Haemodynamic studies at rest and during exercise in pulmonary stenosis after surgery

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Fourteen patients with pulmonary stenosis had circulatory studies performed 1 to 14 years after operation. Preoperatively, the mean right ventricular systolic pressure was 105 mmHg (SD=25). After operation the mean right ventricular systolic pressure for the group was 31 mmHg (SD=7), and during exercise it increased to 46 mmHg (SD=6). The mean pulmonary systolic gradient before operation was 88 mmHg (SD=21) and after operation it was 11 mmHg (SD=2). The mean cardiac index at rest was 4.0 l./min per m² (SD=0.9) and it increased to 7.1 l./min per m² (SD=1.0) on exercise. The relation between oxygen consumption and cardiac output during exercise was normal in all patients.

The results of this study indicate that a normal cardiac output response to exercise may be regularly achieved after successful surgical treatment of pulmonary stenosis.

Although it is widely believed that pulmonary valvotomy is a successful operation, the only two postoperative haemodynamic studies have shown persistent abnormalities in a high proportion of patients. It was found by Johnson (1962) that 7 of the 17 patients studied had an abnormal cardiac output response during exercise. The other postoperative study (Jonsson and Lee, 1968) showed that 4 of the 9 patients investigated had an impaired cardiac output response during exercise. Several possible mechanisms have been proposed to explain the abnormal postoperative haemodynamics. It has been suggested that the tendency for a low cardiac output during exercise after operation was due to an adaptation of the peripheral circulation which allowed greater extraction and utilization of oxygen (Jonsson and Lee, 1968). A more likely explanation is that increased resistance to right ventricular filling caused by myocardial fibrosis was the most important factor (Johnson, 1962). The presence of patchy myocardial fibrosis has been shown in patients with pulmonary stenosis (Allanby and Campbell, 1949).

Investigation of patients with pulmonary stenosis before operation (Dow *et al.*, 1950; Lewis *et al.*, 1964; Howitt, 1966; Ikkos, Jonsson and Linderholm, 1966; Moller, Rao, and Lucas, 1972) has shown that, in general, patients with mild and moderate stenosis had normal exercise haemo-

dynamics. However, many patients with severe pulmonary stenosis had an impaired cardiac output response during exercise. Some of the patients investigated postoperatively by Johnson had moderate to severe residual pulmonary stenosis (Johnson, 1962) and 3 of the patients studied by Jonsson and Lee (1968) had moderate residual stenosis. It is possible, therefore, that adequate surgical relief of the pulmonary stenosis with consequent reduction in ventricular hypertrophy and increased ventricular compliance could result in normal exercise haemodynamics. The present study examines the postoperative haemodynamics in 14 patients who had moderate to severe pulmonary stenosis preoperatively. Every patient was shown to have a normal cardiac output response during exercise.

Patients and methods

Fourteen patients, 6 male and 8 female, were investigated 1 to 14 years (mean 7 years) after operation for pulmonary stenosis with intact ventricular septum. All the patients were asymptomatic at the time of investigation and were selected only on the basis of their willingness to participate in the study.

Preoperative clinical and haemodynamic data are shown in Table 1. Open pulmonary valvotomy was performed in 12 patients on cardiopulmonary bypass. Infundibular resection alone for anatomical infundibular stenosis was done on Cases 3 and 6. Cases 5 and 10 had resection of anatomical infundibular stenosis as well as pulmonary valvotomy. Cases 2 and 10 had small ostium secundum atrial septal defects which were closed.

TABLE 1 *Preoperative clinical and haemodynamic data*

Case No.	Sex	Age at operation (yr)	Right ventricular pressure (mmHg)	Pulmonary arterial pressure (mmHg)	Pulmonary-right ventricular systolic gradient (mmHg)
1	F	14	160/10	35/-	125
2	M	6	80/2	22/-	58
3	F	5	105/5	10/7	95
4	F	14	115/10	28/12	87
5	M	8	105/5	15/-	90
6	F	6	90/10	—	—
7	M	6	100/10	10/-	90
8	F	13	—	—	—
9	F	9	85/8	24/7	61
10	M	9	130/0	25/5	105
11	M	9	108/0	18/5	90
12	M	6	—	—	—
13	M	49	66/5	10/5	56
14	F	15	120/5	16/8	104

Preoperatively the right ventricular systolic pressure exceeded 80 mmHg in 11 patients. According to the criteria of Wood (1956), 8 patients had severe pulmonary stenosis (right ventricular systolic pressure > 100 mmHg) and 4 were moderate (right ventricular systolic pressure > 50 mmHg); Case 12 was not catheterized before operation but his electrocardiogram showed grade 4 right ventricular hypertrophy. Preoperative data on Case 8 were unobtainable.

