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Effect of Exercise in Pulmonary Stenosis with Intact Ventricular Septum

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There are only a few reports on the hæmodynamic effect of exercise in pulmonary stenosis (Ikkos, 1963†; Hugenholtz and Nadas, 1963; Lewis *et al.*, 1964), and the exercise tolerance, evaluated by quantitative and objective methods, has not been studied previously.

The adaptation to exercise in patients with increased "volume work" of the right ventricle, in atrial septal defect, has been described earlier (Jonsson, Linderholm, and Pinardi, 1957). In the present study patients with pulmonary stenosis with increased "pressure work" of the right ventricle are examined in a similar way.

Subjects and Methods

All patients referred to the department of clinical physiology at Karolinska Sjukhuset for heart catheterization during the years 1953–1963 are included. In Table I are listed some anthropometric data and the anatomical diagnosis. The type of stenosis and the existence of an intact ventricular septum were based not only on physical and hæmodynamic findings, but also on angiocardiography with injection of contrast medium into the right ventricle.‡ None had clinical signs of heart decompensation. All had sinus rhythm.

An atrial septal defect or open foramen ovale was demonstrated in 11 instances. Patients with a combination of slight pulmonary stenosis and an atrial septal defect with significant left-to-right shunt were excluded from this series. Only one patient (Case 25) had a small left-to-right shunt (1·5 l./min.) and in addition a small right-to-left shunt (1·1 l./min.) at rest. Another patient (Case 24) with an atrial septal defect and an abnormal venous return had a right-to-left shunt. The anomalous vein from the upper lobe of the right lung to the superior vena cava was too small to give rise to a significant left-to-right shunt: at operation its diameter was 5 mm. A right-to-left shunt was present at rest in 7 and only during exercise in 4 further patients. The shunt was marked at rest (arterial O_2 saturation less than 85%) in 3 patients (Cases 7, 9, and 21).

The patients were compared with normal subjects studied at the same laboratory and with the same methods during the course of this investigation (Holmgren *et al.*, 1957; Holmgren, Jonsson, and Sjöstrand, 1960; Bevegård, Holmgren, and Jonsson, 1960).

Methods for the determination of physical working capacity with the aid of a bicycle ergometer (Sjöstrand, 1947; Wahlund, 1948), heart volume (Kjellberg, Rudhe, and Sjöstrand, 1949; Larsson and Kjellberg, 1948), as well as the procedures of heart catheterization (Jonsson *et al.*, 1957, Bevegård *et al.*, 1960), have been described previously.

For the determination of the *physical working capacity*, the patients worked in the sitting posture on the bicycle ergometer (Holmgren and Mattsson, 1954). The work load was increased stepwise, each period lasting for 6 minutes. Usually the work was continued until the heart rate was about 170 beats a minute. In some cases, however, the work test was discontinued at a lower rate because of some abnormal signs or subjective complaints.

The physical working capacity at heart rate 170 (PWC_{170}) was estimated using the approximately linear relation between work load and pulse rate after 6 minutes of work at each work load. By inter- or extrapolation, the work load in kpm./min. corresponding to a heart rate of 170 beats a minute was obtained.

The maximal work intensity performed at a relative steady state (W_{max}) was expressed at the heaviest work load that the patient actually performed for 6 minutes. If the patient was able to continue the work for a few but not all of the 6 minutes at a heavier load a fraction of the increase in work load was added corresponding to the fraction of the 6-minute period that the patient was able to continue the work (Strandell, 1964).

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† This report included some patients of the present study.

‡ Examinations performed in the radiological departments of the pædiatric and thoracic clinics in Karolinska Sjukhuset.

TABLE I

GENERAL CHARACTERISTICS OF 46 PATIENTS WITH PULMONARY STENOSIS INCLUDING ANATOMICAL DIAGNOSIS

Case No., sex, and age (yr.)	Height (cm.)	Weight (kg.)	BSA ($m.^2$)	Heart volume (ml.)	Total Hb (g.)	Total Hb % of weight	Blood vol. (l.)	Maximum pulse rate	PWC_{170} (kpm./min.)	W_{max} (kpm./min.)	Anatomy
1 F 25	161	47·7	1·47	690	430	9·0	3·4	126	—	200	VPS
2 F 30	158	45·8	1·44	570	485	10·6	3·7	164	500	330	VPS
3 M 17	160	46·0	1·45	530	450	9·8	3·9	172	600	600	VPS
4 M 29	174	64·7	1·79	860	720	11·1	5·1	176	600	600	IPS + ASD
5 F 20	165	56·0	1·60	605	470	8·4	4·0	184	470	470	VPS
6 M 17	171	57·2	1·62	780	500	8·8	3·5	178	760	700	VPS
7 F 25	162	50·5	1·53	1000	620	12·2	4·8	140	150	85	VPS + ASD
8 M 45	183	94·5	2·18	1050	975	10·3	6·2	158	950	700	IPS
9 M 24	180	65·1	1·85	1220	1115	17·1	5·7	180	500	530	VPS + ASD
10 M 29	183	73·0	1·96	927	640	8·8	4·3	164	750	700	VPS
11 M 43	176	56·3	1·72	945	580	10·2	4·8	154	900	700	VPS
12 F 35	160	68·0	1·70	780	605	8·9	4·5	167	620	600	VPS
13 M 25	172	64·0	1·75	1600	665	10·4	4·9	164	450	400	VPS + IPS
14 M 53	163	63·9	1·69	1065	—	—	—	170	1100	1100	IPS
15 F 41	177	52·0	1·63	650	535	10·3	5·7	172	560	470	VPS
16 M 19	170	75·2	1·86	800	615	8·2	4·8	187	750	900	VPS
17 F 34	162	57·0	1·60	590	470	8·3	4·0	174	500	470	VPS
18 M 38	176	79·2	1·96	1220	703	8·9	5·3	160	750	670	VPS
19 M 39	167	64·1	1·72	790	651	10·2	4·6	172	850	900	IPS
20 F 23	155	48·4	1·45	450	340	7·0	2·9	179	350	370	VPS
21 F 15	142	38·0	1·22	510	497	13·1	3·1	144	250	200	VPS + ASD
22 M 57	184	80·9	2·14	—	931	11·5	6·0	155	760	630	VPS + ASD
23 F 24	166	56·4	1·64	690	527	9·3	3·7	167	400	330	IPS
24 M 20	178	58·2	1·76	1570	791	13·6	4·6	146	500	400	VPS + ASD + AVR
25 F 31	159	58·1	1·60	710	547	9·4	4·6	160	450	400	VPS + ASD
26 M 35	170	48·7	1·57	638	594	12·2	3·7	160	400	400	VPS + ASD
27 M 26	179	79·0	2·00	1270	765	9·7	6·0	168	900	900	IPS
28 F 28	158	59·5	1·60	760	432	7·3	3·9	177	400	470	VPS
29 F 14	160	52·0	1·54	570	477	9·2	3·8	166	450	450	IPS
30 M 19	161	52·5	1·54	500	492	9·2	4·1	160	650	600	VPS
31 F 21	144	45·0	1·32	—	326	7·3	2·6	172	450	430	VPS + IPS
32 F 17	161	54·5	1·57	570	485	8·9	4·0	175	580	600	VPS
33 F 47	172	73·9	1·87	—	735	10·0	5·7	148	770	600	VPS
34 M 35	172	75·0	1·78	950	964	12·8	6·1	154	1030	900	VPS
35 M 30	182	75·0	1·98	740	759	10·1	5·3	151	750	600	VPS
36 F 51	165	65·9	1·72	1120	543	8·3	4·8	160	450	450	VPS
37 F 27	167	57·5	1·66	625	503	8·8	4·3	162	500	430	VPS
38 M 18	192	64·9	1·96	980	755	11·6	5·4	167	900	900	VPS
39 F 31	157	65·0	1·64	645	413	6·4	3·4	170	600	600	VPS
40 F 30	170	65·9	1·78	660	614	9·3	4·5	175	570	600	VPS
41 F 37	160	59·7	1·62	810	460	7·7	4·3	152	750	600	VPS
42 M 18	187	76·0	2·04	785	635	8·4	4·7	168	600	600	VPS + ASD
43 F 21	160	48·4	1·48	450	393	8·1	3·3	152	500	400	VPS
44 F 29	158	55·3	1·55	610	420	7·6	3·1	180	450	430	VPS + ASD
45 M 35	173	72·5	1·87	—	—	—	—	—	—	—	VPS + ASD
46 M 54	163	76·0	1·81	800	643	8·5	4·5	180	660	700	VPS

PWC_{170} and W_{max} are measures of exercise tolerance (see under methods). VPS, valvular pulmonary stenosis; IPS ,infundibular pulmonary stenosis; ASD, atrial septal defect; AVR, abnormal venous return.

Right heart catheterization was performed with the patient in recumbent position. The reference point for zero pressure in this position was taken as 5 cm. below the insertion of the fourth rib at the sternum. The cardiac output was determined according to the direct Fick principle. In the beginning of this series (Cases 1–12) the blood gases were analysed according to the manometric method described by van Slyke. The normal value for arterial oxygen saturation was 95 (94–97) per cent. Later (Cases 13–46) the oxygen saturation was measured spectrophotometrically (Holmgren and Pernow, 1959), and the normal arterial oxygen saturation was 98 (95–100) per cent in this series. Should there be decreased arterial oxygen saturation, the pulmonary flow is calculated using a predicted value for the saturation in pulmonary venous blood (if not determined) of 95 per cent in the earlier and 98 per cent in the later series. A right-to-left shunt between the atria was assumed to be absent if the arterial oxygen saturation were only slightly decreased at rest and did not decrease significantly during exercise.

