VALVOTOMY AS A CURATIVE OPERATION FOR SIMPLE PULMONARY STENOSIS

BY

MAURICE CAMPBELL

From the Cardiac Department, Guy's Hospital, and the Institute of Cardiology

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Four years ago we reported the results of pulmonary valvotomy in 58 patients with simple pulmonary stenosis (Campbell and Brock, 1955). This, I think, is the best term for pulmonary valvular stenosis with a closed ventricular septum, whether the foramen ovale is unsealed in which case central cyanosis will develop if the stenosis is severe enough, or whether it is sealed in which case there cannot be central cyanosis, however high the right ventricular pressure. We gave our reasons for thinking it was a good operation. As with operation for Fallot's tetralogy, it relieved the symptoms and cyanosis, if these were present. In addition it enabled a large heart to become smaller and right ventricular strain to become less—changes that cannot be expected with Fallot's tetralogy where generally, with the increased activity that is made possible by a successful operation, the size of the heart and the right ventricular strain increase.

We are now reporting the further progress of these patients and of another 18 operated on up to the end of 1956, making 76 in all. There were 13 more acyanotic and only 5 more cyanotic patients, making a total of 46 acyanotic and 30 cyanotic. But our main purpose is to assess the results more critically and to consider how far pulmonary valvotomy for simple stenosis can be considered a curative operation. More patients have been recatheterized, and the significance of the pressure readings taken at operation is now better understood.

At first, results were judged mainly on clinical grounds, and improvement in the size of the heart and in the electrocardiogram were so welcome, and perhaps so unexpected, that they were added as something extra. Now we have tried to assess, mainly by the objective changes, how many patients have improved enough to be regarded as nearly normal. Previously, we had studied the diminution of T inversion across the chest leads, which, even when it had been present from V1 to V4, often disappeared entirely or nearly so: now we are adding the diminution of right ventricular preponderance as shown by the decrease of the size of the R wave in V1 and of the sum of SI and RIII, which are among the reliable measures (Woods, 1952).

Earlier, we excluded one girl with sole infundibular stenosis and thought this was rarely found alone or in combination with valvular stenosis when the ventricular septum was closed, though it so often is with Fallot's tetralogy. Now, however, we have included her and two others operated on since. Apart from true infundibular stenosis, the greatly hypertrophied muscle of the right ventricle often produces infundibular obstruction, sometimes with a large gradient. Campbell and Brock (1955) emphasized that when a gradient remained at the time in spite of a successful valvotomy, recatheterization a year or so later might show that it had become much smaller. The great improvement in some such patients, clinically and in the reduction of right ventricular preponderance and strain, convinced us that such a residual gradient could regress. In retrospect, I am surprised that we did not attribute this to infundibular muscular obstruction rather than "underdevelopment of the valve ring and of the right ventricular outflow tract," for since a necropsy in 1950 I had been impressed by the apparent obstruction that could be caused by the greatly hypertrophied muscle of the right ventricle.

Kirklin *et al.* (1953) had discussed this question, and later in 1955, when the infundibular obstruction had been recognized at operation and sometimes relieved by infundibular resection, Brock (1955 and 1957) described and illustrated this secondary infundibular obstruction after pulmonary valvotomy: he suggested that even incomplete relief of the valvular stenosis might be enough to allow regression of the infundibular obstruction. Johnson (1959) has now studied this question in detail and confirmed this view. He found that in 8 of 10 such cases with full data, the obstruction regressed completely in spite of some residual valvular stenosis, but much less completely if the right ventricular pressure was still as high as 100 mm. after valvotomy. Of his total of 75 cases, 60 are the same as those in this series and 15 have been operated on since in 1957–58.

Results

All but one of these patients were in the group of severe pulmonary stenosis as defined by Wood (1956), for the right ventricular systolic pressure was over 100 mm. Hg in all except one (V79) where it was 90 mm. The largest number fell in the group with pressures between 140 and 159 and the mean of the pressures was 152 mm. There was no great difference between the cyanotic and acyanotic groups, and in both the range was quite wide (see Table I, which includes all who were catheterized except some early patients where only mean pressures were measured).

