Haemodynamic Effects of Exercise in Isolated Pulmonary Stenosis Before and After Surgery

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Surgical treatment of pulmonary stenosis has frequently been evaluated by the reduction of pressure gradient across the valve. In only a few patients, however, have exercise tolerance and haemodynamic response to muscular work been reported both before and after operation. Johnson (1962) compared the findings in 7 patients after pulmonary valvotomy with those in 8 patients without operation. A decreased cardiac output during exercise was common to both groups. Because of differences between patients in such a group it seems preferable to study the same patient before and after operation.

Ikkos, Jonsson, and Linderholm (1966) reported the circulatory response to exercise in patients with pulmonary stenosis. Some of these patients have now been re-examined after operation and a comparison of their pre- and post-operative working capacity and haemodynamic findings constitutes this report.

SUBJECTS AND METHODS

All adult patients with pulmonary stenosis and intact ventricular septum who were investigated before operation at this laboratory and operated on between 1957 and 1964 have been readmitted to hospital 9 months or more after the operations, which were performed in the Department of Surgery, Thoracic Clinic, Karolinska Sjukhuset, either under hypothermia or with extracorporeal circulation. Patients operated on before 1957 were excluded from this study except for one (Case 17) who had an isolated infundibular pulmonary stenosis corrected in 1953. Of the remaining 16 patients, 12 had pulmonary valvotomy through the pulmonary artery, and 4 (Cases 3, 9, 13, and 15) had, in addition, resection of infundibular stenosis through a ventriculotomy incision.

The patients were divided into two groups. Group A (Cases 1-9) comprised those patients without an associ-

ated atrial septal defect; Group B (Cases 10-17) were those with either an atrial septal defect or a patent foramen ovale in addition to their pulmonary valvular lesion.

Such defects were not closed at operation. All patients were examined both at rest and during exercise at post-operative cardiac catheterization, though 5 patients were studied only at rest during their pre-operative examination. However, an exercise tolerance test was carried out in all patients both before and after operation.

The methods used were those described in an earlier report (Ikkos *et al.*, 1966). All blood gas analyses, except for 4 patients, were done with the spectrophotometric method which gave a normal arterial oxygen saturation of 98 per cent (95-100%). Blood gases were measured by the Van Slyke method in Cases 14 to 17. When patients had arterial desaturation, the pulmonary flow was calculated by assuming that the pulmonary venous saturation was 98 per cent. In calculating the systemic flow in the presence of a left-to-right shunt at the atrial level, the blood in the superior vena cava was accepted as a representative sample of the mixed venous blood. In such patients systemic flow could not be calculated during exercise as it was not certain whether the left-to-right shunt existed during exercise. Those patients with a left-to-right shunt at rest who developed arterial desaturation during exercise are designated (+) in Table IIB. When the shunt was only from right to left at rest it was assumed that no left-to-right shunt developed during exercise. The same assumption was also made if no shunt was found at rest and a right-to-left shunt appeared during exercise. All patients had normal lungs by radiological examination and spirometry.

Exercise tolerance tests were carried out according to the method previously described (Ikkos *et al.*, 1966). All patients continued graded exercise to reach a heart rate of about 170 beats a minute and their physical working capacity was estimated at this level of exercise (PWC 170).

RESULTS

Age, sex, body size, heart volume, physical working capacity, and the type of cardiac malformation