The area of right ventricular outflow tract was calculated according to the equation given by Gorlin and Gorlin (1951),

$$A = \frac{F}{44{\cdot}5 \cdot \sqrt{RV_{sm} - PA_{sm}}} = \frac{SV}{t_{ej} \cdot 44{\cdot}5\sqrt{\Delta P_{sm}}} \qquad 1$$

where A = the area of the pulmonary valve in $cm.^2$, F = the mean flow rate during the period of ejection in ml./sec., t_{ej} = the duration of right ventricular ejection in sec., SV = the stroke volume in ml., and $RV_{sm} - PA_{sm} = \Delta P_{sm}$ = the mean systolic pressure difference between the right ventricle and pulmonary artery during the period of ejection in mm. Hg.

The pressures of the right ventricle and pulmonary artery were, in most cases, determined simultaneously through a double-lumen catheter. The mean pressures

of the right ventricle and the pulmonary artery during the period of systolic ejection, RV_{sm} and PA_{sm}, were obtained by graphic integration of the recorded pressure curves.

The duration of the right ventricular ejection was the time interval when the right ventricular pressure exceeded the pulmonary artery pressure. In normal controls at rest this period was in most cases not well defined on the pressure tracing and was then taken as the time interval between the first rise in the pulmonary arterial pressure and the beginning of the isometric relaxation of the right ventricle. The last point is usually well defined as an angle between the systolic plateau and the rapid pressure fall. During exercise, however, the period when the right ventricular pressure exceeded the pulmonary artery pressure was well defined also in normal subjects.

The duration of right ventricular systole was measured on the ventricular pressure curve as the time from the beginning of isometric contraction to the end of isometric relaxation.

Determination of cardiac output and stroke volume was done with the catheter tip in the pulmonary artery. The stenosis was thus further obstructed by the cross-sectional area of the catheter, approximately 0·04 cm.^{2} This might be of some importance only in patients with the most severe stenosis. The figures for the right ventricular outflow area are given without correction for catheter area.

Results

The findings in the individual cases are shown in Tables I and II. The degree of stenosis varied considerably and was expressed in terms of the right ventricular outflow area in cm.^{2} m.^{2} body surface area. The material was classified in 4 groups, the mildest with an area index of 1·00 cm.^{2} m.^{2} body surface area or more, and 3 groups below 1·00. In patients studied during exercise, the area index used in this classification was the arithmetic mean of the calculated area indices at rest and during exercise. The area index in Group I was $< 0{\cdot}33$; in Group II, $0{\cdot}33 - 0{\cdot}65$; in Group III, $0{\cdot}66 - 0{\cdot}99$; in Group IV, $\geqslant 1{\cdot}00$. The 3 with a marked right-to-left shunt (Cases 7, 9, and 21), who all belonged to Group I, are indicated as Group Ia, and the rest of Group I as Group Ib. Mean values of various measures of each group are given in Table III. There was no marked difference between these groups with regard to age, height, weight, and sex.

The physical working capacity. Most of the patients reached high pulse rates at the end of the work test (Table I), though the mean maximal pulse rate was slightly lower in Group I than in the other groups. Of 17 patients in Group Ia and Ib, 5 had maximal pulse rates below 150 beats a minute as compared to one patient in the other groups. The maximal work intensity performed at a relative steady state (W_{max}) was at an average about 50 kpm./min. lower than the physical working capacity (PWC_{170}) in all groups.

The cyanotic patients of the Group Ia had a particularly low physical working capacity. The average physical working capacity in Group Ib was also low. It was higher in the other groups and normal in Group IV (see Table III).

The total amount of hæmoglobin per kg. body weight was slightly low except in the patients of Group Ia with arterial hypoxæmia, who had a larger total amount of hæmoglobin per kg. body weight, and also a slightly higher blood volume per kg. body weight.

The heart volume was on an average larger in patients with pulmonary stenosis than in normal subjects. In particular the patients of Group Ia and Ib had large hearts, but in some patients of Group I and in most patients of other groups the heart was within the normal range (Fig. 1). A marked increase in heart volume was found in only 6 patients (5 in Group Ia and Ib and 1 in Group II). One patient (Case 9) had a heart volume of 1220 ml., which was normal in relation to the total amount of hæmoglobin (1115 g.). He had, however, a marked polycythæmia with a hæmoglobin concentration of 19·6 g./100 ml. If related to the blood volume the heart was abnormally large.

The mean cardiac output at rest and cardiac index increased from low values in Group I to normal values in Group IV (Table III). If it is compared with the linear regression line relating cardiac output to oxygen uptake of normal subjects, the cardiac output of all cases of Group I was low (see Fig. 2) and in half of these cases it was more than twice the standard error of estimate from the regression line.

The cardiac output during exercise (Fig. 2) was low in relation to the oxygen uptake in all patients in Group I (more than twice the standard error of estimate from the regression line of normal subjects) but was normal or only slightly decreased in the patients in the other groups.

The mean stroke volume at rest and the mean stroke volume as a fraction of blood volume or heart volume increased from low values in Group I to normal values in Group IV (Table III). The stroke volume per litre of blood volume was small in most of the patients in Group I (Fig. 3), and showed a tendency to decrease during exercise.

The systolic pressure in the right ventricle at rest (see Fig. 4). The lowest pressure was 30 mm. Hg with a pressure gradient over the outflow tract of 14 mm. Hg (Cases 33 and 40). In these patients anatomical changes in the valves were demonstrated on angiocardiography. The highest pressure at rest was 220 mm. Hg.

