Cardiac output during submaximal and maximal work[1]

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ÅSTRAND, P., T. E. CUDDY, B. SALTIN, AND J. STENBERG. *Cardiac output during submaximal and maximal work.* J. Appl. Physiol. 19(2): 268–274. 1964.—In the present study oxygen uptake, cardiac output, stroke volume (dye-dilution technique) and oxygen content of arterial blood were determined in 11 women and 12 men, 20–31 years of age, at rest, and when performing submaximal and maximal work. At rest plasma volume (T-1824) and heart volume were determined. Sitting on the bicycle ergometer the stroke volume was 40–90% (mean 63%) of the maximum attained during exercise. Maximal stroke volume was essentially reached at a workload with an oxygen uptake of about 40% of the maximum and a heart rate about 110. No tendency to a decrease in stroke volume was noticed when maximal work was performed. The variation in stroke volume was ±4% during exercise in the range from 40 to 100% of the individual's aerobic work capacity. The maximal cardiac output was 18.5 liters/min for women and 24.1 liters for men. The correlation between heart volume on one side and maximal stroke volume and cardiac output on the other side was high and the expected one from the dimension of the individual. On submaximal as well as maximal exercise the women had a higher cardiac output per liter oxygen uptake than the men, and this can be explained by the lower concentration of hemoglobin in the women's blood.

cardiac function during exercise   cardiac output   stroke volume   cardiac output and arterial O_2 content

THE MAIN OBJECT of these experiments was to study the cardiac output and stroke volume in young healthy women and men performing submaximal and maximal exercise and to analyze how the cardiac output varied with the oxygen content of the arterial blood.

MATERIALS

Eleven female and twelve male students in physical education completed the various studies. They were healthy and well trained by almost daily physical activity. Four subjects (*5, 12, 18, 19*) took part in competitions in endurance events. Anthropological data and age are presented in Table 1.

A clinical examination including chest X ray and ECG recordings at rest, during and after submaximal and maximal exercise, did not reveal any signs of pulmonary and circulatory disease.

METHODS

Oxygen uptake, heart rate, and blood lactate concentration were determined during 600 kpm/min[3] (women) or 900 kpm/min (men) and on a predicted maximal workload that exhausted the subject after about 6 min (6). From the data obtained a series of convenient workloads were selected.

Within a week the subject came to the laboratory in the morning after a light breakfast. Teflon catheters were inserted percutaneously into the brachial artery and cubital vein so that the tips reached proximally to the axilla (technique see (7)).

Studies were done at rest with the subjects sitting on a Krogh bicycle erogometer and during 3 or 4 submaximal (exception *subject 4*) and one maximal workload. Two or three determinations of oxygen uptake and cardiac output were done on each workload after about 5 min exercise. ECG was recorded frequently and from the recordings heart rate was counted. During and after work arterial blood was sampled for analyses of concentration of hemoglobin and lactates. At rest, during exercise on 600 kpm/min, and during maximal work arterial blood was drawn for determinations of its oxygen content and capacity.

The sequence of workloads was usually 3–4 submaximal workloads, prolonged rest for 45–60 min, one submaximal, and finally maximal work.

Oxygen uptake was determined by the Douglas bag method. The volume of air was measured in a balanced

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[3] kpm = kilopond meter; 1 kp is the force acting on the mass of 1 kg at normal acceleration of gravity. (100 kpm/min = 723 foot-pounds/min = 16.35 w.).

