in power of 25 W each minute until exhaustion. The exercise protocol on the rowing ergometer was identical to that previously described in part 1 of the study. HR, $\dot{V}_E$, $\dot{V}O_2$, and $\dot{V}CO_2$ were measured every 30 s during the exercise tests.

Approximately 1 wk later, $\dot{Q}$ was measured by the CO_2 re-breathing method at rest and at three different sub-maximal levels of steady-state exercise on the cycle and rowing ergometers on two successful days. Based on previous experience, we selected similar intensities of exercise by matching $\dot{V}O_2$ on the cycle and rowing ergometers. For exercise level 1, 50 W on the cycle ergometer was compared with 26 $km \cdot h^{-1}$ on the rowing ergometer; for exercise level 2, 125 W on the cycle ergometer was compared with 32 $km \cdot h^{-1}$ on the rowing ergometer; and for exercise level 3, 175 W on the cycle ergometer was compared with 38 $km \cdot h^{-1}$ on the rowing ergometer. We were therefore able to evaluate the cardiovascular responses to cycle and rowing exercises at the same oxygen requirements. The order of testing for each subject was identical to the initial 2 d of maximal exercise tests; four subjects were initially tested on the cycle ergometer, while the other four participants exercised on the rowing ergometer on the first day. Testing was performed at the same time of day in the fasting state. $\dot{Q}$ was determined three times at rest as well as at each level of exercise and averaged for calculation of SV. Systolic and diastolic blood pressures were measured by auscultation using a cuff sphygmomanometer at rest and within 5 s upon completion of cycle and rowing exercises at the three sub-maximal levels in 5 of the 8 subjects tested. Systolic pressure was determined as the point of appearance of Korotkoff sounds, while the point of disappearance of these sounds was considered to be the diastolic pressure.

TABLE 2. Physiologic measurements at maximal exercise on the rowing ergometer.

	Female ($N = 10$)	Male ($N = 11$)
HR_{max}		
$b \cdot min^{-1}$	187 ± 13	187 ± 9
$\dot{V}_{Emax}$		
$l \cdot min^{-1}$	113 ± 17	154 ± 24
$\dot{V}O_{2max}$		
$l \cdot min^{-1}$	3.0 ± 0.6	4.0 ± 0.5
$ml \cdot kg \cdot min^{-1}$	48.0 ± 7.6	55.7 ± 9.2
$\dot{V}CO_{2max}$		
$l \cdot min^{-1}$	3.8 ± 0.8	5.0 ± 0.5
Peak power production W	263 ± 56	340 ± 96

Values are mean ± SD. $\dot{V}_{Emax}$ = maximal exercise ventilation; $\dot{V}CO_{2max}$ = maximal CO_2 production.

Mean arterial pressure was calculated by adding one-third of the difference between systolic and diastolic pressures to the diastolic pressure. Systemic vascular resistance (SVR) was determined by the formula:

$$\text{SVR } (\text{dynes} \cdot \text{s} \cdot \text{cm}^{-5}) = \frac{80 \times \text{mean arterial pressure (mm Hg)}}{\dot{Q}\ (\text{l} \cdot \text{min}^{-1})}.$$

STATISTICAL ANALYSIS

Part 1. The relationship between $\dot{Q}$ and $\dot{V}O_2$ during rowing exercise was determined by linear regression analysis. Changes in SV during the three levels of sub-maximal exercise for the women and men were evaluated by ANOVA with repeated measures. Individual slopes ($\dot{Q}/\dot{V}O_2$), $\dot{V}O_2$, and cardiovascular responses to rowing for the female and male groups were compared using a mixed-factor ANOVA with repeated measures.

Part 2. A two-way ANOVA with repeated measures was used to compare the various physiological variables on the cycle and rowing ergometers.

P less than 0.05 was considered significant. Values are presented as mean ± SD.

RESULTS

Part 1. Maximal exercise values on the rowing ergometer for the female and male subjects are shown in Table 2. Levels of $\dot{V}O_{2max}$ reflect moderate aerobic fitness in both groups of subjects (2). The higher physiological values, except for HR_{max}, observed in the male subjects reflect greater fitness and larger body dimensions compared with the female subjects. Rowing experience did not appear to affect the results.

$\dot{V}O_2$ and the cardiovascular responses to rowing in these same objects are presented in Table 3. There were no significant differences in $\dot{V}O_2$ ($ml \cdot kg \cdot min^{-1}$) at rest or at the three levels of exercise between the female and male subjects. This indicates that the intensities of rowing exercise were similar for the two groups relative

TABLE 3. $\dot{V}O_2$ and cardiovascular responses at rest and during three levels of sub-maximal exercise on the rowing ergometer.