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TABLE I

BODY SIZE, HEART VOLUME, AND PHYSICAL WORKING CAPACITY BEFORE AND AFTER OPERATION

Case No.	Age at operation (yr.)	Sex	Interval between operation and examination (mth.)	Height (cm.)	Weight (kg.)	B.S.A. (m. ²)	Heart vol. (ml.)	Working capacity (kpm/min.)	Type of heart malformation
1	20	M	Pre-op.	170	75	1.86	800	750	Valve stenosis
			14 Post-op.	171	71	1.84	830	825	
			57 Post-op.	172	70	1.82	770	840	
2	27	F	Pre-op.	167	57	1.66	625	500	Valve stenosis
			10 Post-op.	168	58	1.67	710	420	
3	25	M	Pre-op.	172	64	1.75	1600	450	Valve and infundibular stenosis
			10 Post-op.	172	66	1.79	1020	580	
			24 Post-op.	172	66	1.79	—	580	
			36 Post-op.	172	73	—	760	590	
4	28	F	Pre-op.	159	59	1.60	760	400	Valve stenosis
			30 Post-op.	159	55	1.56	860	570	
5	33	M	Pre-op.	172	75	1.78	950	900	Valve stenosis
			16 Post-op.	172	77	1.90	1100	900	
6	39	F	Pre-op.	153	56	1.53	1000	625	Valve stenosis
			10 Post-op.	154	53	1.50	920	670	
			41 Post-op.	153	54	1.49	900	600	
7	51	F	Pre-op.	165	66	1.72	1120	450	Valve stenosis
			17 Post-op.	166	64	1.72	880	510	
			29 Post-op.	165	64	1.70	950	500	
8	55	M	Pre-op.	163	76	1.81	800	660	Valve stenosis
			14 Post-op.	162	69	1.73	1000	690	
9	38	M	Pre-op.	176	79	1.96	1220	750	Valve stenosis
			65 Post-op.	176	78	1.94	1150	900	
10	15	F	Pre-op.	142	38	1.22	510	250	Valve stenosis; intra-atrial communication
			9 Post-op.	144	43	1.29	510	450	
			36 Post-op.	149	51	1.42	705	550	
11	19	M	Pre-op.	187	76	2.04	785	600	Valve stenosis; intra-atrial communication
			9 Post-op.	192	86	2.18	880	660	
12	20	M	Pre-op.	178	58	1.76	1570	500	Valve stenosis; intra-atrial communication; abnormal pulmonary venous return
			36 Post-op.	180	68	1.88	1070	1350	
13	22	F	Pre-op.	144	45	1.32	500	450	Valve and infundibular stenosis; intra-atrial communication
			9 Post-op.	143	41	1.26	581	400	
14	24	M	Pre-op.	181	65	1.85	1220	500	Valve stenosis; intra-atrial communication
			91 Post-op.	181	71	1.95	1240	840	
15	31	F	Pre-op.	159	58	1.60	710	450	Valve stenosis; intra-atrial communication
			30 Post-op.	159	56	1.58	915	550	
16	36	M	Pre-op.	170	49	1.57	638	400	Valve stenosis; intra-atrial communication
			15 Post-op.	170	52	1.61	680	450	
17	29	M	Pre-op.	174	65	1.79	860	600	Infundibular stenosis; intra-atrial communication
			135 Post-op.	175	82	1.98	850	800	

are listed in Table I and the findings at heart catheterization in Table II. At the final post-operative study the *right ventricular systolic pressure* at rest was between 52 and 71 mm. Hg in 5 patients and below 40 mm. Hg in the others. The estimated *pulmonary valve area* increased considerably after operation. The average valve area was 0.3 cm.²/m.² B.S.A. before operation and 1.2 cm.²/m.² B.S.A. after operation. Post-operatively, it was more than 1 cm.²/m.² B.S.A. in 11 and between

0.49 and 0.97 cm.²/m.² B.S.A. in the remaining 6 patients.

The *right ventricular end-diastolic pressure* decreased significantly after operation in Group A, but the change was less in Group B (Fig. 1 and Table III). The rise in end-diastolic pressure during exercise was less conspicuous following operation. In all 17 patients studied after operation this pressure was measured during exercise and in only 4 was it more than 10 mm. Hg (highest