TABLE I

Range of Right Ventricular Systolic Pressures

Range of R.V. systolic pressure (mm. Hg)	80 to 99	100 to 119	120 to 139	140 to 159	160 to 179	180 to 199	200 and over
Cyanotic patients	—	3	5	5	3	2	1
Acyanotic patients	1	9	8	12	7	2	1
Total	1	12	13	17	10	4	2

Most of these patients were operated on by the transventricular route, though some more recent ones have had open operations under hypothermia (see p. 426).

Operative Mortality. There were 12 deaths among the 76 patients who had an operation, at the time or immediately after, but 5 were among the first 6 operated on and several of them were gravely ill with congestive failure. Among the 7 later deaths, two were equally late cases, one was in the early stages of using hypothermia, and only four were average cases so that the expected mortality is under 6 per cent.

Length of Follow-up. This leaves 64 patients (21 cyanotic and 43 acyanotic) for consideration of the results, and they have now been followed up for an average period of 6 years, many for 7 to 8 years, and one for 10 years.

Cyanotic Patients

Here the results are easy to judge because the patient always had symptoms and nearly always signs of right ventricular (R.V.) strain: about half had an enlarged heart. All of them were better clinically and only two showed any residual cyanosis. Including them, the average arterial oxygen saturation was increased from 78 to 94 per cent and the pulmonary flow from 2·5 to 4·2 litres. Corresponding to this, the polycythæmia and hæmoglobin percentages fell to normal, from 120 to 88 per cent on the average.

In the 10 with a large heart this became smaller and in 7 much smaller (Table V) Nearly half lost all the T inversion and much of their R.V. preponderance and in others it became less. The

average systolic gradient across the pulmonary valve had been reduced from 138 to 27 mm. Hg in the seven who have been recatheterized, and in five, where this has not yet been done, it was reduced from 74 before valvotomy to 26 mm. afterwards. Comparing these last figures with those found at catheterization before operation they are often too low because of the conditions at the time. Most of the gradients that are shown in the Tables were measured by cardiac catheterization before and after operation. The figures in brackets were obtained at the time of valvotomy; if the gradient immediately before this was much lower than that obtained at catheterization previously, it and the gradient obtained after valvotomy were both increased proportionally and such figures are marked with an asterisk.

In the more detailed analysis that follows, three patients from overseas, all of whom were doing well, have been omitted so that 18 remain. Some results for 9 of these where we have full data are shown in Table II. In seven (V23, V47, V95, and V138 of Table II and three others who have not

TABLE II

RESULTS OF PULMONARY VALVOTOMY IN NINE CYANOTIC PATIENTS

Case No.	Sex and age	Reduction in systolic gradient	Reversal of T inv. in leads	Reduction of R in V1	Reduction of SI +RIII	Reduction in cardio-thoracic ratio
V 23	F 11	90 to 11	V5–V1	14 to 4	58 to 14	Normal
V 47	F 7	160 to 30	V4–V1	24 to 4	50 to 29	Normal
V 95	F 33	101 to 31	V2–V1	4 to 0	15 to 10	Normal
V 138	F 3	(101 to 26)	V6–V3	28 to 6	60 to 19	60 to 54
V 78	F 7	83 to 21	Normal	23 to 2	45 to 19	Normal
V 107	F 19	97 to(21)*	Normal	8 to 1	22 to 2	Normal
V 41	M 11	126 to 45	V5 V4	31 to 3	61 to 23	58 to 50
V 73	F 19	131 to 44	V4	13 to 6	32 to 8	64 to 54
V 114	M 4	102 to(23)*	V5	52 to 3	48 to 11	65 to 53
Average		110 to 28	—	22 to 3	43 to 15	—

* In most cases shown in Tables II–IV the gradients were measured by cardiac catheterization before and after operation. The figures in brackets were obtained at the time of operation. If the gradient just before valvotomy was much below the gradient at catheterization before operation, this and the gradient measured after valvotomy were both increased proportionally and such figures are marked also by an asterisk.

been recatheterized) the reversal of the T inversion was almost complete: the average R in V1 was reduced from 31 to 6 mm. and the sum of SI+RIII from 49 to 22 mm. In three others (including V78 and V107 of Table II) there was no T inversion and the signs of R.V. preponderance were less severe before operation: they were, however, equally reduced, the average R in V1 falling from 20 to 2 mm. and the sum of SI+RIII from 27 to 8 mm. These 10 patients still have some pulmonary stenosis, but it has been reduced to a level where we do not think it will ever be of importance.