	Females				Males			
	$N = 10$			$N = 9$	$N = 11$			$N = 9$
	Rest	26 $km \cdot h^{-1}$	32 $km \cdot h^{-1}$	38 $km \cdot h^{-1}$	Rest	26 $km \cdot h^{-1}$	32 $km \cdot h^{-1}$	38 $km \cdot h^{-1}$
$\dot{V}O_2$								
$ml \cdot min^{-1}$	223 ± 25	993 ± 109	1,467 ± 146	2,207 ± 366	259 ± 41	1,122 ± 145	1,614 ± 228	2,371 ± 177
$ml \cdot kg \cdot min^{-1}$	3.5 ± 0.5	15.9 ± 2.1	23.4 ± 2.6	34.9 ± 5.9	3.6 ± 0.7	15.5 ± 2.2	22.4 ± 3.5	32.8 ± 5.1
HR								
$b \cdot min^{-1}$	64 ± 13	100 ± 19	121 ± 24*	153 ± 24*	58 ± 10	91 ± 11	108 ± 13*	137 ± 12*
$\dot{Q}$								
$l \cdot min$	5.2 ± 0.8	10.2 ± 0.8	12.6 ± 0.9	14.1 ± 1.5	5.6 ± 1.0	11.9 ± 1.9	14.2 ± 2.1	17.4 ± 1.5
$l \cdot min \cdot m^{-2}$	3.0 ± 0.5	5.9 ± 0.6	7.4 ± 0.7	8.2 ± 0.7*	3.0 ± 0.4	6.3 ± 1.1	7.5 ± 1.2	9.2 ± 0.8*
SV								
ml	83 ± 24	103 ± 17	107 ± 18	94 ± 16	101 ± 24	126 ± 12	128 ± 11	126 ± 15
$ml \cdot m^2$	48 ± 13	60 ± 9	62 ± 9	54 ± 8*	53 ± 11	67 ± 5	67 ± 5	66 ± 6*

Values are mean ± SD.

* $P < 0.05$ comparing values for females and males at the same level of exercise.

to body weight. At 26 and 32 $km \cdot h^{-1}$ rowing speeds, there were no significant differences for $\dot{Q}$ ($l \cdot min \cdot m^{-2}$) and SV ($l \cdot min \cdot m^{-2}$) between women and men. However, the significantly higher SV ($l \cdot min \cdot m^{-2}$) and significantly lower HR for the men at 38 $km \cdot h^{-1}$ is consistent with greater exercise capacity ($\dot{V}O_{2max}$) in the male subjects.

The relationship between $\dot{Q}$ and $\dot{V}O_2$ was linear with a slope of 5.2 ± 1.1 for women ($r = 0.57$; $P < 0.001$) and 6.1 ± 1.4 for men ($r = 0.58$; $P < 0.001$) (Fig. 1). There was no significant difference in the slopes ($\dot{Q}/\dot{V}O_2$) between the women and men. In general, SV increased from rest to the first level of steady-state exercise, then reached a plateau, and was maintained or subsequently declined between the second and third levels of exercise. SV decreased during the transition from 32 to 38 $km \cdot h^{-1}$ in 7 of 10 females and in 7 of 11 males; this decline occurred at 41 ± 12% of $\dot{V}O_{2max}$ in females and at 37 ± 6% in males. In a group, the decrement in SV between the second and third levels of exercise was statistically significant in the 10 females (107 ± 18 vs 94 ± 16 ml; $P < 0.05$), but not in the 11 males (128 ± 11 vs 126 ± 15 ml; P = not statistically significant). However, the precise point of plateau in SV could not be defined in this study.

Part 2. $\dot{V}O_{2max}$ was identical on the cycle (4.2 ± 0.4 $l \cdot min^{-1}$) and rowing (4.2 ± 0.3 $l \cdot min^{-1}$) ergometers in the eight male subjects (P = not statistically significant). In addition, HR_{max} was similar during cycling (185 ± 12 $b \cdot min^{-1}$) and rowing (186 ± 11 $b \cdot min^{-1}$) (P = not statistically significant).