TABLE IIA
RESULTS OF HEART CATHETERIZATION IN 9 PATIENTS WITH INTACT ATRIAL SEPTUM

Case and cathet. No.	Interval between op. and cath. (mth.)	Work load (kpm/min.)	Pulse rate (beats/min.)	Oxygen uptake (ml./min.)	Art. O ₂ -sat. (%)	AV-O ₂ diff. (ml./l.)	Cardiac output (l./min.)	Stroke volume (m.)	Pressures (mm. Hg)									Duration of rt. vent. systole (% cardiac cycle)	Rt. vent. outflow (cm. ³ /m. ² B.S.A.)
									Rt. atr.	Rt. ventr.		Pulm. artery			Aorta				
										Syst.	End-diast.	Syst.	Diast.	Mean	Syst.	Diast.	Mean		
1 62/59	Pre	Rest 250	70 118	277 928	99 98	46 92	6.0 10.1	86 85	—	111	9	15	5	—	145	73	—	51	0.33
147/61	14	500	152	1362	97	110	12.4	81	—	—	—	—	—	—	167	70	—	39	0.81
75/65	57	Rest	64	262	97	46	56.7	89	7	49	8	16	6	14	119	67	89	39	1.02
		700	151	1726	96	117	14.7	98	7	73	3	19	7	14	185	79	116		
		Rest	62	248	100	46	5.4	87	4	37	5	14	5	9	111	67	87		
		400	100	1119	98	104	10.8	108	—	42	3	31	9	18	144	76	104		
800	163	1988	97	119	16.7	103	—	76	10	39	7	19	174	87	121				
2 31/62	Pre	Rest	64	282	99	40	7.0	109	11	84	10	18	8	11	132	77	—	50	0.53
9/63	10	300	130	963	96	82	11.7	90	10	131	17	—	—	10	156	68	—	48	1.24
		Rest	71	229	98	33	7.0	98	6	32	5	16	5	13	124	74	98		
		300	138	865	99	75	11.6	84	7	67	3	20	5	12	160	83	110		
3 171/58	Pre	Rest	74	250	99	93	2.7	37	12	167	19	—	—	13	116	74	87	55	0.13
120/59	10	250	119	841	99	104	8.1	69	10	63	9	25	12	19	105	68	83	52	0.40
		Rest	74	255	96	52	4.9	67	—	—	—	—	—	—	—	—	—		
		500	169	1257	99	139	9.1	54	—	130	6	31	13	24	158	81	103		
		Rest	71	245	95	38	6.4	90	9	164	5	45	7	24	187	87	113		
104/60	24	Rest	75	251	98	46	5.4	72	—	56	6	20	7	18	—	—	—	51	0.60
173/61	36	Rest	120	1089	100	110	9.9	83	—	52	10	25	11	17	128	78	97		
		400	175	1251	98	110	9.9	83	—	52	10	25	11	17	128	78	97		
4 69/61	Pre	Rest	64	181	99	54	3.3	52	13	142	14	22	9	—	122	77	96	48	0.20
205/64	30	150	108	502	98	97	5.2	45	—	178	15	26	7	—	128	77	94	42	1.27
		300	154	684	98	119	5.6	37	—	185	20	26	9	—	122	82	100		
		Rest	62	195	100	61	3.22	52	12	23	4	17	7	12	122	83	105		
		250	115	803	99	115	6.98	61	—	36	6	25	7	13	137	76	107		
		500	168	1277	98	135	9.45	56	—	40	3	26	9	16	134	88	111		
5 145/61	Pre	Rest	85	350	98	50	7.0	82	5	82	6	19	7	14	119	74	91	54	0.63
10/63	16	400	111	1141	97	94	12.2	110	—	112	12	27	8	16	147	78	105	46	0.97
		800	149	1835	98	115	16.0	107	—	159	9	26	2	18	186	81	116		
		Rest	69	283	96	49	5.8	84	6	35	6	18	9	13	126	79	98		
		400	97	1016	98	98	10.4	107	—	61	11	30	12	21	154	83	108		
		800	135	1680	95	112	15.0	111	—	81	5	32	13	18	171	80			
6 124/62	Pre	Rest	60	254	95	46	5.6	58	7	125	8	20	11	14	—	—	—	54	0.33
28/65	41	400	69	240	99	42	5.7	83	5	60	6	21	7	13	137	64	86	46	1.13
		Rest	130	1065	97	103	10.4	80	—	90	17	40	12	24	162	71	114		
		400	79	278	99	43	6.5	82	2	29	2	9	3	5	136	72	95		
		300	110	890	99	98	9.1	82	9	62	12	26	12	18	171	84	129		
7 4/62	Pre	Rest	60	255	97	60	4.2	70	12	156	11	20	11	10	134	72	96	56	0.22
68/64	17	350	139	1044	100	131	8.0	57	—	—	—	29	8	20	163	82	115	51	0.49
		Rest	—	—	—	—	—	—	4	76	3	16	6	12	144	79	105		
		300	125	874	98	118	7.1	59	—	133	8	28	14	19	179	89	131		
		450	144	1112	100	134	8.3	58	—	141	7	28	13	19	180	93	124		
		Rest	58	261	100	53	4.9	83	9	62	7	24	4	10	146	85	112		
8 72/64	Pre	Rest	74	276	99	58	4.8	64	—	70	3	23	8	17	150	84	117	47	0.40
119/65	14	600	148	1288	97	121	10.7	72	—	120	18	25	18	22	205	103	140	51	1.71
		Rest	73	288	96	55	5.2	71	—	29	2	24	8	14	138	81	105		
		600	143	1525	98	138	11.0	77	—	50	12	48	27	35	223	121	167		
9 122/59	Pre	Rest	70	311	97	55	5.7	81	7	134	15	17	10	—	128	69	86	54	0.30
83/65	5 yr.	Rest	83	383	100	53	7.3	87	4	38	6	22	3	12	112	67	85	51	0.79
		400	124	1347	96	117	11.5	93	—	—	—	29	8	17	162	84	113		
		800	160	2311	95	149	15.5	97	—	98	11	44	6	20	164	83	112		