TABLE II

RESULTS OF HEART CATHETERIZATIONS

Case No., Cath. No.	Work load (kpm./min.)	Pulse rate (beats/min.)	O_2 uptake (ml./min.)	O_2 capacity of blood (ml./100 ml.)	Art. O_2-sat. (%)	AV-O_2 diff. (ml./l.)	Cardiac output (l./min.)	Stroke volume (ml.)	Pressures (mm. Hg)							Duration RV ejection (sec.)	Duration RV systole (sec.)	RV outflow area (cm.^{2} m.^{2} BSA)
									Right ventricle		Pulmonary artery			Brachial artery				
									S	De	S	D	M	S	D			
1	Rest	100	192	15·9	94	37	5·3	53	155	7	20	4	18	—	—	0·30	0·32	0·29
16/52																		
2	Rest	75	177	14·7	93	33	5·4	72	60	10	15	10	12	—	—	0·34	0·38	0·65
19/53	Work[1]	100	370	—	98	50	7·4	74	97	11	24	—	—	—	—	—	—	—
3	Rest	95	200	17·8	93	39	5·1	54	80	5	15	3	8	—	—	0·36	0·40	0·38
26/53	Work[1]	—	534	—	93	52	10·3	—	110	5	25	6	—	—	—	—	0·30	—
4	Rest	95	158	20·8	90	68	2·3	24	125	—	17	4	8	—	—	0·36	0·40	0·11
28/53	—	—	—	—	—	(49)	(3·2)	(34)	—	—	—	—	—	—	—	—	—	—
	Work[1]	150	776	—	87	107	7·4	49	206	—	15	5	11	—	—	—	—	—
						(82)	(9·5)	(63)										
5	Rest	100	205	16·8	97	27	7·5	75	40	7	22	9	—	153	82	0·34	0·40	0·94
17/54	200	130	627	—	98	63	9·9	76	—	—	—	—	—	—	—	—	—	—
	400	160	769	—	97	70	11·0	69	—	—	—	—	—	—	—	—	—	—
6	Rest	84	258	18·1	96	33	7·8	93	35	7	17	8	12	115	61	0·34	0·40	1·15
6/55	300	112	828	—	96	86	9·6	86	51	6	—	—	19	145	79	—	0·34	—
	600	172	1467	—	96	123	11·9	69	76	1	32	9	18	162	100	—	0·24	—
7	Rest	110	203	19·7	69	110	1·8	16	220	18	—	—	8	109	67	0·40	0·42	0·05
56/56						(58)	(3·5)	(32)										
8	Rest	79	315	20·5	95	43	7·3	92	74	8	20	5	13	—	—	0·38	0·44	0·36
8/57	300	107	892	21·3	95	92	9·7	91	107	13	19	7	13	—	—	0·33	0·35	—
	600	138	1466	21·8	95	112	13·1	95	139	21	31	6	18	—	—	0·28	0·31	—
9	Rest	84	332	26·1	83	86	3·9	46	146	12	12	4	7	145	87	0·40	0·44	0·15
22/57						(50)	(6·7)	(80)										
	200	123	764	26·2	58	169	4·5	37	—	—	15	3	7	157	84	—	—	—
						(72)	(10·6)	(86)										
	400	165	1096	27·0	40	218	5·0	30	—	—	22	0	13	187	89	—	—	—
						(64)	(17·2)	(104)										
10	Rest	84	287	17·6	98	40	7·1	85	105	12	19	5	11	121	69	0·34	0·40	0·42
46/57	300	126	923	17·6	98	76	12·2	97	157	25	27	4	15	148	74	0·28	0·30	—
	600	159	1410	18·1	96	92	15·3	96	187	27	27	5	—	174	72	0·24	0·26	—
11	Rest	74	326	16·4	95	42	7·8	106	71	10	36	23	—	148	86	0·30	0·40	1·00
81/57	200	98	788	16·8	96	71	11·0	118	—	—	40	10	—	—	—	0·25	0·36	—
	400	108	1072	17·0	95	87	12·3	114	106	14	42	15	—	173	104	0·22	0·33	—
12	Rest	76	244	17·6	95	31	7·7	102	35	0	14	6	—	119	62	0·32	0·43	1·17
21/58	200	96	706	17·5	94	63	11·3	117	54	4	21	7	—	144	76	—	0·36	—
	400	118	1001	18·0	95	79	12·6	108	63	1	19	10	—	154	73	—	0·32	—
13	Rest	74	250	19·2	99	94	2·7	37	167	19	—	—	13	116	74	0·38	0·42	0·13
171/58																		
14	Rest	79	284	19·8	97	42	6·8	86	43	2	26	11	14	120	63	0·26	0·42	1·21
9/59	300	111	1066	20·1	95	79	13·5	121	84	6	42	17	30	158	81	0·22	0·32	—
	600	138	1599	20·5	96	104	15·3	111	105	10	38	15	30	195	96	0·19	0·26	—
	900	167	2146	20·8	92	129	16·6	99	123	12	42	18	30	195	96	0·17	0·24	—
15	Rest	86	237	17·8	98	41	5·7	66	64	2	13	5	7	150	74	0·29	0·39	0·57
41/59																		
16	Rest	70	277	18·6	99	46	6·0	86	111	9	15	5	—	145	73	0·36	0·44	0·33
62/59	250	118	928	19·4	98	92	10·1	85	—	—	—	—	—	—	—	—	—	—
	500	152	1362	20·0	97	110	12·4	81	—	—	17	8	—	167	70	—	—	—
17	Rest	94	217	15·9	100	35	6·1	65	70	7	17	5	—	110	70	0·34	0·38	0·46
91/59	200	134	735	16·4	98	76	9·7	72	—	—	15	9	—	—	—	—	—	—
	400	158	1021	17·1	96	87	11·7	74	—	—	24	10	—	147	74	—	—	—
18	Rest	70	311	19·2	97	55	5·7	81	134	15	17	10	—	128	69	0·39	0·44	0·30
122/59																		
19	Rest	59	272	18·8	94	50	5·4	82	48	6	26	9	15	125	68	0·34	0·43	0·84
12/60	800	162	1878	20·2	92	119	15·8	98	104	6	40	8	28	210	86	0·19	0·26	—
20	Rest	98	151	15·3	100	25	6·1	62	35	3	10	4	6	125	59	0·28	0·38	0·87
39/60	150	127	487	15·9	100	57	8·5	67	47	0	16	2	9	139	59	0·24	0·28	—
	300	156	760	16·3	99	75	10·1	65	58	−1	19	1	10	145	59	0·21	0·26	—
21	Rest	98	245	20·9	81	65	3·8	38	76	2	17	4	8	83	45	0·37	0·44	0·31
84/60						(28)	(8·9)	(91)										
22	Rest	69	249	18·8	95	56	4·5	65	65	5	14	4	8	116	68	0·40	0·48	0·30
100/60	500	124	1334	20·1	84	121	11·1	89	166	21	28	16	20	181	87	0·28	0·32	—
23	Rest	70	248	19·8	98	46	5·4	77	97	5	19	3	8	120	62	0·42	0·48	0·25
101/60																		
24	Rest	68	279	24·7	91	92	3·0	45	164	14	10	0	—	114	70	0·43	0·48	0·16
118/60						(73)	(3·8)	(52)										
	300	121	948	24·3	81	182	5·2	43	192	35	—	—	—	159	78	0·32	0·34	—
						(137)	(6·9)	(57)										
25	Rest	81	228	18·4	94	38	6·0	70	126	10	15	6	—	114	69	0·32	0·40	0·35
185/60						(42)	(5·4)	(63)										
	200	151	916	18·6	86	93	9·9	65	178	17	29	9	—	163	90	0·24	0·26	—
						(68)	(13·5)	(90)										
26	Rest	60	223	21·8	95	57	3·9	65	158	12	—	—	10	130	67	0·41	0·42	0·24
198/60	300	138	946	22·6	80	131	7·2	52	228	21	—	—	14	168	82	0·27	0·28	—
						(97)	(9·8)	(71)										
27	Rest	72	318	19·0	99	42	7·6	106	102	6	13	4	8	129	77	0·42	0·45	0·40
46/61	300	106	1001	19·6	96	83	12·0	113	158	11	22	7	14	149	83	0·34	0·38	—
	600	140	1451	20·0	98	98	14·5	104	178	14	32	8	20	144	53	0·28	0·32	—

[1] Work load not defined.

Cont'd overleaf

TABLE II—*continued.*

Case No., Cath. No.	Work load (kpm./min.)	Pulse rate (beats/min.)	O_2 uptake (ml./min.)	O_2 capacity of blood (ml./100 ml.)	Art. O_2-sat. (%)	AV-O_2 diff. (ml./l.)	Cardiac output (l./min.)	Stroke volume (ml.)	Pressures (mm. Hg)							Duration RV ejection (sec.)	Duration RV systole (sec.)	RV outflow area (cm.^{2} m.^{2} BSA)
									Right ventricle		Pulmonary artery			Brachial artery				
									S	De	S	D	M	S	D			
28	Rest	64	181	15·7	99	54	3·3	52	142	14	22	9	—	122	77	0·40	0·45	0·20
69/61	150	108	502	16·4	98	97	5·2	45	178	15	26	7	—	128	77	0·32	0·36	—
	300	154	684	16·4	98	119	5·7	37	185	20	26	9	—	122	82	0·26	0·29	—
29	Rest	80	187	17·8	99	46	4·1	51	126	10	20	8	—	112	76	0·41	0·45	0·24
75/61	400	164	972	19·0	97	118	8·2	51	200	12	27	8	—	144	80	0·26	0·28	—
30	Rest	56	213	17·4	100	41	5·2	92	58	10	28	13	—	128	77	0·40	0·48	0·70
77/61	300	119	766	17·8	97	79	9·7	81	82	12	38	16	—	127	78	—	—	—
31	Rest	88	202	17·6	97	48	4·2	48	132	8	16	5	10	145	86	0·43	0·45	0·21
91/61																		
32	Rest	94	275	16·7	99	40	6·9	74	32	4	16	5	9	118	74	0·30	0·37	1·00
105/61	400	162	1173	18·0	98	99	11·9	74	57	−4	20	7	14	166	74	0·22	0·26	—
33	Rest	70	245	17·8	97	40	6·2	88	30	8	16	8	12	111	69	0·36	0·44	0·98
127/61	400	119	1159	18·7	98	99	11·7	99	60	—	29	11	20	152	86	0·30	—	—
34	Rest	85	350	21·8	98	50	7·0	82	82	6	19	7	14	119	74	0·31	0·38	0·63
145/61	400	111	1141	22·1	97	94	12·2	110	112	12	27	8	16	147	78	0·29	0·34	—
	800	149	1835	22·9	98	115	16·0	107	159	9	26	2	18	186	81	0·25	0·28	—
35	Rest	70	231	20·3	96	41	5·7	81	104	3	21	4	12	105	69	0·42	0·46	0·27
166/61	300	108	870	21·2	99	107	8·1	75	168	14	29	9	18	129	85	0·34	0·39	—
	600	146	1307	21·9	98	132	9·9	68	202	16	27	10	19	155	95	0·28	0·30	—
36	Rest	60	255	15·3	97	61	4·2	70	156	11	20	11	14	134	72	0·46	0·48	0·22
4/62	350	139	1044	16·8	99	131	8·0	57	—	—	29	8	20	163	82	—	0·30	—
37	Rest	64	282	15·6	99	40	7·0	109	84	10	18	8	11	132	77	0·45	0·48	0·53
31/62	300	130	963	16·1	96	82	11·7	90	131	17	—	—	14	156	68	0·28	0·31	—
38	Rest	82	290	19·6	98	31	9·4	115	34	0	16	3	9	123	58	0·34	0·38	1·12
44/62	600	150	1434	19·7	97	85	16·9	112	57	0	28	7	16	155	68	0·22	0·26	—
39	Rest	81	261	17·9	95	39	6·8	84	34	6	19	8	13	141	84	0·28	0·36	1·27
212/62	400	126	1043	18·3	99	105	9·9	89	54	7	28	15	20	154	84	0·21	0·30	—
40	Rest	85	286	18·8	95	37	7·7	90	30	2	16	7	11	119	70	0·29	0·37	1·12
225/62	400	129	1051	19·5	94	84	12·6	98	52	0	22	7	14	147	77	0·22	0·26	—
41	Rest	62	223	14·3	97	35	6·4	104	37	5	21	5	12	111	64	0·38	0·44	1·01
20/63	500	114	1191	15·0	99	82	14·5	127	79	8	26	9	—	174	74	0·25	0·32	—
42	Rest	100	302	18·2	98	37	8·2	82	96	3	16	1	4	133	81	0·32	0·36	0·41
34/63	1000	196	2166	20·0	88	140	15·6	80	176	14	29	8	21	210	91	0·18	0·24	—
						(118)	(18·4)	(94)										
43	Rest	115	249	16·3	99	27	9·4	82	44	6	20	12	17	113	76	0·24	0·32	1·15
60/63	400	156	822	16·8	97	75	10·9	70	67	5	33	17	27	137	89	0·21	0·26	—
44	Rest	68	186	18·4	89	53	3·5	50	64	6	12	5	8	117	71	0·42	0·45	0·28
61/63						(38)	(4·9)	(72)										
	150	105	544	19·0	84	95	5·7	54	—	—	15	6	11	151	78	—	—	—
						(73)	(7·5)	(71)										
	300	142	801	19·4	78	104	7·7	54	—	—	—	—	—	—	—	—	—	—
						(73)	(11·1)	(78)										
45	Rest	71	276	23·1	95	58	4·8	68	116	6	11	2	8	113	62	0·38	0·44	0·24
106/63	400	124	1285	24·3	80	151	8·5	69	240	16	14	6	—	170	78	0·32	0·34	—
						(110)	(11·7)	(94)										
46	Rest	72	276	20·6	99	58	4·8	64	70	3	23	8	17	150	84	0·34	0·42	0·40
72/64	600	148	1288	21·2	97	121	10·7	72	120	18	25	18	22	205	103	0·23	0·30	