Values for $\dot{V}O_2$ and cardiovascular variables on the cycle and rowing ergometers are shown in Table 4. There were no significant differences for $\dot{V}O_2$ or $\dot{Q}$ at rest or at the three intensities of exercise between cycle and rowing exercise. Accordingly, HR and SV responses were evaluated on the cycle and rowing ergometers at similar metabolic requirements. HR became progressively higher during rowing than during cycling as the workload increased. The difference between HRs reached statistical significance at 38 $km \cdot h^{-1}$ (cycling: 131 ± 10 $b \cdot min^{-1}$ vs rowing: 139 ± 13 $b \cdot min^{-1}$; $P < 0.05$). In contrast, SV was significantly lower during rowing than during cycling at the two highest levels of exercise (Table 4 and Fig. 2). Peak SV was uniformly higher on the cycle (150 ± 15 ml) than on the rowing ergometer (137 ± 12 ml) ($P < 0.05$).

There were no significant differences in systolic, diastolic, or mean arterial blood pressures at rest or during exercise on the cycle and rowing ergometers (Table 4). Systemic vascular resistance was similar at rest and during exercise on the two ergometers (Table 4).

DISCUSSION

The results of our study showed that SV initially increased, then leveled off, and subsequently declined with progressive sub-maximal rowing in the female subjects. This decrement contrasts with the expected plateau in SV observed during cycle or treadmill exercise (2–4, 8), which was also observed in our male subjects on the rowing ergometer. Direct comparison

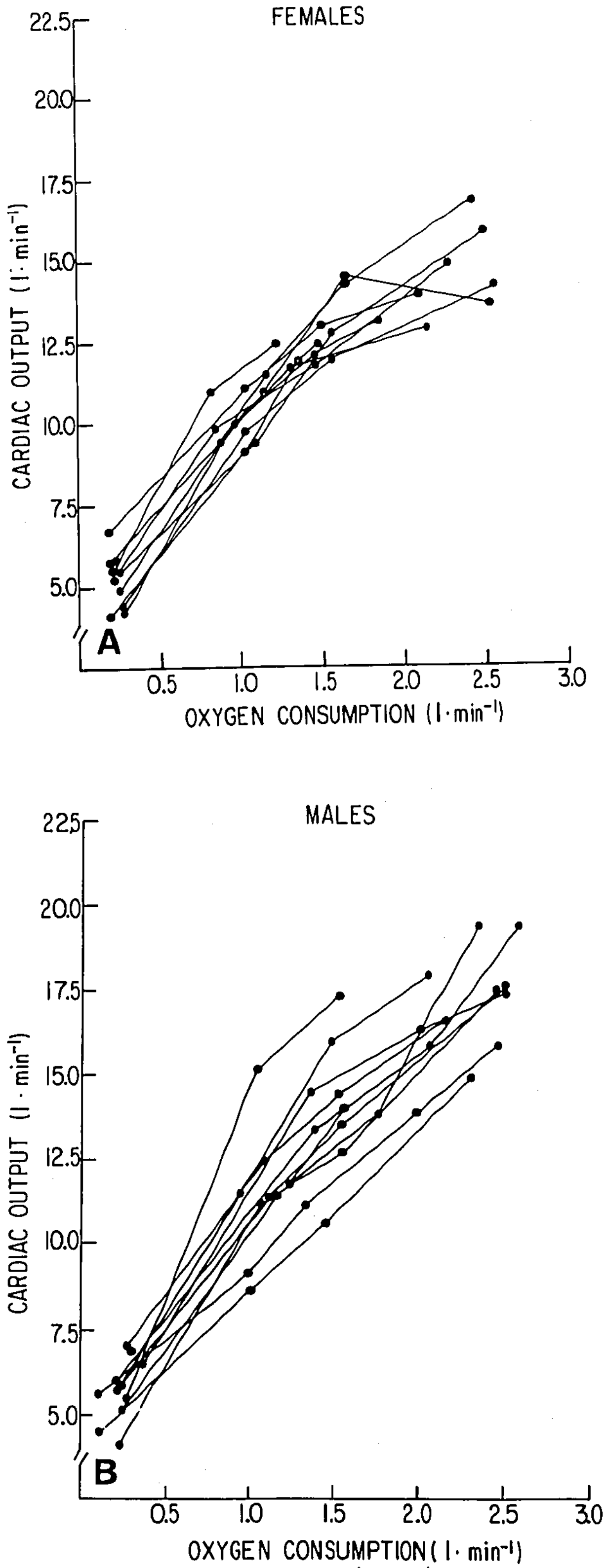

Figure 1—The relationship between $\dot{Q}$ and $\dot{V}O_2$ at rest and submaximal rowing exercise in 10 female subjects (A) and 11 male subjects (B).

TABLE 4. Comparison of $\dot{V}O_2$ and cardiovascular responses on the cycle and rowing ergometers in eight male subjects.