TABLE I

See Legend	$\dot{V}O_2$[a], l.	$\dot{Q}$[b], l.	Heart Rate	SV[c], ml	A-V[d], diff.	CaO_2, ml	Hb, g%	HLa,[e] mEq/l.
1 22 yr	0.26	5.9	82	72	4.4	15.3	11.6	
168 cm	0.92	12.3	139	88	7.5		12.5	
62 kg	1.54	15.2	182	84	10.1	16.2	13.0	2.6
2.9 l.	2.24	19.1	202	95	11.7		13.4	6.6
690 ml	2.67	20.7	207	100	12.9	16.1	13.6	10.5
2 20 yr	0.28	6.7	77	87	4.2	16.8	12.5	
170 cm	0.91	11.0	117	94	8.3		13.0	
60 kg	1.44	14.9	158	94	9.7	16.8	13.4	3.4
2.3 l.	2.11	18.0	183	98	11.7		13.6	8.9
610 ml	2.55	18.1	194	93	14.1	17.0	13.7	12.5
3 21 yr	0.25	4.9	75	65	5.1	16.1	11.5	
163 cm	0.90	11.0	105	105	8.2		11.5	
59 kg	1.58	15.3	162	94	10.3	16.4	12.4	3.2
2.4 l.	2.32	19.8	197	101	11.7		12.8	7.2
620 ml	2.35	20.9	195	107	11.2	16.2	12.8	9.7
4 22 yr	0.30	5.3	82	65	5.7	16.8	11.5	
170 cm	0.95	9.6	97	99	9.9		12.8	
65 kg	1.47	14.6	132	111	10.1	16.7	12.6	4.8
3.2 l.	2.50	18.6	188	99	13.4	17.3	13.3	11.2
640 ml								
5 22 yr	0.27	4.3	62	69	6.3	15.5	11.2	
176 cm	0.85	9.5	94	101	8.9		12.0	
63 kg	1.41	12.7	126	101	11.1	15.1	12.8	1.8
3.9 l.	2.10	19.0	168	113	11.1		12.7	6.5
625 ml	2.62	18.4	194	95	14.2	15.5	12.6	14.1
6 20 yr	0.15	4.5	72	63	3.3	17.0	12.5	
165 cm	0.80	8.9	106	84	9.0		13.0	
63 kg	1.32	12.4	135	92	10.6	17.2	13.3	3.7
2.6 l.	1.89	16.6	168	99	11.4		14.0	7.8
600 ml	2.42	17.4	179	97	13.9	17.4	13.8	15.7
7 19 yr	0.26	5.7	87	66	4.6	17.2	13.0	
165 cm	0.90	9.0	114	79	10.0		13.8	
58 kg	1.54	11.8	158	75	13.1	17.4	13.8	5.1
2.5 l.	2.12	15.6	183	85	13.6		14.2	10.5
650 ml	2.36	17.1	189	90	13.8	17.8	14.2	15.3
8 20 yr	0.31	5.4	77	70	5.7	16.2	11.8	
168 cm	0.92	10.5	101	104	8.8		12.3	
64 kg	1.50	15.6	140	111	9.6	16.5	12.6	0.9
3.5 l.	1.93	15.7	153	103	12.3		12.3	1.4
755 ml	2.52	19.2	182	105	13.1		13.3	3.9
	3.02	18.8	197	95	16.1	17.3	12.8	7.3
9 23 yr	0.20	4.6	74	62	4.3	17.7	12.8	
170 cm	0.83	9.0	101	89	9.2		13.6	
64 kg	1.45	12.3	161	76	11.8	17.6	13.8	2.0
2.6 l.	1.83	13.4	169	79	13.7		14.3	4.4
590 ml	2.41	15.1	193	78	16.0		14.8	10.1
	2.51	16.0	200	80	15.7	18.6	14.9	13.4
10 20 yr	0.30	6.0	74	81	5.0	16.2	12.3	
169 cm	0.95	11.4	109	105	8.3		13.1	
64 kg	1.54	14.0	151	93	11.0	16.1	12.5	
2.8 l.	2.03	17.0	165	103	11.9		13.2	2.9
640 ml	2.66	19.2	187	103	13.9		13.7	7.6
	2.86	18.7	191	98	15.3	17.2	13.2	10.2
11 20 yr	0.30	4.9	74	66	6.1	16.8	13.5	
176 cm	0.93	8.0	107	75	11.6		14.2	
68 kg	1.52	13.4	156	86	11.3	17.6	14.1	2.0
2.9 l.	1.92	13.9	173	80	13.8		14.7	5.5
585 ml	2.44	16.3	191	85	15.0		15.0	10.5
	2.73	17.4	104	85	15.7	18.9	15.2	13.4
12 23 yr	0.37	5.5	66	83	6.7	19.7	14.9	
188 cm	1.46	11.7	96	122	12.5	20.3	15.5	
80 kg	2.14	16.1	120	134	13.3		15.8	0.9
4.2 l.	3.31	22.3	162	138	14.8		16.2	4.3
995 ml	4.24	23.8	182	131	17.8		16.8	4.5
	5.39	28.8	200	144	18.7	21.2	16.5	11.0