Note: Figures within brackets for AV-O_2 difference, cardiac output, and stroke volume refer to the systemic circulation. S, systolic; De, end-diastolic; M, mean.

The systolic pressure in the right ventricle during exercise increased more than normal (Fig. 4). Even in mild cases with a pressure at rest only slightly above the normal, the pressure during exercise deviated considerably from the normal. The increase in pressure in relation to increase in cardiac output was more obvious in severe than in mild stenosis and the lines representing each patient converged near the origin. The highest pressure measured during exercise was 240 mm. Hg.

The end-diastolic pressure in the right ventricle was significantly increased at rest in more than half of the patients (Fig. 5, Tables II and III). In some of the most severe cases it was notably increased. During work it increased above the normal range also in many patients with a normal pressure at rest. A high end-diastolic pressure was usually combined with a big heart volume.

The mean pressure difference between the right ventricle and pulmonary artery during the period of systolic ejection (RV_{sm}–PA_{sm}) increased with increasing degree of stenosis and with increasing

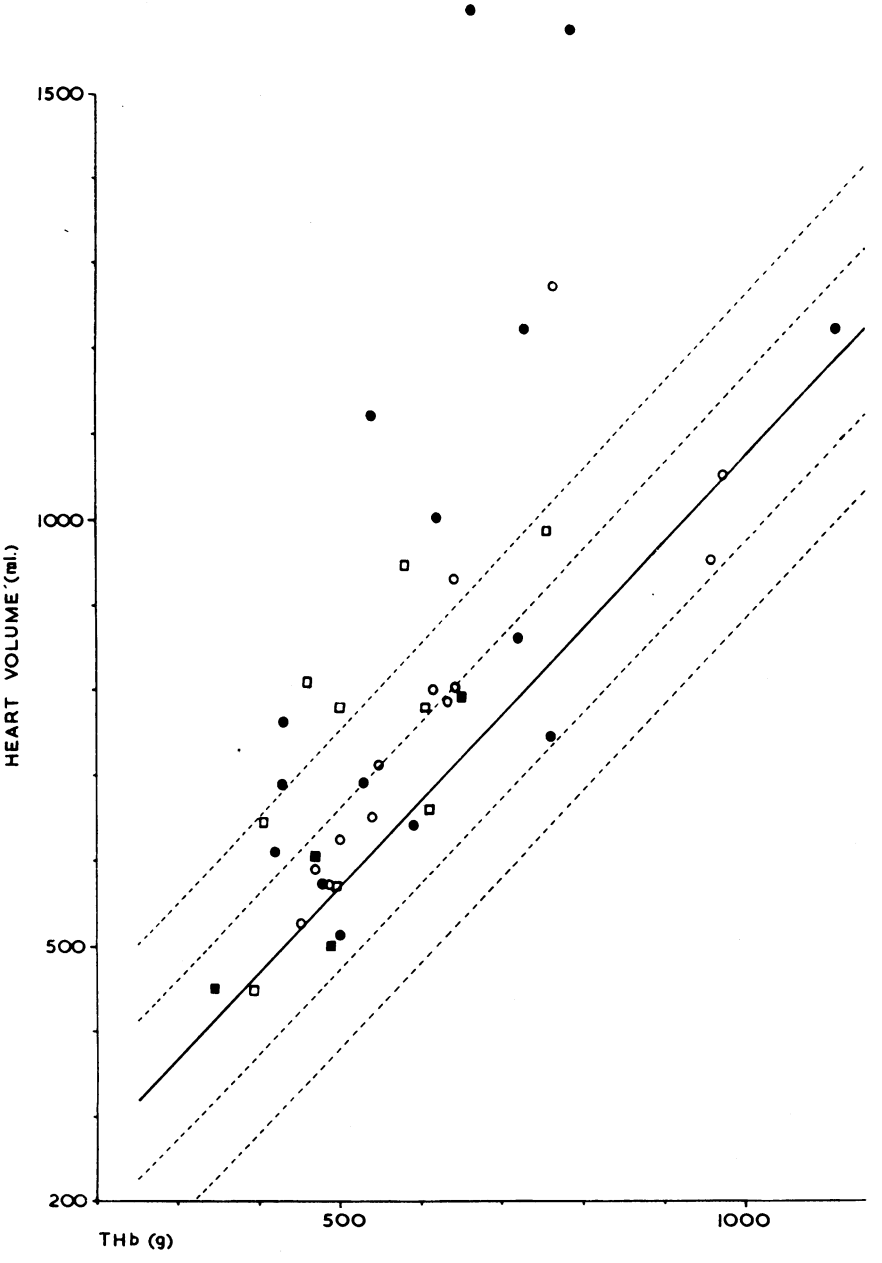

FIG. 1.—Relation between heart volume (HV) and total amount of hæmoglobin (THb). The normal variation is represented by the regression line HV = 1·010 × THb + 63·5; S_{HV} = 93, and once and twice the standard error of estimate (Holmgren *et al.*, 1957). Symbols indicate different degree of stenosis with a right ventricular outflow area, cm.² m.² BSA, of < 0·33 = ●; 0·33 × 0·65 = ○; 0·66 × 0·99 = ■; > 1·00 = □.

cardiac output during exercise (Tables II, III). It was 67 ± 10 per cent (mean ± SD) of the peak systolic pressure difference between the right ventricle and the pulmonary artery.

The duration of the right ventricular ejection (t_{ej}) was increased in most of the patients at rest and during exercise as compared with that of normal subjects (Fig. 6, Table II). It was particularly long in patients of Groups I and II (Table III).

The duration of the systole of the right ventricle

TABLE III

MEAN VALUES OF SOME DATA FOR MEN AND WOMEN WITH VARYING DEGREES OF PULMONARY STENOSIS

	Group Ia		Group Ib		Group II		Group III		Group IV	
RV outflow area (cm.² m.² BSA) {range / mean	< 0·33		< 0·33		0·33–0·65		0·66–0·99		≧ 1·0	
	0·15	0·18	0·22	0·24	0·40	0·50	0·70	0·92	1·12	1·12
Sex	M	F	M	F	M	F	M	F	M	F
No. of patients	1	2	7	7	8	5	2	3	4	6
Age (yr.)	24	20	33	27	31	33	29	30	33	29
Height (cm.)	180	152	177	159	175	165	164	164	176	161
Weight (kg.)	65·1	44·3	67·2	54·5	74·3	54·1	58·3	59·4	60·6	60·3
BSA (m.²)	1·85	1·38	1·85	1·55	1·89	1·59	1·63	1·64	1·75	1·63
Heart volume (ml.)	1220	755	1105	740	889	629	645	528	943	653
Total amount of Hb (g.)	1115	559	738	451	711	508	572	515	613	495
Total amount of Hb/weight (g./kg.)	17·1	12·7	11·1	8·3	9·6	9·5	9·7	8·5	10·2	8·2
Blood weight (l.)	5·7	4·0	5·0	3·6	5·1	4·5	4·4	4·2	4·6	4·0
PWC_{170} (kpm./m.)	500	200	601	433	780	502	750	530	915	603
W_{max} (kpm./m.)	530	143	506	394	750	420	750	480	850	567
Max. pulse rate (beats/min.)	180	142	159	164	169	166	166	170	167	165
Hæmodynamic data										
Pulse rate (beats/min.)	84	104	72	76	82	80	58	89	80	86
AV-O_2 diff. (ml./l.)	86	88	66	49	44	37	46	31	37	35
Cardiac output (l./min.)	3·9	2·8	4·0	4·3	6·6	6·0	5·3	6·6	8·0	7·5
Cardiac index (l./min. m.² BSA)	2·11	2·15	2·13	2·79	3·52	3·81	3·26	4·07	4·54	4·62
Stroke vol. (ml.)	46	27	57	57	81	76	87	75	100	89
Stroke vol. × 100/HV	3·8	4·5	6·0	8·2	9·3	12·2	14·4	13·1	10·7	13·9
Stroke vol./blood vol.	8·1	7·8	11·6	16·0	16·1	17·6	20·1	18·5	23·2	22·5
Blood pressures (mm. Hg)										
RV_s	146	148	117	125	90	81	53	35	46	35
RV_{De}	12	10	11	9	7	8	6	6	5	4
PA_s	12	17	16	18	18	16	27	16	24	18
Mean syst. gradient	85	84	70	70	49	45	22	12	15	14
Mean syst./peak syst. gradient	0·63	0·63	0·59	0·67	0·67	0·65	0·84	0·63	0·68	0·78
Duration of RV ejection at rest (sec.)	0·40	0·39	0·40	0·41	0·35	0·35	0·37	0·33	0·31	0·30
Duration of RV systole at rest (sec.)	0·44	0·43	0·44	0·44	0·41	0·41	0·46	0·41	0·40	0·38
Area (cm.²)	0·28	0·23	0·41	0·37	0·76	0·79	1·14	1·52	1·95	1·83