Variable	Rest	Exercise Levels 1	2	3
$\dot{V}O_2$ (ml·min^{-1})				
C	277 ± 30	1,115 ± 106	1,739 ± 99	2,481 ± 234
R	270 ± 35	1,126 ± 169	1,798 ± 167	2,558 ± 154
P value	NS	NS	NS	NS
HR (b·min^{-1})				
C	64 ± 12	85 ± 10	105 ± 10	131 ± 10
R	61 ± 11	87 ± 16	109 ± 15	139 ± 13
P value	NS	NS	NS	0.02
$\dot{Q}$ (l·min^{-1})				
C	6.2 ± 0.6	11.7 ± 1.7	15.0 ± 1.3	18.6 ± 1.5
R	6.2 ± 0.6	11.3 ± 2.2	14.3 ± 1.6	17.9 ± 1.3
P value	NS	NS	NS	NS
SV (ml)				
C	99 ± 14	138 ± 18	144 ± 15	142 ± 12
R	103 ± 15	130 ± 13	132 ± 15	129 ± 11
P value	NS	NS	0.01	0.02
BP* (mm Hg)				
Systolic				
C	116 ± 7	134 ± 8	144 ± 5	152 ± 14
R	112 ± 5	123 ± 9	133 ± 7	147 ± 12
P value	NS	NS	NS	NS
Diastolic				
C	73 ± 3	74 ± 4	71 ± 3	62 ± 5
R	70 ± 0	71 ± 3	70 ± 5	59 ± 8
P value	NS	NS	NS	NS
SVR* (dynes·s·cm^{-5})				
C	1,150 ± 124	660 ± 95	525 ± 67	405 ± 53
R	1,079 ± 97	709 ± 109	529 ± 59	412 ± 14
P value	NS	NS	NS	NS

Values are mean ± SD. SVR = systemic vascular resistance; C = cycle ergometer; R = rowing ergometer; BP = blood pressure; NS = not statistically significant.
* $N = 5$.

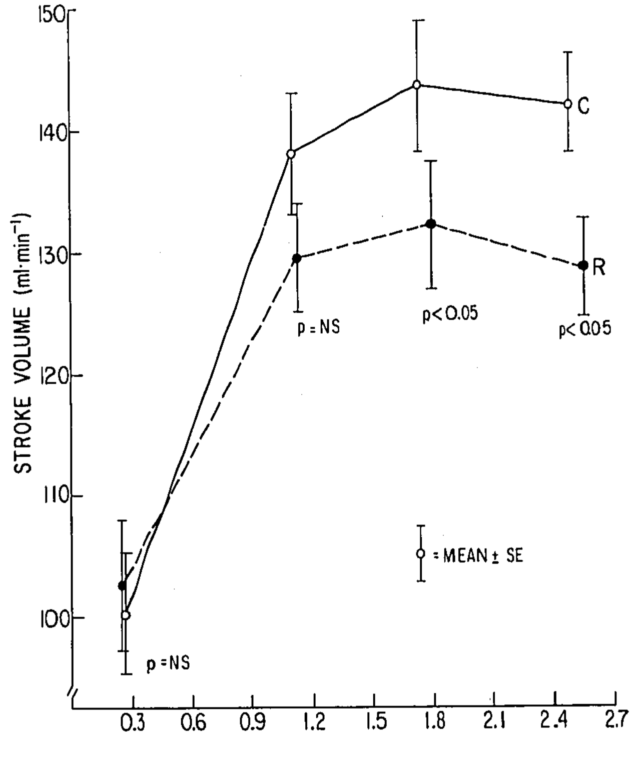

Figure 2—The relationship between SV and $\dot{V}O_2$ on the cycle (C) and rowing (R) ergometers. SV was significantly lower on the rowing ergometer at the second and third exercise levels. NS = not statistically significant.

of cardiac performance during cycle and rowing exercises demonstrated that HR was significantly higher and SV was significantly lower on the rowing ergometer at the same exercise intensity.