See Legend	$\dot{V}O_2$[a], l.	$\dot{Q}$[b], l.	Heart Rate	SV[c], ml	A-V[d], diff.	CaO_2, ml	Hb, g%	HLa,[e] mEq/l.
13 23 yr	0.32	5.2	53	98	6.2		13.9	
171 cm	1.41	10.7	89	120	13.2	18.1	13.8	1.3
69 kg	2.04	15.3	115	133	13.3		14.0	2.5
3.4 l.	2.73	19.7	153	129	13.9		14.5	8.6
915 ml	3.62	23.6	174	136	15.3		14.7	11.9
	3.87	23.8	180	132	16.3	18.2	15.0	15.5
14 22 yr	0.35	5.0	92	54	7.0	20.8	15.2	
180 cm	1.49	12.2	106	115	12.2	20.5	15.5	1.5
79 kg	2.10	15.9	126	126	13.2		15.8	2.0
3.6 l.	2.86	19.2	154	125	14.9		15.8	5.5
820 ml	3.86	23.2	183	127	16.6		15.8	7.9
	4.13	21.5	195	110	19.2	21.1	15.5	15.0
15 30 yr	0.38	5.1	72	71	7.5	18.9	13.8	
185 cm	1.60	12.4	92	135	12.9	18.4	14.2	1.0
87 kg	2.14	15.8	107	148	13.5		13.8	1.1
4.3 l.	3.11	20.2	127	159	15.4		14.0	2.5
1030 ml	4.08	26.5	155	171	15.4		14.5	6.7
	4.61	25.4	169	156	17.5	18.9	14.5	15.1
16 24 yr	0.30	5.8	79	73	5.2	19.7	14.0	
175 cm	1.54	14.6	113	129	10.5	19.6	15.0	
72 kg	2.11	18.2	143	127	11.6		15.8	1.5
3.0 l.	3.23	20.8	183	114	15.5		15.8	5.5
920 ml	4.03	23.5	204	115	17.1	20.5	16.3	12.8
17 22 yr	0.34	5.6	75	75	6.1	18.7	14.1	
170 cm	1.45	13.2	127	104	11.0	19.0	14.7	
65 kg	2.14	19.0	163	117	11.3		15.2	
3.0 l.	2.94	20.9	189	111	14.1		15.8	11.6
670 ml	3.32	22.8	193	118	14.6	20.3	15.8	17.5
18 24 yr	0.42	5.5	61	90	7.6	19.1	14.7	
191 cm	0.99	9.6	77	125	10.3		15.4	
88 kg	1.54	15.1	94	161	10.2	19.0	14.7	1.4
5.0 l.	2.83	22.2	137	162	12.7		15.4	2.2
1170 ml	3.83	26.3	167	157	14.6			6.6
	4.68	29.9	180	166	15.7	18.6	15.8	11.8
19 24 yr	0.36	5.3	89	60	6.8	19.5	14.2	
185 cm	0.89	8.4	83	101	10.6		14.7	
78 kg	1.47	11.6	101	115	12.7	19.5	14.7	1.3
4.0 l.	2.96	18.4	134	137	16.1		15.8	4.2
920 ml	3.98	22.0	161	137	18.1		15.8	9.0
	4.37	23.1	174	133	18.9	19.7	16.3	15.1
20 30 yr	0.28	4.8	74	65	5.8	20.0	15.0	
169 cm	0.87	6.9	97	71	12.6		15.4	
56 kg	1.43	10.2	129	79	14.0	20.2	15.6	3.7
2.5 l.	2.23	14.8	171	87	15.1		16.6	7.3
620 ml	2.66	16.3	181	90	16.3	21.2	16.1	11.9
21 22 yr	0.43	5.0	52	96	8.6	18.0	13.5	
181 cm	0.93	7.7	73	105	12.1		14.2	
80 kg	1.45	12.2	93	131	11.9	18.2	14.9	
4.1 l.	2.60	19.8	139	142	13.1		14.9	4.6
900 ml	3.48	22.5	171	132	15.5		15.6	10.3
	3.97	26.3	183	144	15.1	18.5	14.6	14.7
22 24 yr	0.39	3.8	66	58	10.3	18.6	14.1	
181 cm	0.92	6.8	87	78	13.5		13.8	
72 kg	1.46	10.5	111	95	13.9	18.5	13.5	
3.6 l.	2.31	14.9	149	100	15.5		15.0	3.3
870 ml	3.29	19.1	181	106	17.2		15.9	9.1
	3.45	19.9	181	110	17.3	19.3	15.9	12.3
23 21 yr	0.28	5.1	78	65	5.5	18.3	13.9	
180 cm	1.03	9.8	90	109	10.5		14.3	
70 kg	1.56	12.0	117	103	13.0	18.5	14.7	
	3.23	21.7	172	126	14.9		14.5	
775 ml	4.10	24.7	189	131	16.6	19.0	14.8	12.1

In left column anthropological data: from top, subject's no. and age, body height, body weight, plasma volume, heart volume; in other columns data are listed from studies at rest (first line) and during exercise with different workloads up to maximum. Blood analyses were done on arterial blood. No. 1–11 ♀, 12–23 ♂. [a] Oxygen uptake, STPD. [b] Cardiac output. [c] Stroke volume. [d] Arteriovenous oxygen difference ml/100 ml of blood. [e] Blood lactates.

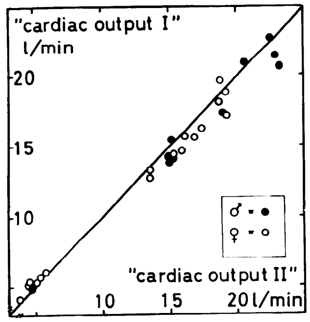

FIG. 1. Cardiac output during exercise calculated with calibration factor obtained on blood drawn during the actual experiment ("cardiac output I") and with an average factor based on calibrations made with blood drawn before, in the midst, and at the end of the experimental period ("cardiac output II").

spirometer and an air sample was analyzed on a modified Haldane apparatus.

Oxygen content and capacity of arterial blood were determined according to van Slyke.

Hemoglobin concentration was determined on a Beckman spectrophotometer model B calibrated from data obtained by van Slyke analyses.