The reference level for zero pressure was taken as 5 cm. below the insertion of the fourth rib at the sternum with the patient in recumbent position.

TABLE IIB

RESULTS OF HEART CATHETERIZATION IN 8 PATIENTS WITH INTRA-ATRIAL COMMUNICATION

Case No. and Cathet. No.	Interval between op. and cath. (mth.)	Work load (kpm/min.)	Pulse rate (beats/min.)	Oxygen uptake (ml./min.)	Art. O ₂ -sat. (%)	AV-O ₂ diff. (ml./l.)		Cardiac output (l./min.)		Stroke vol. (ml.)		Right-to-left shunt (% of system. flow)	Left-to-right shunt (% of pulm. flow)	Pressures (mm. Hg)												Duration of rt. vent. systole (% cardiac cycle)	Rt. vent. outflow area (cm. ² /m. ² B.S.A.)
						System. circ.	Pulm. circ.	System. circ.	Pulm. circ.	System. circ.	Pulm. circ.			Rt. atr.	Rt. vent.		Pulm. artery			Aorta							
															Syst.	End dist.	Syst.	Diast.	Mean	Syst.	Diast.	Mean					
10 84/60 38/61	Pre 9	Rest 300	98 84	245 185	81 91	28 42	65 34	8.9 4.4	3.8 5.4	91 53	38 66	57 20	0 35	4 6	76 30	2 2	17 27	4 8	8 13	83 115	45 75	67 97	72	0.31			
108/63	36	Rest 400	136 136	1110 1110	87 84	33 75	23 75	8.2 11.7	14.8 14.8	100 142	109 109	0 +	30 +	5 8	29 57	4 1	25 32	5 14	11 20	118 147	77 79	94 105	50	3.20			
11 34/63	Pre 9	Rest 1000	100 196	302 2166	98 88	37 118	37 140	8.2 18.4	8.2 15.6	82 94	82 80	0 15	0 0	— —	96 176	3 14	16 29	1 8	4 21	133 210	81 91	—	60	0.41			
15/65		Rest 400	82 133	329 1295	99 98	33 86	33 86	10.0 15.0	10.0 15.0	122 113	122 113	0 0	0 0	4 —	33 78	4 25	13 6	7 18	10 17	142 172	82 82	101 112	52	1.07			
12 118/60	Pre 36	Rest 300	68 121	279 948	91 80	73 137	92 82	3.8 6.9	3.0 5.2	56 43	45 25	21 25	0 0	8 17	164 192	14 35	10 —	0 —	— —	114 159	70 78	84 91	55	0.16			
95/63		Rest 600	65 108	419 1726	98 96	44 —	33 81	9.6 —	12.6 21.3	147 —	195 197	0 0	24 —	9 —	71 120	7 10	17 22	5 9	10 16	120 169	71 87	91 125	45	1.04			
13 91/61 67/62	Pre 9	Rest 300	88 131	202 723	97 92	48 74	48 85	4.2 9.8	4.2 8.5	48 77	48 65	0 13	0 0	— —	132 36	8 7	16 19	5 9	10 17	145 135	86 87	116 115	66 54	0.21 1.19			
14 22/57	Pre 7 yr.	Rest 200	84 123	332 764	83 58	50 62	86 169	6.7 10.6	3.9 4.5	80 86	46 37	42 58	0 0	— —	146 —	12 —	12 15	4 3	7 7	145 157	87 84	—	62	0.15			
245/64		Rest 400	165 71	1096 311	40 97	74 49	62 35	17.2 6.4	5.0 8.8	104 90	30 124	71 0	0 27	— 10	— 35	— 5	22 19	0 4	13 11	187 142	89 88	116 137	45	1.33			
15 185/60	Pre 30	Rest 200	86 151	228 916	94 86	42 68	38 93	5.4 13.5	6.0 9.9	63 60	70 65	20 18	28 26	5 5	126 178	10 17	15 29	6 2	— 9	114 163	69 90	91 118	54	0.35			
101/63		Rest 400	65 136	245 1245	94 92	43 —	38 83	5.7 —	6.5 15.0	88 —	99 111	18 +	— —	— —	44 —	4 —	32 —	11 21	21 159	85 115	115 115	45	2.64				
16 198/60	Pre 15	Rest 300	60 138	223 946	95 80	57 97	57 131	3.9 9.8	3.9 7.2	65 71	65 52	0 27	0 0	7 5	158 228	12 21	— —	— 11	10 13	130 168	67 82	97 114	43	0.24			
36/63		Rest 350	65 137	226 941	96 89	51 98	51 114	4.4 9.6	4.4 8.2	78 70	68 60	0 15	0 0	— —	55 94	8 16	19 39	11 9	13 133	125 133	73 69	84 93	45	0.52			
17 28/53	Pre 10 yr.	Rest Work	95 150	158 776	90 87	49 107	68 107	3.2 9.5	2.3 7.4	34 63	24 84	28 49	0 22	— 5	125 206	— 11	19 17	9 1	15 0	— 130	— 90	— 110	63	0.16			
109/64		Rest 600	168 1499	303 1499	98 98	104 104	104 104	14.4 14.4	14.4 14.4	86 86	86 86	0 0	0 0	3 3	141 141	10 10	26 26	3 3	0 0	168 168	95 95	130 130	52	0.79			