Before operation the electrocardiograms of 6 patients showed grade 4 right ventricular hypertrophy (Goodwin and Abidin, 1959), 1 had grade 3, 5 had grade 2, and 1 showed no evidence of right ventricular hypertrophy. At the time of postoperative study 6 patients had normal electrocardiograms, 1 patient had grade 4, and 1 patient

grade 2 right ventricular hypertrophy. Six patients showed a right bundle-branch block pattern.

Circulatory studies after operation

Right heart catheterization was performed in the fasting state and the patients were not sedated. A No. 9 double lumen Cournand catheter was passed into the pulmonary artery and the resting pulmonary valve pressure gradient was recorded while withdrawing the catheter to the right ventricle. The pressure gradient during exercise was measured by withdrawing the proximal lumen of the catheter to the right ventricle. The pressures were measured by (Sanborn model 267BC) transducers and recorded on an ultraviolet photographic recorder. The

TABLE 2 *Postoperative haemodynamic data*

Case No.	Right ventricular systolic pressure (mmHg)		Right ventricular end-diastolic pressure (mmHg)		Mean pulmonary arterial pressure (mmHg)		Pulmonary-right ventricular systolic gradient (mmHg)		
	Rest	Exercise	Rest	Exercise	Rest	Exercise	Rest	Exercise	
1	38	55	8	5	14	19	19	32	
2	28	44	2	7	13	20	10	25	
3	25	38	4	3	11	22	6	8	
4	37	44	4	6	15	18	13	14	
5	33	53	4	1	12	13	14	35	
6	40	—	10	—	15	20	16	—	
7	34	42	5	10	13	17	15	19	
8	22	32	3	4	8	10	9	16	
9	39	51	5	4	17	22	13	20	
10	34	54	10	13	16	20	6	11	
11	30	47	7	3	13	20	12	20	
12	19	44	7	8	11	16	5	23	
13	21	50	2	6	8	20	10	22	
14	28	49	1	6	11	20	9	21	
	Mean =	31	46	4·6	5·4	13	18	11	20
	SD =	7	6	3	3	3	3	2	8

pulmonary artery and right ventricular pressures were determined over several respiratory cycles. The right ventricular end-diastolic pressure was measured after the 'a' wave. The reference point for zero pressure was 5 cm below the sternal angle. Cardiac output was measured by the direct Fick method. The oxygen saturation of blood samples from the pulmonary and brachial arteries was determined by a spectrophotometric method. The expired air was collected simultaneously in a Tissot spirometer, and gas samples were analysed for oxygen content by the Scholander micro-method. Measurements were made at rest and during the fifth minute of supine submaximal exercise with a bicycle ergometer.

Results

Right heart pressures (Table 2)

The mean right ventricular systolic pressure at rest was 31 mmHg (SD=7); it increased on exercise to 46 mmHg (SD=6). The mean systolic pressure gradient across the pulmonary valve at rest was 11 mmHg (SD=2) and this increased on exercise to 20 mmHg (SD=8). The individual responses are shown in Fig. 1.

The mean right ventricular end-diastolic pressure at rest was 4.6 mmHg (SD=3); it increased on exercise in 8 patients, and decreased in 5 (Fig. 2). The mean pressure on exercise was 5.4 mmHg (SD=3).

FIG. 1 The pulmonary artery-right ventricular systolic gradient at rest and during exercise.

FIG. 2 The right ventricular end-diastolic pressure at rest and during exercise.

Pulmonary diastolic murmurs were present in 5 patients but the right ventricular end-diastolic pressure did not differ significantly from the mean either at rest or during exercise in these patients, indicating that the degree of pulmonary incompetence present was slight.

Cardiac output (Table 3).

The resting cardiac index was 4.0 l./min per m^2 (SD=0.9), and during exercise it increased to 7.1 l./min per m^2 (SD=1.0). The relation between oxygen consumption and cardiac output during exercise was normal in all patients (Fig. 3).