Cardiac output was calculated from the records obtained with a Honeywell visicorder connected to a Gilford densitometer. Cardio-green (Hynson, Westcott and Dunning Inc., Baltimore, Md.) was rapidly injected into the vein from a calibrated syringe (1.0000–1.5000 ml). The arterial blood was continuously drawn through the cuvette by a motor-driven suction syringe at a constant speed of 20 ml/min. The blood was then reinfused into the artery. Before the exercise, during one submaximal load and during maximal exercise (in 14 subjects after maximal exercise) arterial blood was drawn for obtaining calibration lines of the densitometer. Two to three different concentrations were recorded. To keep the blood loss at a minimum, blood for calibrations was not taken in connection with each determination of cardiac output, even if a change in the blood composition during heavy exercise made it desirable to include frequent calibrations. Total blood loss before last measurements of cardiac output was below 150 ml.

In the present study, the calibration factor obtained on blood samples taken before exercise was applied to calculate the cardiac output at rest. An average calibration factor was calculated from calibration lines recorded with the blood drawn at rest, during the submaximal, and during or after maximal load. This factor was used in all calculations of cardiac output during exercise. Figure 1 presents data on cardiac output calculated with (I) a calibration factor obtained on the blood drawn during the actual experiment and (II) the average factor. The value on cardiac output here presented is in some cases somewhat higher in heavy exercise than if blood taken during the actual experiment had been used in the calibration of the densitometer.

From the simultaneously or in close-sequence measured cardiac output, heart rate, oxygen uptake, and oxygen content of arterial blood stroke volume, arteriovenous oxygen difference, and oxygen content of mixed venous blood were calculated.

Since on the same workload repeated determinations were made on cardiac output, heart rate, and oxygen uptake the average is presented. If in the experiments with maximal exercise the difference in values was larger than two times the standard deviation (SD) of a single determination, estimated from experiments with submaximal loads, the highest value was used (3).

The standard deviation of double determinations of cardiac output per liter oxygen uptake was calculated from data on 25 subjects and was ±4% (oxygen uptake about 1.5 liters/min).

Blood lactate concentration was determined with the modified method of Barker and Summerson (3, pp. 14–16).

At rest plasma volume was determined with Evans blue dye (T-1824) technique (25). The subjects did not eat 12 hr prior to the determination. Blood samples were taken 10 and 15 min after the injection of dye.

Heart volume was determined by roentgenograms (16).

Criteria for maximal load on the oxygen transporting system were the usual ones with a "leveling off" of the oxygen uptake despite an increase in workload and high values for blood lactate concentration (3, 4, 6).

RESULTS

In the preliminary studies (I) the maximal oxygen uptake for the female subjects was 2.61 liters/min and maximal heart rate 189. In the experiments with simultaneous measurements of cardiac output (II) the values were 2.60 and 194, respectively. For the male subjects the preliminary studies revealed a maximal oxygen uptake of 4.12 liters/min, heart rate 185. When cardiac output was measured the values obtained were 4.05 and 186, respectively (Table 2). The average difference between I and II was for oxygen uptake 0.04 liters/min, SE = 0.02, SD = 0.10. For maximal heart rate the difference was 3 beats/min, SE = 0.7, SD = 3.5. No difference was found in blood lactate concentration. In the two sets of experiments the amount of work preceding the maximal exercise was different, but the same oxygen uptake and heart rate were roughly attained.

In Table 1 the individual data are listed. The increase

TABLE 2

	$\dot{V}O_2$, l.	Heart Rate	$\dot{Q}$, l.	$\dot{Q}/\dot{V}O_2$, l.	Stroke Volume ml	A-V O_2 diff.	HLa mEq/l.
600 kpm/min							
♀	1.48	151	13.8	9.3	92	10.8	3.0
♂	1.49	106	12.2	8.2	118	12.3	1.7
50% $\dot{V}O_2$							
♀	1.30	137	12.6	9.7	93	10.3	
♂	2.03	124	15.4	7.6	125	13.2	
Maximum							
♀	2.60	194	18.5	7.1	100	14.3	12.1
♂	4.05	186	24.1	5.9	134	17.0	13.7

Mean values for oxygen uptake, some hemodynamic functions and blood lactates (HLa) on 11 women and 12 men working on a bicycle ergometer with a standard submaximal load and a maximal load. By interpolation from individual curves data were obtained from an exercise during which the oxygen uptake was 50% of the individual's maximal oxygen uptake.