Note: Hæmodynamic data were measured at rest in supine position. The groups are defined in the text. Group Ia represents cases with marked right-to-left shunt at rest. The figures for blood flow in cases with shunts refer to the pulmonary circulation. Incompletely examined patients were excluded in the calculation of mean values. Symbols as in Table I.

was above the normal range of variation in several of the Group I patients at rest and during exercise. In general the difference between the pulmonary stenosis patients and the normal controls with regard to the duration of the right ventricular systole was much smaller than in the case of the duration of the right ventricular ejection. The average duration of the systole of the right ventricle was longest in Group I and decreased in the groups with less severe stenosis (Table III).

Relation between physical working capacity and other data. The physical working capacity (PWC_{170}) in relation to the total amount of hæmoglobin of the body (THb) was in the normal range n most patients but was much lower in some patients of Group Ia and Ib. On the other hand some of the patients with fairly tight stenosis had a normal physical working capacity in relation to total hæmoglobin (Fig. 7). The physical working capacity in relation to heart volume was small in most of the patients with a tight pulmonary stenosis (Fig. 8), but fairly normal in most others.

A statistically significant positive correlation was observed between the two measures of physical fitness, PWC_{170}, and W_{max} ($r = 0{\cdot}93$, $n = 44$). There was also a positive correlation between these

TABLE IV

CORRELATION COEFFICIENTS (r) BETWEEN MEASURES OF EXERCISE TOLERANCE AND SOME HÆMODYNAMIC DATA MEASURED IN RESTING STATE (n = 44)

	PWC_{170}	W_{max}
Stroke volume at rest (ml.)	0·66	0·59
Right ventricular peak systolic pressure (mm. Hg)	−0·42	−0·39
Area of right ventricular outflow tract (cm.²)	0·49	0·46

Symbols as in Table I.

TABLE V

LINEAR REGRESSION EQUATION BETWEEN PHYSICAL WORKING CAPACITY AND STROKE VOLUME

Patients with pulmonary stenosis
$PWC_{170} = 5{\cdot}89 \times SV_R + 179$; $S_{PWC_{170}} = 153$; $n = 44$; $r = 0{\cdot}66$
$PWC_{170} = 6{\cdot}04 \times SV_W + 163$; $S_{PWC_{170}} = 132$; $n = 36$; $r = 0{\cdot}73$
$W_{max} = 5{\cdot}22 \times SV_R + 185$; $S_{W_{max}} \times 160$; $n = 44$; $r = 0{\cdot}59$
Normal subjects*
$PWC_{170} = 10{\cdot}02 \times SV_W - 195$; $S_{PWC_{170}} = 129$; $n = 27$; $r = 0{\cdot}88$

* The regression equation is based on measurements described by Bevegård *et al.* (1960) and Holmgren *et al.* (1960).

SV_R, stroke volume at rest; SV_W, mean stroke volume during exercise; $S_{PWC_{170}}$, $S_{W_{max}}$, standard error of estimate; r, correlation coefficient; and n, number of subjects examined. Other symbols as in Table I.

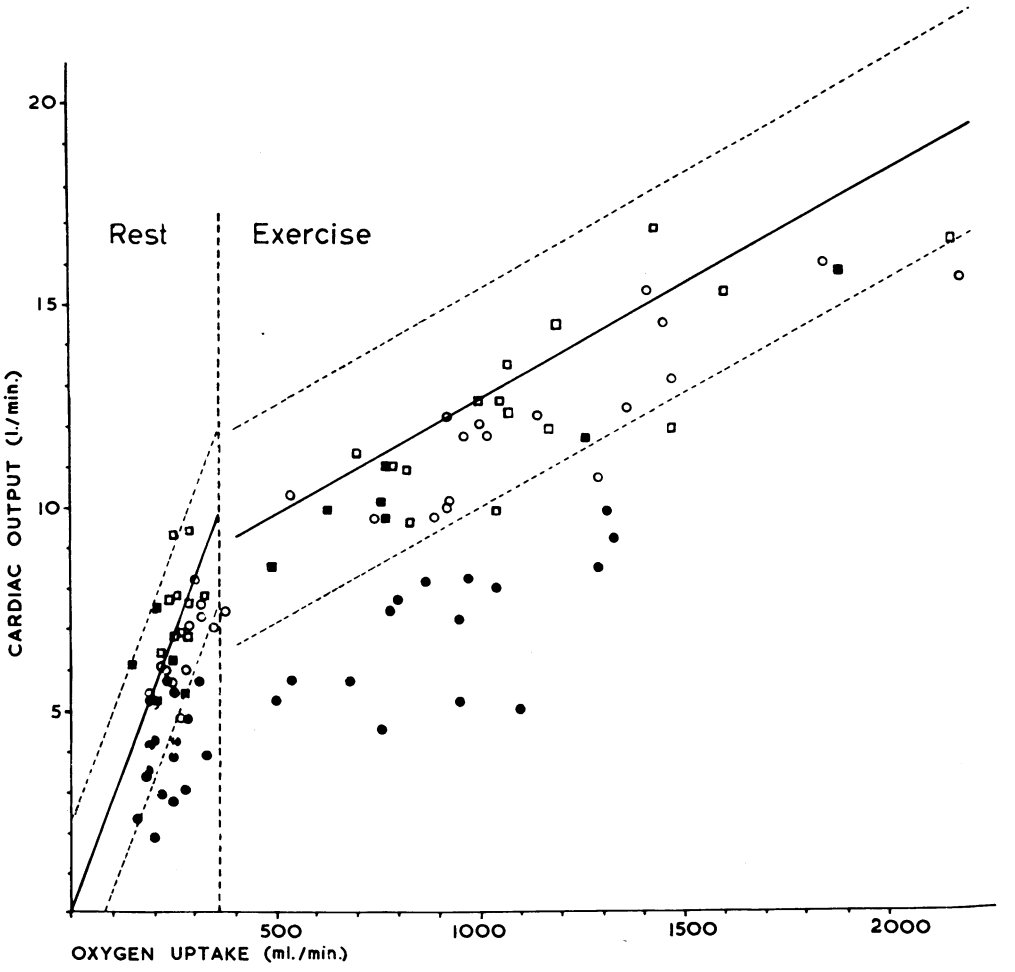

FIG. 2.—Relation between cardiac output ($\dot{Q}$) and oxygen uptake ($\dot{V}_{O_2}$) at rest (supine) and during exercise. Symbols as in Fig. 1. The regression line at rest $\dot{Q} = 0{\cdot}0274 \times \dot{V}_{O_2}$; $S_{\dot{Q}} = 1{\cdot}14$; $n = 27$, and during exercise $\dot{Q} = 7{\cdot}00 + 0{\cdot}0057 \times \dot{V}_{O_2}$; $S_{\dot{Q}} = 1{\cdot}36$; $n = 70$, with twice the standard error of estimate indicates the normal variation (calculations from results given by Holmgren *et al.* (1960) and Bevegård *et al.* (1960)).

two measures of exercise tolerance and the stroke volume (Table IV).

The correlation seems to be less good between the measures of physical working capacity and the right ventricular systolic pressure at rest or the right ventricular outflow area (Table IV).

The linear regression equations for the relation between physical working capacity and stroke volume are given in Table V.

DISCUSSION

The ability to perform work with large muscle groups in steady state (aerobic work capacity) depends on the capacity to transport oxygen from the respiratory tract to the tissues. The limiting factor in normal subjects is the circulation and not the lung function (Holmgren and Linderholm, 1958). As the mechanical efficiency is fairly constant, the work performed is in proportion to the oxygen uptake. The work per unit time which an individual is able to perform at a given heart rate, e.g. 170 beats a minute, is, therefore, a function of the stroke volume and the arteriovenous oxygen difference at that heart rate, as expressed in Fick's equation: $\dot{V}_{O_2} = f \times SV \times AV\ O_2\text{-diff.}$, where $\dot{V}_{O_2}$ = the oxygen uptake, f = the heart rate (here 170), SV = stroke volume, and AV O_2-diff. = arteriovenous oxygen difference.