value being 16 mm. Hg). Of 8 patients studied in this respect before operation, it was 14 mm. Hg or more in all but one patient (highest value being 33 mm. Hg). The duration of *right ventricular systole*, measured from the beginning of isometric contraction to the end of relaxation and expressed as a proportion of the cardiac cycle, decreased after operation in both groups (Table III).

The average *resting right ventricular stroke volume* increased by 8.5 ml. in Group A and 61.6 ml. in Group B following operation (Table III). Only the latter difference was significant. In accord with

this observation, the *arteriovenous oxygen difference* in the pulmonary circulation did not change after operation in Group A but was much reduced in Group B (from 61 ml./l. to 37 ml./l.). On the other hand, the resting *arteriovenous oxygen difference* in the systemic circulation did not alter significantly after operation in either group, which means that the systemic output was unchanged.

During exercise, the *right ventricular stroke volume* in Group B was 54 ml. before and 104 ml. after operation. *Cardiac output during exercise* was determined before and after operation in 6 patients of

FIG. 1.—End-diastolic pressure in the right ventricle in relation to the stroke volume before and after operation in patients (A) without and (B) with an intra-atrial communication.

Group A. In 3 patients of Group B systemic flow during exercise could not be calculated because of a bidirectional shunt at rest. In most cases the cardiac output was low in relation to the oxygen uptake before as well as after operation (Fig. 2).

An *interatrial shunt before operation* was found in 7 of the 8 patients belonging to Group B. In 5 (Cases 10, 12, 14, 15, and 17) a right-to-left shunt was present at rest, on average amounting to 34 per

cent of the systemic flow. In one of these (Case 15) a left-to-right shunt was also present. In 2 patients (Cases 11 and 16) a right-to-left shunt was demonstrated only during exercise. One (Case 13) was not exercised during his pre-operative investigation; a small right-to-left shunt (13%) was detected during exercise after operation.