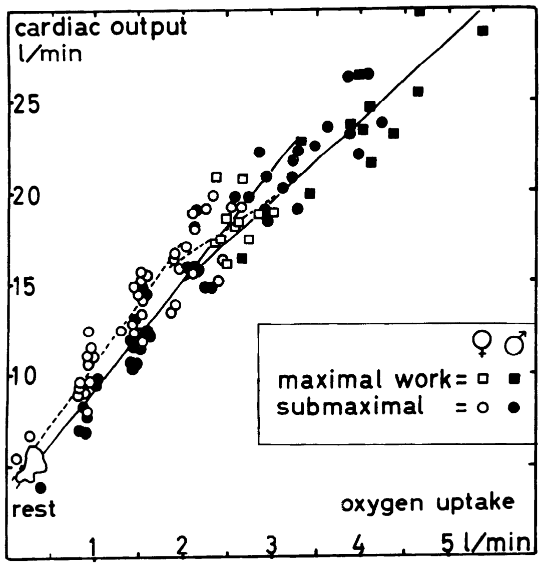

FIG. 2. Individual values on cardiac output in relation to oxygen uptake at rest, during submaximal and maximal exercise with 23 subjects sitting on a bicycle ergometer. Regression lines (broken lines for women) were calculated for experiments where the oxygen uptake was *1*) below 70% of the individual's maximum and *2*) above this per cent. Equations: ♀ *1*) $y = 3.66 + 6.81x$, *2*) $y = 9.98 + 3.23x$; ♂ *1*) $y = 3.07 + 6.01x$, *2*) $y = 6.55 + 4.35x$.

in cardiac output with oxygen uptake is illustrated by Fig. 2. Average maximal cardiac output was 18.5 (16.0–20.9) and 24.1 (16.3–29.9) liters/min for women and men, respectively. The relative increase in cardiac output with increasing oxygen uptake was significantly less as the maximal values were approached, see Fig. 2 (difference in slope for regression lines for women $P < 0.001$, for men $0.01 > P > 0.001$).

The values for heart rate and calculated stroke volume as the oxygen uptake increases are illustrated by Fig. 3. Maximal stroke volume and oxygen uptake attained were set to 100% for each individual case and the values from the other experiments were expressed as per cent of these maxima. With the subject sitting at rest on the bicycle ergometer the stroke volume ranged from 40 to 90% of the maximum (mean 63%). During exercise demanding an oxygen uptake of 40% of the aerobic work capacity, heart rate being about 110 beats/min, the stroke volume was already maximal or close to maximum. The calculated regression line for the stroke volume shows a slight increase from a 92% stroke volume at 40% load on the oxygen transporting system up to 96% stroke volume at maximal oxygen uptake. The standard deviation for the mentioned line is ±4%. Eleven of the subjects reached maximal stroke volume during maximal exercise. An analysis of the cases with a slight reduction in stroke volume at maximal exercise revealed that high heart rate or large heart volume could not explain the decrease in stroke volume, as no significant correlation was found between heart volume or stroke volume and maximal heart rate.

For the female subjects the hemoglobin concentration of arterial blood increased from 12.2 g/100 ml of blood

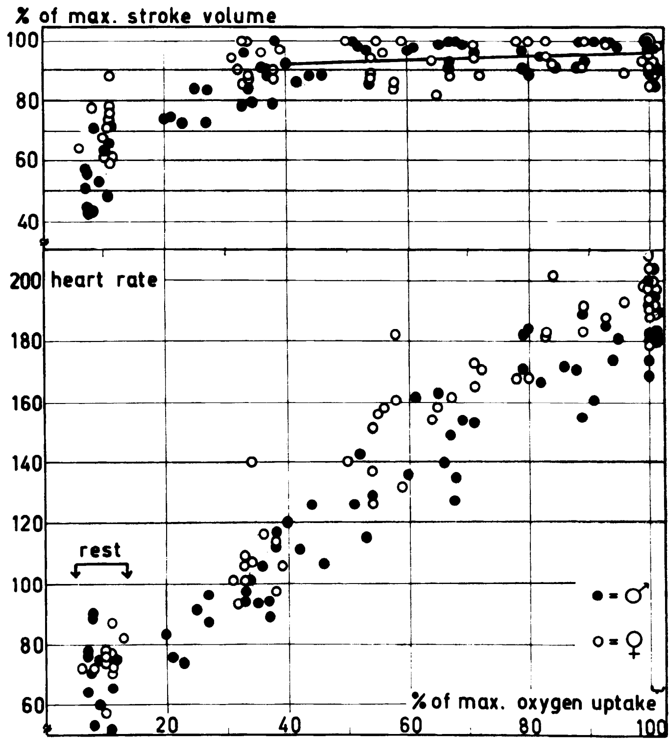

FIG. 3. Stroke volume in per cent of the individual's maximum and heart rate at rest and during exercise. The oxygen uptake on the *abscissa* is expressed in per cent of the subject's maximum. Circled dot at "100%" represents 11 of the 23 subjects. Measurements were done with the subjects in sitting position.

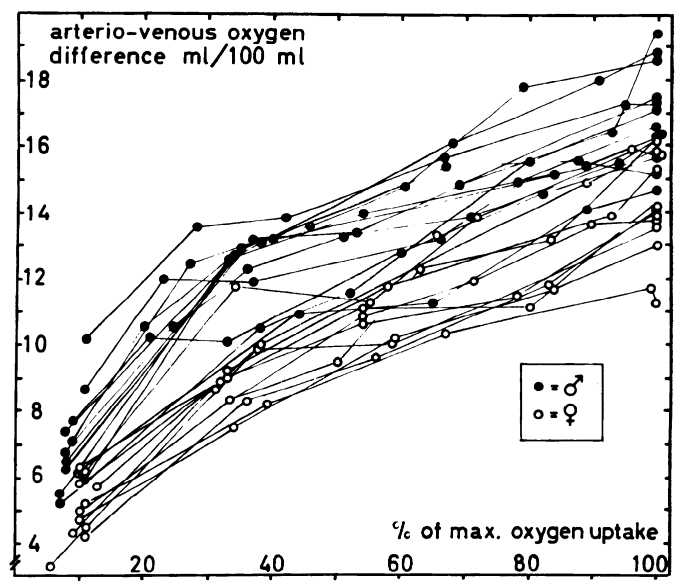

FIG. 4. Increase in arteriovenous oxygen difference for the 23 subjects as oxygen uptake during exercise increases from resting values to the individual's maximum (= "100%").