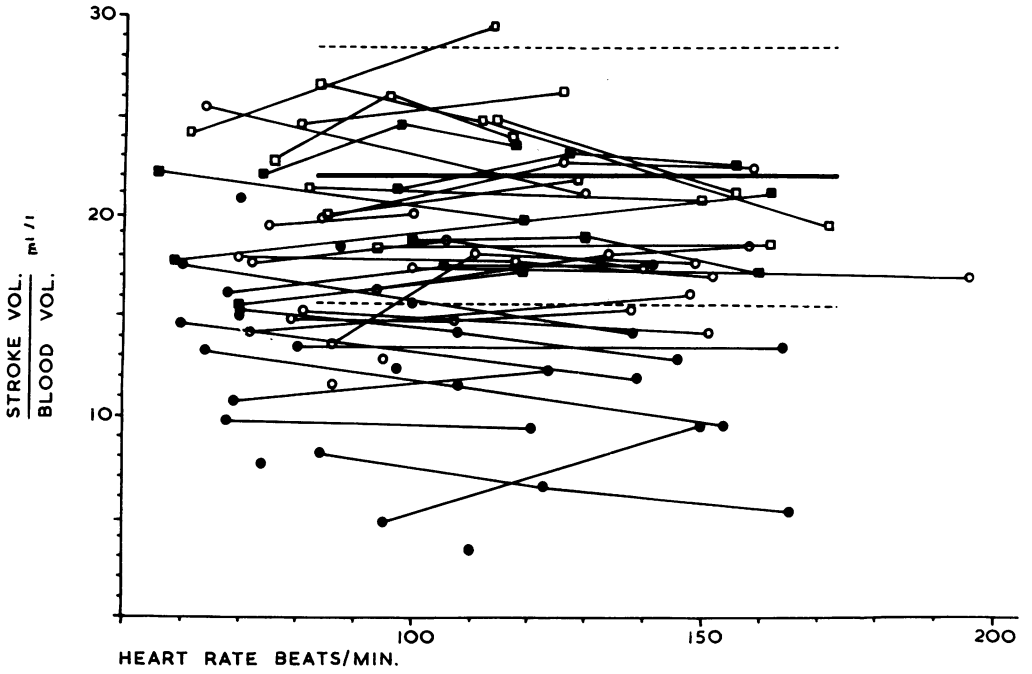

FIG. 3.—Stroke volume per litre of blood volume at various heart rates at rest and during exercise in the supine posture. The symbols (as in Fig. 1) representing one patient are connected with a thin line. The thick line and the dotted lines represent the mean normal value and twice the standard deviation for stroke volume during exercise at pulse rate 129 (86–175), mean (range), obtained from Holmgren *et al.* (1960) and Bevegård *et al.* (1960).

It was demonstrated by Kjellberg *et al.* (1949) that the aerobic work capacity was closely related to the dimension of the cardiovascular system in normal subjects. Thus the physical working capacity, heart volume, and blood volume or total amount of hæmoglobin were all related to each other in a linear way. It has also been shown (Bevegård *et al.*, 1960; Holmgren *et al.*, 1960) that in normal subjects there is a linear relation between the work performed at a heart rate of 170 beats a minute and the stroke volume. In heart disease, deviations from the normal relation may occur (Sjöstrand, 1960).

The results in the present material show that such deviations occur mainly in the patients with tight stenosis (Group I). The deviation from the normal relation between physical working capacity, heart volume, and total amount of hæmoglobin was, however, small in the majority of the patients with pulmonary stenosis, and was much smaller than in patients with atrial septal defect (Jonsson *et al.*, 1957).

In pulmonary stenosis the right ventricle compensates for the outflow tract obstruction with muscular hypertrophy and increased systolic pressure. The compensation may well be enough to maintain a normal stroke volume. During exercise the systolic pressure must rise further in order to maintain the stroke volume, because of a much shorter duration of systole during work. In many cases the right ventricular pressure was sufficiently raised to deliver a normal stroke volume at a high heart rate, thus maintaining a normal physical working capacity. There should, however, be an upper limit for the pressure rise in the right ventricle. In the patients studied the maximal right ventricular systolic pressure observed was 240 mm. Hg. Therefore, if the stenosis is tight, the compensation by increasing the right ventricular systolic pressure may be incomplete.

A prolonged duration of systole should enhance the maintenance of a normal stroke volume, and was found in most of the patients, particularly in Group I, but was also in Groups II and III (Table III, Fig. 6). However, a prolongation of systole during exercise at a high pulse rate results in a shorter diastole, which might impede the ventricular filling and thus limit compensation in this way.

In spite of a high right ventricular systolic pressure and a prolonged duration of systole, the

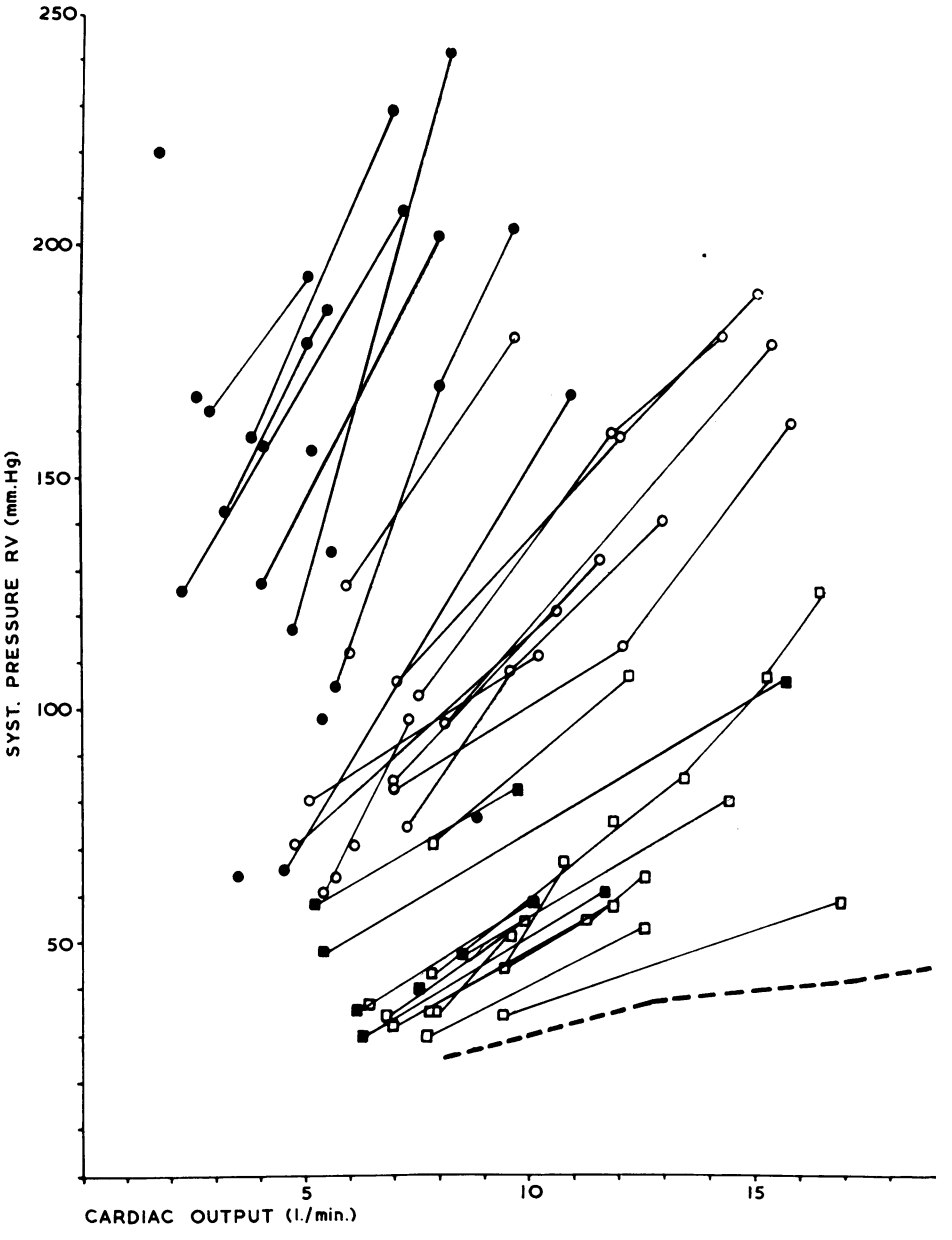

FIG. 4.—Systolic pressure of the right ventricle in relation to the cardiac output (lesser circulation). Symbols as in Fig. 1. Thick dotted line indicates mean normal values (from results obtained in 33 young healthy subjects, most of them described by Holmgren *et al.* (1960) and Bevegård *et al.* (1960)).

compensation was incomplete in many patients with tight stenosis; and the stroke volume was small. In these cases the cardiac output was low in relation to the oxygen uptake during exercise and the arterio-venous oxygen difference was high (Group I, Table III). This partly compensates for the small stroke volume, and, therefore, the physical working capacity may be fairly normal also in some cases with fairly tight pulmonary stenosis. In general, however, there was a close positive correlation between the physical working capacity (PWC_{170}) and the stroke volume (Table IV), the linear