Following operation a right-to-left shunt at rest disappeared in 4 out of 5 patients in whom such a

TABLE III
HAEMODYNAMIC DATA BEFORE AND AT LATEST POST-OPERATIVE EXAMINATION

	PWC ₁₇₀ (kpm/min.)	Heart vol. (ml.)	Stroke vol. (ml.)	AV-O ₂ diff. (ml./l.)	Rt. vent. end-diast. (mm. Hg)	Rt. vent. syst. duration (% cardiac cycle)
<i>Group A</i>						
Pre-operative	609	986	71.0	55.8	10.5	52.1
SD	171	296	21.3	15.4	4.9	3.2
Post-operative	668	911	79.5	48.8	5.2	45.2
SD	176	153	13.1	8.1	2.5	4.3
Difference, pre- and post-operative	-58	75	-8.5	7.0	5.3	6.9
SD of difference	86	312	137.9	15.6	3.5	3.8
No. of cases	9	9	9	9	9	9
Probability	> 0.05	> 0.4	> 0.8	> 0.2	< 0.01 > 0.001	< 0.001
<i>Group B</i>						
Pre-operative	469	849	52.3	48.0	8.7	59.4
SD	113	371	18.8	13.5	4.6	8.8
Post-operative	700	865	113.9	41.5	5.7	48.5
SD	305	216	41.6	6.6	1.5	3.9
Difference, pre- and post-operative	-231	-16	-61.6	6.5	3.0	10.9
SD of difference	283	222	47.7	10.3	3.6	7.0
No. of cases	8	8	8	8	7	8
Probability	> 0.05	> 0.8	< 0.01 > 0.001	> 0.1	> 0.05	< 0.01 > 0.001

shunt had been present. In 1 patient who had a bidirectional shunt before operation (Case 15) a small right-to-left shunt (18%) remained. A left-to-right shunt (mean 28%) was demonstrated in 4 patients. Three of these patients (Cases 10, 12, and 14) showed no evidence of this shunt before operation. Comparison of the right-to-left shunt before and after operation, during exercise, was not possible since systemic flow during exercise could not be calculated in patients with a left-to-right shunt at rest.

In Group B the mean arterial oxygen saturation at rest was 91 per cent before and 97 per cent after operation. During exercise, the mean arterial oxygen saturation was 77 per cent before and 93 per cent after operation, indicating that the right-to-left shunt during exercise was much reduced after operation. This occurred in spite of the exercise being somewhat more severe during the post-operative investigation (Table II).

The mean physical working capacity was 609 kpm/min. before and 668 kpm/min. after operation in Group A and the corresponding values for Group B were 469 and 700 kpm/min. These differences were not statistically significant (Table III). The larger difference in Group B results mainly from a large rise in one patient (Case 9) and a moderate rise in two others (Cases 10 and 14). The average heart volume did not change significantly after operation (Table III). However, in only 2 patients were the hearts much enlarged before operation. Case 3, with the highest resting right ventricular systolic and end-diastolic pressures, had a heart volume of 1600 ml. before operation and a normal volume of 760 ml. three years after operation. In another patient (Case 12), who also had a markedly increased right ventricular systolic pressure, the heart volume decreased from 1570 to 1070 ml. three years after operation. This figure was normal in relation to his post-operative physical working capacity.

DISCUSSION

The oxygen transport capacity (aerobic working capacity) is a function of the stroke volume (SV), arteriovenous oxygen difference (AVD), and heart rate (f), as expressed in Fick's equation: $Vo_2 = f \times SV \times AVD$. Therefore, for a given heart rate during exercise the working capacity depends on the stroke volume and the arteriovenous oxygen difference, i.e. oxygen pulse. In patients with severe valvular heart disease with a resultant small stroke volume, such as found in tight mitral, pulmonary, or aortic stenosis (Granath, 1965; Ikkos *et al.*, 1966; Lee *et al.*, 1967), a large arteriovenous oxygen difference is found. This observation has