at rest to 13.7 g during maximal work. For the male subjects the values were 14.3 at rest and 15.6 g/100 ml of blood during maximal work.

The oxygen content increased for women from 16.5 at rest to 17.2 ml/100 ml of arterial blood during maxi-

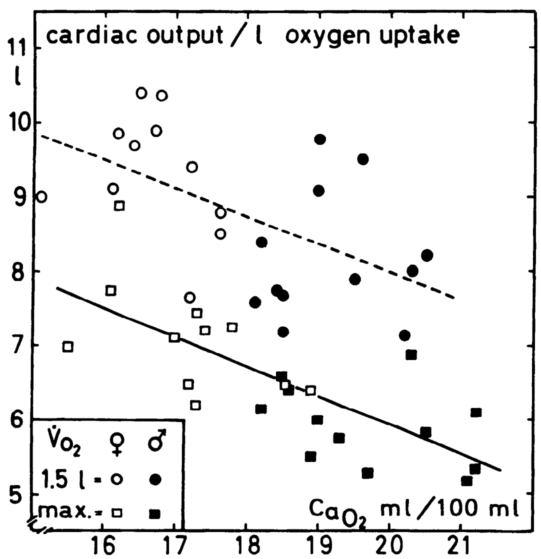

FIG. 5. Cardiac output per liter oxygen uptake in relation to oxygen content of arterial blood during submaximal and maximal exercise, respectively.

TABLE 3

x \ y	Heart Volume, ml	Plasma Volume, liters	$\dot{V}o_2$, liters	$\dot{Q}$, liters	Stroke Volume, ml
Body wt.					
♀	52(8.3)	.46(15.8)	.18(7.1)	1.5(8.7)	12(12.8)
♂	75(8.9)	.27(7.4)	.42(10.1)	2.2(9.5)	14(8.2)
Heart vol.					
♀		.47(16.6)	.18(8.5)	1.4(8.6)	10(11.0)
♂		.35(10.6)	.44(11.2)	2.3(10.2)	9(9.8)
Plasma vol.					
♀			.19(7.1)	1.2(8.7)	10(11.1)
♂			.47(11.9)	2.2(6.3)	12(10.1)
$\dot{V}o_2$					
♀				1.6(8.7)	11(12.6)
♂				1.8(7.8)	14(11.0)
$\dot{Q}$					
♀					8(8.2)
♂					10(7.1)

Standard deviation for a variety of functions studied on 11 women and 12 men. First figure = the arithmetic value for SD; within parentheses SD in per cent calculated from the best straight regression line of the logarithmic values.

mal exercise, and from 19.2 to 19.7 ml for the men.

The gradual increase in the calculated arteriovenous oxygen difference is illustrated by Fig. 4. For the female subjects the average value at rest was 5.0 ml/100 ml of blood and during maximal exercise 14.3 ml. For the male subjects the increase was from 6.9 to 17.0 ml/100 ml of blood.

Figure 5 gives the individual data on cardiac output per liter oxygen uptake in relation to the determined oxygen content of arterial blood *1*) during mild exercise with 600 kpm/min ($\dot{V}o_2$ = 1.5 liters/min) and *2*) during maximal exercise. The cardiac output per liter oxygen uptake was in average 8.2 for men and 9.3 liters for women during the submaximal load ($0.01 > P > 0.001$) and 5.9 and 7.1 liters, respectively, during maximal work ($P < 0.001$).

The maximal pulmonary ventilation was 97 liters/min for women and 144 liters for men. Table 3 presents the relations between various parameters and functions studied. In this material maximal cardiac output and stroke volume could be predicted from heart volume, maximal oxygen uptake, or plasma volume with a SD of 6–12%.

DISCUSSION

The dye-dilution technique for determination of cardiac output in man has been studied and analyzed by several groups, and opinions are reviewed by Dow (13). During hard work the technique was applied by Asmussen and Nielsen, Chapman et al., Grimby and Nilsson, and Wang et al. (1, 2, 11, 14, 17, 23, 24). In general the method is accepted as convenient and reliable.

In the present study the absolute values on cardiac output for men performing submaximal exercise agrees with the findings of previous studies (22, pp. 60–61, 8). The smaller increase in cardiac output when oxygen uptake approaches maximum is noticeable (Fig. 2).