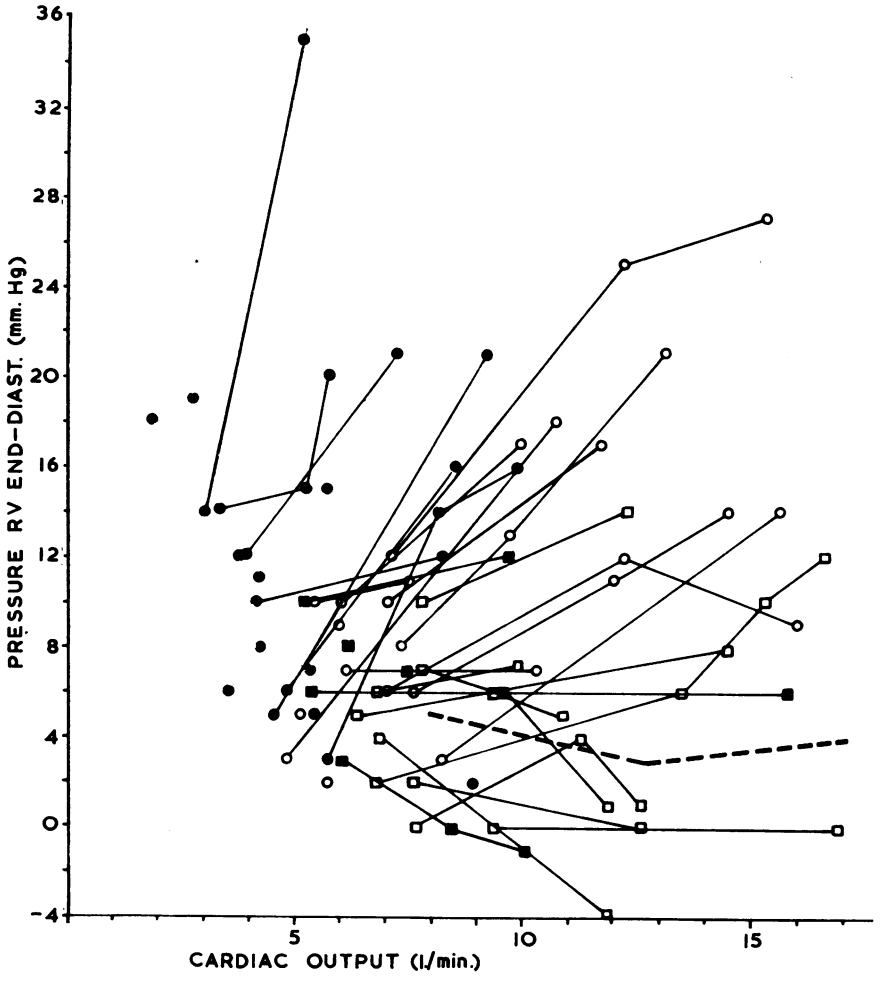

FIG. 5.—End-diastolic pressure of right ventricle in relation to cardiac output. Symbols as in Fig. 4.

regression equations for normal subjects and patients with pulmonary stenosis being quite similar (Table V). The wider range of deviation of individual results from the regression line in the group of pulmonary stenosis than in normal subjects is probably due to a greater variability of the AV O_2-difference at a pulse rate of 170.

The right ventricular systolic pressure at rest, or the calculated area of right ventricular outflow tract, was less closely correlated to the physical working capacity than stroke volume was (Table IV). This indicates that the various compensatory mechanisms discussed previously were utilized in different ways in the individual patients. This may be demonstrated by applying equation 1, according to which the stroke volume is a product of the square root of the mean pressure difference between the right ventricle and the pulmonary artery during systole, the duration of the systolic ejection, the area of the right ventricular outflow tract, and a constant. For a given area of the right ventricular outflow tract the stroke volume, and therefore also the physical working capacity, depends on the duration of the systole and the ability of the myocardium to produce a high right ventricular systolic pressure. A given stroke volume may, therefore, be associated with quite different pressure gradients and areas of the right ventricular outflow tract.

It is possible to estimate roughly the degree to which the increase in right ventricular systolic pressure and prolongation of the right ventricular systolic duration compensates for the pulmonary stenosis. Using the value of predicted normal

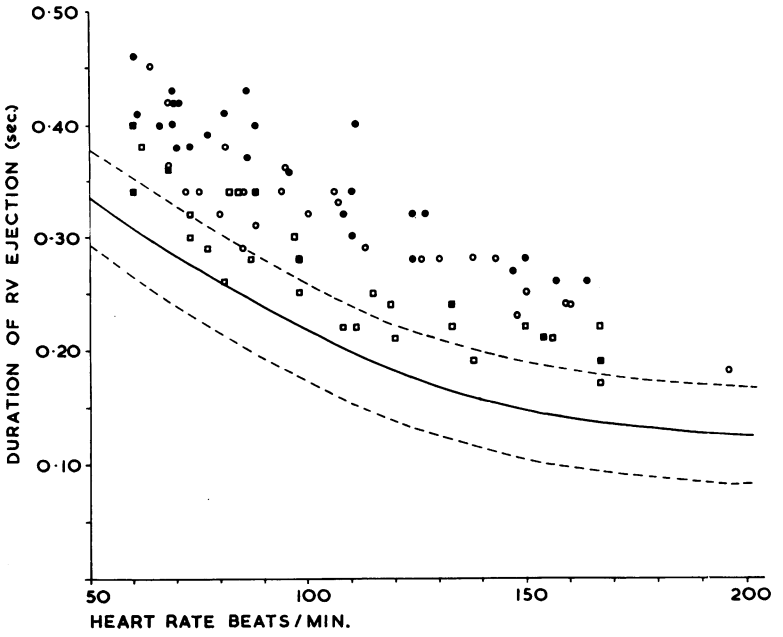

FIG. 6.—Duration of right ventricular ejection t_{ej} (sec.) in relation to heart rate, f (beats/min.). Symbols as in Fig. 1. The thick line represents equation $t_{ej} = 0{\cdot}504 - 3{\cdot}86 \cdot 10^{-3} \cdot f + 9{\cdot}89 \cdot 10^{-6} \cdot f^2$; SE: $2{\cdot}04 \cdot 10^{-2}$, Eqn. 2, calculated according to the method of least squares from results obtained in 24 healthy male subjects, most of them described by Holmgren *et al.* (1960) and Bevegård *et al.* (1960). The thin lines represent twice the standard error of estimate.

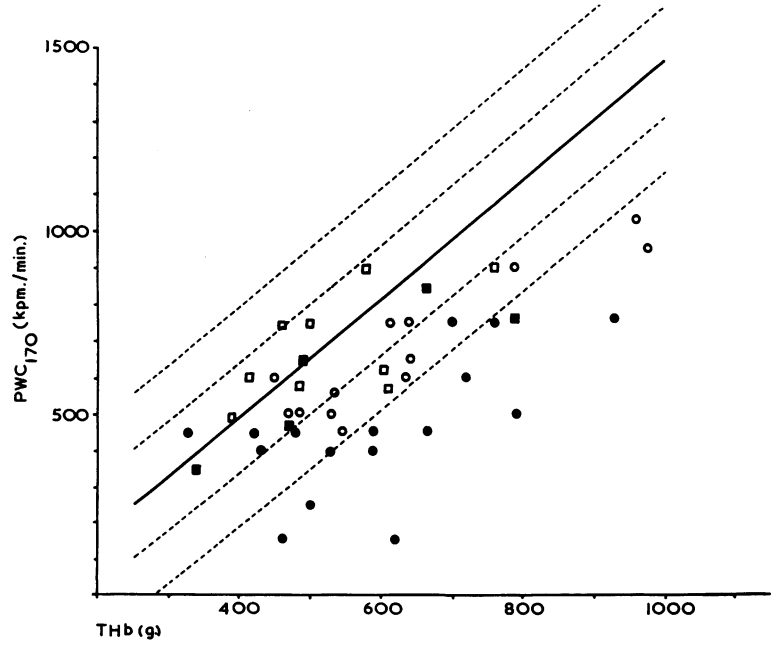

FIG. 7.—Relation between physical working capacity (PWC_{170}) and total amount of hæmoglobin (THb) The normal variation is represented by the regression line $PWC_{170} = 1{\cdot}60 \cdot \cdot THb - 141$; $S_{PWC_{170}} = 150$, and once and twice the standard error of estimate (Holmgren *et al.*, 1957). Symbols as in Fig. 1.