In the first part of our study, the relationship between $\dot{Q}$ and $\dot{V}O_2$ was similar for both groups of subjects (females: 5.2 ± 1.1; males: 6.1 ± 1.4; P = not statistically significant). The response of $\dot{Q}$ to progressive rowing exercise is consistent with previous investigations during exercise on a cycle ergometer (3, 11). The female subjects experienced a significant decline in SV between the second ($\dot{V}O_2$ = 1.5 ± 0.1 l·min^{-1}) and third ($\dot{V}O_2$ = 2.2 ± 0.4 l·min^{-1}) levels of exertion, while there was no significant change in SV in the male subjects. Although the metabolic requirements per body weight ($\dot{V}O_2$, ml·kg·min^{-1}) at the three levels of exercise were similar for the women and men, values for $\dot{V}O_2$, as percentages of $\dot{V}O_{2max}$, were different. $\dot{V}O_2$ at the highest intensity of rowing (38 km·h^{-1}) represented an average of 73% of $\dot{V}O_{2max}$ for the women, but only 59% of $\dot{V}O_{2max}$ for the men. The decline in SV in the women compared with the plateau observed in the men may reflect the higher relative exercise intensity in the female subjects. On the other hand, steady-state conditions are required for accurate measurement of $\dot{Q}$ using the CO_2 re-breathing method. At an exercise level of 73% of $\dot{V}O_{2max}$, it is possible that the female subjects did not achieve a CO_2 "steady-state" due to changes in blood lactate.

To investigate whether the cardiovascular responses to rowing were different from another type of dynamic exercise, $\dot{Q}$, HR, and SV were determined during exercise on both cycle and rowing ergometers in eight additional subjects. The cycle ergometer was chosen for comparison because an individual's body weight is supported during both rowing and cycle exercises. Based on previous experience, we were able to select comparable exercise levels so that oxygen requirements were similar at each of the three exercise intensities on the different ergometers. At the same metabolic rates, there were no significant differences in cardiac output on the cycle and rowing ergometers. However, differences were seen in the two components, HR and SV, which produce $\dot{Q}$. HR was significantly higher (level 3) and SV was significantly lower (levels 2 and 3) on the rowing ergometer (Table 4 and Fig. 2).

The mechanism for this difference is unclear. Normal augmentation in SV during sub-maximal exercise depends upon both increased ventricular contractility and the Frank-Starling mechanism (2, 16). Although contractile properties of the myocardium were not examined, we believe that it is unlikely that ventricular contractility was different at similar levels of $\dot{V}O_2$ on the two ergometers. A more likely explanation is that venous blood return to the right side of the heart might be affected as a result of the mechanics of rowing. A rower breathes approximately 1.5 to 2 times during each rowing stroke and usually coordinates his breathing pattern so that exhalation occurs during the "recovery" phase of the rowing stroke just prior to the "catch" or start. The "catch" corresponds to an extreme forward position with flexion of elbows, knees, hips, and thorax. During this phase of the rowing stroke, pleural pressure would be expected to become highly positive due to the combined effects of expiration and compression of the chest and abdomen. These physiologic changes might intermittently impede venous return and thus reduce right ventricular end-diastolic volume. Furthermore, the sudden muscular effort at the beginning of each rowing stroke may initiate a Valsalva maneuver which would further contribute to diminish ventricular preload (7).

Blood pressure measurements were comparable at different intensities of exercise on the cycle and rowing ergometers (Table 4). These findings are in agreement with previous studies in which blood pressure was maintained at the same level during leg exercise as with combined arm and leg activity (20, 22). Since systemic vascular resistance, which reflects afterload on the left ventricle, was also similar during cycling and rowing, we consider it unlikely that alterations in left ventricular afterload could account for the observed differences in SV for the two types of exercise.

As a result of repeated exercise, cardiac dimensions increase according to the predominant stimulus, i.e., volume or pressure over-load. In a previous study, Kuel et al. (14) found that left ventricular wall thickness and end-diastolic volume were similar in oarsmen and a group of endurance athletes. These data combined with the results of our study suggest that the major cardiac adaptation to training for rowing may be enlargement of ventricular volume rather than hypertrophy of the left ventricular wall. However, a longitudinal study of cardiac chamber size during a training season for competitive rowing would be necessary to answer this question.

From the measurements obtained in this study, it is possible to estimate peak $\dot{Q}$ by multiplying peak SV and HR_{max}. This value is based on the assumption that SV will be maintained with "all-out" exertion. Since HR_{max} was nearly identical for cycling and rowing, the estimated peak $\dot{Q}$ would be higher for cycle exercise than rowing. However, $\dot{V}O_{2max}$ was similar for the two sports in the eight males in part 2 of this study and in 17 untrained females in another investigation (1). None of these subjects were active participants in cycling or rowing. Overall, these findings suggest that peripheral factors in the muscles are particularly important as determinants of maximal oxygen uptake during rowing.

In summary, we found that the cardiovascular responses to rowing are distinct from upright cycle exercise. For augmentation in $\dot{Q}$ during rowing, there was a greater reliance upon the increase in HR than the SV response compared to cycling. Whether these physiologic differences might limit $\dot{Q}$ during vigorous rowing and ultimately impair rowing performance remains to be determined.

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