In transition from rest to exercise there was consistently an increase in stroke volume. For the women the average stroke volume was at rest 68 ml and a maximum of 100 ml was reached during exercise. For the men the values were 88 and 134 ml, respectively, that is in both groups a 50% increase. This finding confirms previous studies on man (8, 9, 11, 12, 22–24, 26).

In exercise with a heart rate above about 110 beats/min and an oxygen uptake above 40% of the individual's aerobic work capacity the maximal stroke volume was roughly attained. In the healthy, fairly well-trained subjects here studied maximal work could be maintained for at least 6 min without any decrease in stroke volume as compared with less severe exercise (Fig. 3). Apparently, at exercise, at a heart rate of or above 200, the diastolic filling of the heart allows maximal stroke volume.

In this group of subjects the high correlation between heart volume and plasma volume on one side and stroke volume, cardiac output, and oxygen uptake during maximal exercise on the other side, is noticeable. Such relations have been suggested (19–21, 24) but have actually not previously been demonstrated to exist (Table 3).

Figure 6*A* shows the relations between heart volume and maximal stroke volume; *B*, maximal cardiac output; and *C*, maximal oxygen uptake. The standard deviation around the mean is 8–11%. In the calculation of the best straight regression line of the logarithmic values ($y = a \times x^b$, where a is a constant) the exponent is expected to be 1.00 when volumes or masses are related, but 0.67 if volume per unit time or effect is

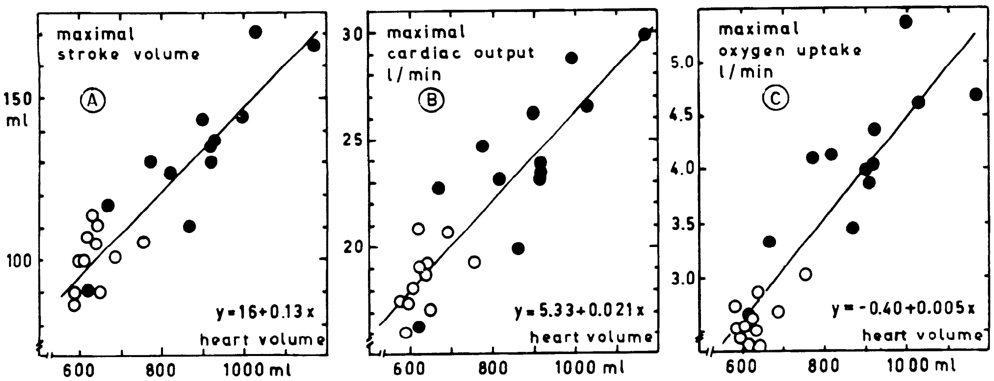

FIG. 6. *A:* maximal stroke volume; *B:* cardiac output; *C:* oxygen uptake in relation to measured heart volume from roentgenograms (○ = women; ● = men).

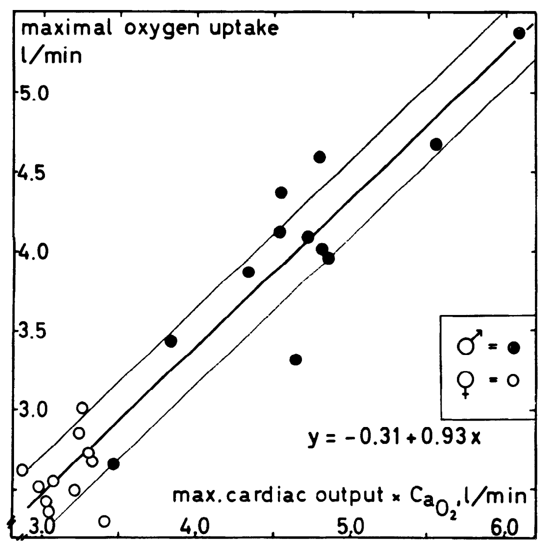

FIG. 7. Maximal oxygen uptake in relation to the volume of oxygen transported from the left heart per minute during maximal work (thin lines denote ±1 SD).

related to volume or mass (10, 21). For the regression line of the relation illustrated by Fig. 6*A* (but with logarithmic values) the *b*-value is 0.87 or not significantly different from 1.00 ($P > 0.05$). When relating maximal cardiac output to heart volume the *b*-value is 0.76 or not significantly different from the "expected" 0.67 ($P \gg 0.05$) but different from 1.00 ($0.02 > P > 0.01$). The regression line for maximal oxygen uptake in relation to heart volume gives a *b*-value of 1.14 which is significantly different from 0.67 ($P < 0.001$). This suggests that some biological mechanism(s) is (are) involved causing a more efficient oxygen transport in our subjects with a large heart volume.