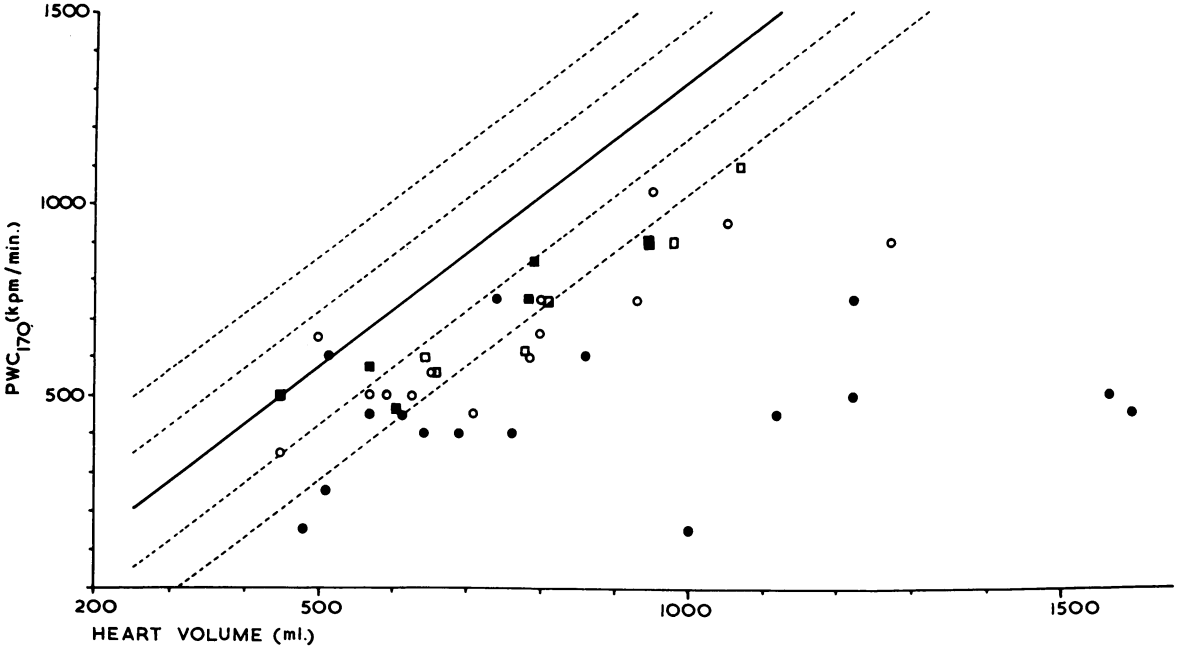

FIG. 8.—Relation between physical working capacity (PWC_{170}) and heart volume (HV). Symbols as in Fig. 1. The normal variation is represented by the regression line $PWC_{170} = 1{\cdot}48 \times HV - 170$; $S_{PWC_{170}} = 148$. The dotted lines indicate once and twice the standard error of estimate (calculations from the same material as in Fig. 1).

TABLE VI

DEGREE TO WHICH RIGHT VENTRICLE COMPENSATES FOR PULMONARY STENOSIS BY INCREASE IN MEAN SYSTOLIC PRESSURE GRADIENT (P_{sm}) AND DURATION OF SYSTOLIC EJECTION (t_{ej})

	Observed stroke volume (% of predicted normal value)	Observed t_{ej} (% of predicted normal t_{ej})	Observed ΔP_{sm} (% of ΔP_{sm} required for a normal stroke volume at observed t_{ej})	Observed ΔP_{sm} (% ΔP_{sm} required for a normal stroke volume at predicted normal t_{ej})
	Average values at rest for groups of male patients			
Group Ib (7)	52	145	31	15
Group II (8)	72	140	55	28
Group III (2)	90	119	80	56
Group IV (4)	99	116	103	71
	Results at rest and during exercise in one patient			
Case 35 (at rest)	70	150	43	19
Case 35 (300 kpm./m.)	65	195	45	15
Case 35 (600 kpm./m.)	59	146	39	11

stroke volume (22 ml./l. blood volume*) in equation 1, it is possible, for a given area, to calculate the mean pressure gradient, ΔP_{sm}, necessary for a normal stroke volume at the observed duration of the right ventricular ejection, t_{ej}. If the predicted normal duration of the right ventricular ejection, calculated from equation 2 (Fig. 6), is used instead of the observed duration of the right ventricular ejection, the mean pressure gradient necessary to overcome the obstruction at a normal stroke volume and a normal duration of the systole can be calculated. Such comparisons for mean values of Groups Ib, II, III, and IV (males) at rest and for Case 35 at rest and during exercise are demonstrated in Table VI.

The hypertrophic right ventricle needs a higher

* This does not apply to cyanotic patients who have an abnormally large blood volume (Sjöstrand, 1953).

diastolic pressure to be filled to a normal diastolic volume. To increase the systolic pressure further during work the ventricular filling pressure also must increase as has also been pointed out by Hugenholtz and Nadas (1963) and Lewis *et al.* (1964). The high end-diastolic pressure in the right ventricle should not be regarded as a sign of failure but a prerequisite for the ventricle to overcome the increased outflow resistance caused by the obstruction and to maintain a normal stroke volume. The high end-diastolic pressure in pulmonary stenosis with increased pressure load contrasts with the low end-diastolic pressure in atrial septal defect with increased volume load, in spite of the fact that the stroke work may be of the same magnitude in the two conditions (cf. Jonsson *et al.*, 1957).

Hypertrophy of the right ventricle does not add much to the total heart volume which was in the normal range in most of the patients. The increased right atrial pressure may be associated with increased atrial volume and may therefore cause some heart enlargement. A marked increase in the heart volume, however, must be associated with a large residual volume of the right ventricle. Therefore, the stroke volume is small in relation to heart volume in patients with tight stenosis (Table III). In 6 patients the heart was considerably enlarged. The patient with the largest heart (Case 13) had the highest diastolic pressure in the right ventricle at rest. None had clinical signs of heart failure.

Decreased arterial oxygen saturation was present in 11 patients, during exercise only in 4, and at rest in 7. Only 3 patients with very severe pulmonary stenosis (Cases 7, 9, and 21 of Group Ia) had a marked arterial hypoxæmia ($<85\%$) and a comparatively high hæmoglobin concentration and high total amount of hæmoglobin. Only Case 9 had a high cardiac output in the systemic circulation during exercise. The others had an abnormally low cardiac output in the systemic circulation. The decreased arterial oxygen saturation was combined with a marked decrease of the saturation in the mixed venous blood. This, together with the polycythæmia, resulted in a larger than normal arterio-venous oxygen difference in the systemic circulation.

In pulmonary stenosis and in atrial septal defect, the right ventricle has to perform an increased "pressure work" and an increased "volume work", respectively. Only in the latter instance is the heart regularly enlarged (Jonsson *et al.*, 1957). However, the physical fitness of the two types of patients seems to vary widely and is independent of the degree of primary hæmodynamic disturbance, i.e. the increase in resistance through the right ventricular outflow in pulmonary stenosis or the magnitude of the shunt in atrial septal defect. The functional compensation in these patients with a congenital pulmonary stenosis is evidently better than in patients with an acquired obstruction of the pulmonary artery (Ehrner, Garlind, and Linderholm, 1959).

In atrial septal defect the cardiac function is deteriorating with increasing age (Jonsson *et al.*, 1957). In pulmonary stenosis the same might occur. In the present material there were only 5 patients with severe stenosis (Groups I and II) over the age of 40 years, but all with a well-compensated heart function. The long-term prognosis cannot be evaluated from our data, but it is evident that at least some patients are able to maintain an efficient cardiac function to a relatively old age. This is in agreement with the experience of other writers (Engle, Ito, and Goldberg, 1964).

Without cardiac catheterization measuring cardiac output and pressures simultaneously, it is difficult to evaluate the severity of pulmonary stenosis. A low physical working capacity (in relation to total amount of hæmoglobin and heart volume) and a large heart volume (in relation to total amount of hæmoglobin or body weight) indicates that several compensating mechanisms have been utilized but not sufficiently to maintain a normal functional capacity.

Summary

Patients with pulmonary stenosis of varying degrees were studied at rest and during exercise. The physical working capacity was below the average for normal subjects, particularly in patients with a severe stenosis (Group I: calculated area of the right ventricular outflow tract of less than 0·33 $cm.^2$ $m.^2$ body surface area). In most of these Group I subjects the physical working capacity was low in relation to total amount of hæmoglobin and also to heart volume, but in a few it was in the normal range. The cardiac output in relation to O_2 uptake, and the stroke volume in relation to blood volume and heart volume, were below the normal, and the increase in right ventricular systolic pressure during exercise in relation to increase in cardiac output was the highest. In less severe stenosis, conditions more or less approached the normal state. In the whole group studied the working capacity was fairly closely correlated with the stroke volume, but less closely with the right ventricular outflow area or the right ventricular systolic pressure at rest.

The hæmodynamic changes were discussed with regard to the mechanisms of maintaining a sufficient circulation in spite of the stenosis. The obstruction

was more or less compensated by a high right ventricular systolic pressure. Maximal right ventricular systolic pressures of 220 and 240 mm. Hg were recorded at rest and during exercise, respectively. It is unlikely that much higher pressures can be generated even by a severely hypertrophied right ventricle; so that this compensatory mechanism has its limit. The systolic pressure rise is insufficient to give a normal stroke volume in most patients with a high grade stenosis, particularly during exercise. A prolonged duration of systole was observed in most of the pulmonary stenosis patients and helped to compensate for the impeded ejection of the right ventricular stroke volume. A high right ventricular filling pressure, increasing during work, was also regarded as a compensatory mechanism and a prerequisite for the ventricle to maintain a normal stroke volume. A conspicuous increase in the heart volume, probably due to an increased residual volume of the right ventricle and the enlarged right atrium, was found among the patients with severe stenosis. In most of the patients the heart volume was normal or only slightly increased in relation to the total amount of hæmoglobin.

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