TABLE 3 Postoperative haemodynamic data

Case No.	Body surface area (m ²)	Heart rate/min		Cardiac index (l./min per m ²)		Oxygen uptake index (ml/min per m ²)		Stroke volume (ml)	
		Rest	Exercise	Rest	Exercise	Rest	Exercise	Rest	Exercise
1	1.59	90	144	4.74	8.61	149	621	84	95
2	1.54	72	141	5.44	9.89	183	735	116	108
3	1.60	72	132	4.74	6.41	191	568	105	78
4	1.48	60	130	3.46	6.63	106	458	53	75
5	1.50	70	125	6.02	7.11	169	784	129	85
6	1.37	68	114	4.07	6.99	163	626	82	84
7	1.83	84	108	3.87	6.50	157	530	84	110
8	1.66	81	144	3.35	6.12	138	537	69	71
9	1.70	87	123	3.71	5.95	98	430	72	82
10	1.16	60	100	3.32	6.73	121	422	60	83
11	1.79	69	117	2.65	6.37	131	616	69	97
12	1.25	90	126	3.65	7.59	179	707	51	75
13	1.97	84	129	3.67	6.57	148	492	86	100
14	1.79	72	144	3.47	7.88	126	674	86	98
Mean =		75	124	4.01	7.10	147	586	82	89
SD =		10	14	0.92	1.04	29	114	23	13

FIG. 3 Relation between cardiac output and oxygen uptake during exercise. The normal regression line and three grades of impairment are also shown (Donald *et al.*, 1955).

Stroke volume (Table 3 and Fig. 4)

The stroke volume rose on exercise in 11 patients and fell in 3. The mean stroke volume at rest was 82 ml (SD=23) and on exercise it increased to 89 ml (SD=13).

Arteriovenous oxygen difference

The mean arteriovenous oxygen difference at rest was 3.3 vol per cent (SD=1.5) and during exercise it increased to 7.3 vol per cent (SD=1.8). The response to exercise (Donald *et al.*, 1955) was normal in all except one patient.

Discussion

Patients with mild pulmonary stenosis have normal exercise haemodynamics (Ayres and Lukas, 1960; Lewis *et al.*, 1964; Howitt, 1966; Moller *et al.*, 1972). In our patients with trivial or mild residual pulmonary stenosis after operation the circulatory responses during exercise were also normal.

These results differ from those of Johnson (1962) who found that the response of the cardiac output during exercise was normal in 10 patients and abnormal in 7. The abnormal results are probably explained by inadequate relief of the pulmonary stenosis because the mean resting right ventricular systolic pressure for the group was 58 mmHg, with a range of 24 to 129 mmHg. The age at operation and therefore the duration of the lesion was also greater in this study than in ours.

The results of operation were better in the group studied by Jonsson and Lee (1968); 6 had mild and 3 had moderate residual pulmonary stenosis. Five patients had a normal cardiac output response during exercise, 3 had grade 2 impairment, and 1 had grade 1 impairment. This group of patients was also older than ours; their mean age at the time of operation was 35 years.

In normal subjects the response of stroke volume to exercise is variable (Donald *et al.*, 1955); it usually increases or remains the same but it may fall. Moller and his colleagues found that patients with mild pulmonary stenosis increased their stroke volume on exercise; when the stenosis was more severe the stroke volume remained constant (Moller *et al.*, 1972). In our study the stroke volume increased in 11 patients (mean increase 17 ml) and fell in 3 (mean fall 26 ml) (Fig. 4). The stroke index

FIG. 4 The stroke volume at rest and during exercise.

increased during exercise in 10 patients and this increase was accompanied by a rise in right ventricular end-diastolic pressure in 7 patients (Fig. 5). The right ventricular end-diastolic pressure normally decreases during exercise, and though the increase in our cases never exceeded 5 mmHg it nevertheless probably indicates impairment of right ventricular compliance caused by persisting muscle hypertrophy or myocardial fibrosis. A major fall in stroke index during exercise occurred in 2 patients but it is unlikely that this was caused by impaired

FIG. 5 Changes in stroke index and right ventricular end-diastolic pressure during exercise.

cardiac contractility because the right ventricular end-diastolic pressure also fell in these patients (Fig. 5).

The cardiac output response during exercise was normal in this group of patients whose residual pulmonary stenosis was mild or trivial. It seems likely that the successful surgical relief of the pulmonary stenosis was the most important factor in achieving this result. More detailed studies of myocardial function are necessary to determine the importance of the impairment of right ventricular compliance.

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