In this material the subjects with the large heart volumes (and stroke volumes) are men and their hemoglobin content and therefore oxygen content of arterial blood is higher than in the women. Figure 7 presents the relation between aerobic work capacity and the volume of oxygen offered to the tissues (maximal cardiac output times oxygen content of arterial blood). The close correlation is illustrated by a SD around the mean of only 7 %. The coefficient of oxygen utilization ($\dot{V}o_2 \times 100/\dot{Q} \times Ca_{O_2}$) has a mean value for women and men of 83 and 86 %, respectively, difference being not significant ($P > 0.05$). The calculated oxygen content of the mixed venous blood is not significantly different in the two groups of subjects (average 3.0 ml for women and 2.8 ml/100 ml of blood for men). During submaximal exercise variations in the oxygen content of the arterial blood are met by compensatory modifications in the cardiac output. During maximal exercise the lower content of the women's arterial blood can apparently not be compensated for since the maximal cardiac output is related to the dimensions of their hearts (*b*-value was 0.76) and therefore the maximal oxygen uptake is relatively low (*b*-value was 1.14). When exercising the lower concentration of hemoglobin for women is no doubt a handicap from a circulatory viewpoint.

The calculated oxygen content of the blood entering the pulmonary capillaries is very low, so an overestimation of the maximal cardiac output cannot be large (up to 30 liters/min in man and 20 liters/min in women; see discussion of calibration factor).

The arteriovenous oxygen difference increases with increasing oxygen uptake all the way from rest to maximal exercise (Fig. 4). From a large number of experiments Wade and Bishop (22) conclude that oxygen uptake and arteriovenous oxygen difference are related by a hyperbolic function. The reason why our results and those of Williams et al. (26) differ from mentioned conclusion are probably that we and Williams et al. have related the increase in arteriovenous oxygen difference to the individual's maximal oxygen uptake (Fig. 4).

Our subjects were working in a sitting position. It should be emphasized that maximal oxygen uptake during exhausting leg work in the supine position is lower than during maximal work in an upright position (5), and that the hemodynamics are different in the two positions (8, 19, 22).

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REFERENCES

1. Asmussen, E., and M. Nielsen. *Acta Physiol. Scand.* 27: 217, 1953.
2. Asmussen, E., and M. Nielsen. *Acta Physiol. Scand.* 35: 73, 1955.
3. Åstrand, I. *Acta Physiol. Scand.* 49: Suppl. 169, 1960.
4. Åstrand, P.-O. *Experimental Studies of Physical Working Capacity in Relation to Sex and Age.* Copenhagen: Munksgaard, 1952.
5. Åstrand, P.-O., and B. Saltin. *J. Appl. Physiol.* 16: 977, 1961.
6. Åstrand, P.-O., and B. Saltin. *J. Appl. Physiol.* 16: 971, 1961.
7. Bernéus, B., A. Carlsten, A. Holmgren, and S. Seldinger. *Scand. J. Clin. Lab. Invest.* 6: 217, 1954.
8. Bevegård, S., A. Holmgren, and B. Jonsson. *Acta Physiol. Scand.* 57: 26, 1963.
9. Bishop, J. M., K. W. Donald, and O. L. Wade. *Clin. Sci.* 14: 329, 1955.
10. Brody, S. *Bioenergetics and Growth.* New York: Reinhold, 1945.
11. Chapman, C. B., J. N. Fischer, and B. J. Sproule. *J. Clin. Invest.* 39: 1208, 1960.
12. Christensen, E. H. *Arbeitsphysiologie* 4: 470, 1931.
13. Dow, P. *Physiol. Rev.* 36: 77, 1956.
14. Grimby, G., and N. J. Nilsson. *Scand. J. Clin. Lab. Invest.* 15: Suppl. 69, 44, 1963.
15. Holmgren, A., B. Jonsson, and T. Sjöstrand. *Acta Physiol. Scand.* 49, 343, 1960.
16. Jonsell, S. *Acta Radiol.* 20: 325, 1939.
17. Mitchell, J. H., B. J. Sproule, and C. B. Chapman. *J. Clin. Invest.* 37: 538, 1958.
18. Reeves, J. T., R. F. Grover, S. G. Blount, Jr., and G. F. Filley. *J. Appl. Physiol.* 16: 283, 1961.
19. Reindell, H. *Herz Kreislaufkrankheiten und Sport.* München: Barth, 1960.
20. Sjöstrand, T. *Forum Cardiologicum 3 in "Studienreihe Boehringer."* Mannheim-Waldhof: Boehringer & Soehne GmbH, 1962.
21. Von Döbeln, W. *Acta Physiol. Scand.* 38: 193, 1956.
22. Wade, O. L., and J. M. Bishop. *Cardiac Output and Regional Blood Flow.* Oxford: Blackwell, 1962.
23. Wang, Y., R. J. Marshall, and J. T. Shepherd. *J. Clin. Invest.* 39: 1051, 1960.
24. Wang, Y., J. T. Shepherd, R. J. Marshall, L. Rowell, and H. L. Taylor. *Circulation* 24: 1064, 1961.
25. Wiklander, O. *Acta Chir. Scand.* Suppl. 208, 1956.
26. Williams, C. G., G. A. G. Bredell, C. H. Wyndham, N. B. Strydom, J. F. Morrison, J. Peter, P. W. Fleming, and J. S. Ward. *J. Appl. Physiol.* 17: 625, 1962.