FIG. 2.—Cardiac output in relation to oxygen uptake during exercise before and after operation in 6 patients in Group A. The continuous and broken lines indicate the regression line $\pm$ and two standard errors of estimate, respectively, in normal subjects (calculated from data published by Bevegård, Holmgren, and Jonsson, 1960; Holmgren, Jonsson, and Sjöstrand, 1960).

also been made in complete atrioventricular block with normal or increased stroke volume but low cardiac output (Bevegård *et al.*, 1967). Thus a high arteriovenous oxygen difference is an adaptation in order to maintain an oxygen transport in situations where cardiac output is reduced. A similar adaptation is also found during intensive physical training (Åstrand *et al.*, 1965; Andrew, Guzman, and Becklake, 1966; Holmgren *et al.*, 1957).

Because of these phenomena, the physical working capacity was normal in spite of the low stroke volume during exercise in most patients in Group A before operation, and showed no increase after operation. However, in patients in Group B in whom a right-to-left shunt was present at rest as well as during exercise, resulting in reduced arterial oxygen content, a low working capacity was present before operation and an increase was found after operation. This was mainly due to the change in arterial oxygen saturation during exercise from 77 before to 93 per cent after operation.

This study has confirmed the persistence of a low cardiac output during exercise following pulmonary valvotomy, as reported by Johnson (1962). It has been suggested (Johnson, 1962; McIntosh and Cohen, 1963) that the low cardiac output after pulmonary valvotomy is due to a persistent myocardial fibrosis and a consequent resistance to right ventricular filling. This was not, however, the finding

in the present study because the right ventricular end-diastolic pressure decreased considerably after operation. Further evidence against this arises from our observation that right-to-left interatrial shunts before operation changed in direction and became left-to-right shunts after operation, with an increase in right ventricular stroke volume and the right ventricular systolic duration shortened.

If one accepts the theory that cardiac output is primarily regulated to supply the tissue oxygen requirement (Guyton, 1963), the increased peripheral oxygen extraction may be interpreted as an adaptational phenomenon in patients unable to maintain a normal cardiac output and the adaptation persists after operation. This is in agreement with the observation made in some patients with tight mitral stenosis who did not show any increase in cardiac output following successful mitral commissurotomy (Granath, 1965; Donald *et al.*, 1957).

The limiting factor for restoring a normal cardiac output after operation may be the size of the left ventricle which is expected to be small as the pulmonary stenosis has been present since birth. From this study it is evident that in cases with an intra-atrial communication the right ventricle is able to increase its stroke volume after the stenosis is relieved. However, the left ventricle must also increase its stroke volume and this may be possible only by intensive physical training, giving rise to periods with a high left ventricular filling pressure.

SUMMARY

Seventeen patients with pulmonary stenosis and an intact ventricular septum were studied before and after operation. Nine patients had an intact atrial septum and 8 had an interatrial shunt. The physical working capacity and the haemodynamic effects of exercise were examined. A low cardiac output during exercise in relation to the oxygen uptake persisted after operation. This did not appear to be the result of irreversible damage of the right ventricular myocardium because the ventricular end-diastolic pressure decreased considerably, the duration of systole shortened, and a rise in right ventricular stroke volume at rest and during exercise was demonstrated in those patients with interatrial shunts.

It was concluded that the tendency for low cardiac output during exercise after operation was a result of an adaptation of peripheral circulation, from early childhood, resulting in the ability to extract and utilize oxygen to a greater degree. Once such an adaptation has occurred there may be no necessity to increase cardiac output to meet the demand for oxygen transport. The importance of a persisting small left ventricle is discussed.

An appreciable increase of the physical working capacity was shown only in those patients who had a right-to-left shunt before operation. This was attributed to the increased arterial oxygen saturation during exercise, as a result of the diminished right-to-left shunt at the atrial level after operation. The considerable reduction in the right ventricular end-diastolic pressure was apparently responsible for the decreased right-to-left shunt. In patients without an interatrial shunt, physical working capacity was generally normal before operation and did not change after operation. The normal working capacity in the presence of reduced stroke volume during exercise was possible because of the widened arteriovenous oxygen difference.

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