There were, however, 8 patients (including V41, V73, and V114 of Table II) where the T inversion was reversed to some extent but much less than in the first group and less than was hoped for. In spite of this, the reduction of R.V. preponderance was nearly as much, the average R in V1 falling from 27 to 8 mm. and the average sum of SI+RIII from 52 to 24 mm. There is no doubt that they were greatly improved, but in two who were recatheterized the gradients were still 44 and 45 mm. and we are less certain about their future though all are still doing well. Age seemed to have some influence on the results obtained, for in this group four were between 19 and 26 years and the other four averaged 7 years of age, while in the former group only one, aged 33, was over 20 and the other nine averaged 6 years of age.

On these findings, all the patients have been greatly improved and 10 of the 18 have obtained an excellent result that is nearly perfect. One, however, is not likely to maintain it because she

developed rather free pulmonary regurgitation (V84). Only two others, both children, developed a lesser degree of this and after five years it has not prevented great improvement clinically and objectively (V94 and V114).

Acyanotic Patients

Here the degree of improvement is not always as easy to assess because often operation was advised mainly because of the high right ventricular pressure, but half of them had fairly severe symptoms. Only 11 of the 43 showed much enlargement of the heart but 25 showed R.V. strain, perhaps an undue proportion because I regarded this as a strong indication for operation.

Only one of the 43 patients failed to benefit (V104). Though he feels about the same and still plays football, bundle-branch block has persisted since the operation, his heart has become larger, and the gradient has hardly been reduced. Recatheterization revealed that the obstruction was infundibular and this had not been recognized. No patient has lost any of the improvement he had gained, but one has died from other causes, a boy who obtained a good result but developed tuberculosis and died from this after a chest operation six years later (V78).

All but two of the other 41 patients were able to resume active lives. Five of the girls have married, and this includes nearly all who could have done so, which is not the case after successful operations for Fallot's tetralogy. Three who were married have had children for the first time. The clinical judgment of improvement was supported by objective signs in nearly all. In 16 of the 25 where there was R.V. strain, it diminished greatly and the R.V. preponderance also diminished. In 10 of the 12 where the heart was large it became smaller. The average systolic gradient across the pulmonary valve had been reduced from 123 to 41 mm. in the 22 who have been recatheterized, and from 85 before valvotomy to 27 mm. after it in six of the recent cases where this has not yet been done.

The Best Results. In 25 patients the result seemed nearly as good as one could wish. Eight of them are shown in the upper part of Table III. The average systolic gradient across the pulmonary valve was reduced from 122 to 27 mm. The T wave inversion in the left chest leads was always reversed in V2, V3 and V4, and also in V5 if it had spread so far, and often in V1 also. The average R wave in V1 was reduced from 23 to 6 mm. and the sum of SI+RIII from 37 to 19 mm. In 7 others there was the same improvement in all these particulars, the average R in V1 falling from 26 to 11 mm. and the sum of SI+RIII from 35 to 20 mm. but the gradient had not been measured since their operations. The oldest patients among these fifteen were aged 21, 20, and 19 years and all the others were aged 16 or less.

In the other 10 of the 25, the results were equally good and the only reason for separating them was that originally they had not shown signs of R.V. strain. The results are given in the lower part of Table III. The average systolic gradient was reduced from 103 to 28 mm. T inversion had never spread beyond V1 and when present here it was generally reversed. The average R wave in V1 was reduced from 14 to 6 mm. and the sum of SI+RIII from 22 to 14 mm. The oldest patients were aged 22, 20, 19, and 19 years and the others were aged 14 or less.

Less Good Results. There were 14 patients in this group. Four of the earliest seemed very good at the time but in retrospect they were only improved and not nearly cured. With them in the upper part of Table IV we are including a fifth with equally severe stenosis and a similar result. The systolic gradient was reduced to half or less in four of the five and recatheterization failed in the fifth. Of the two where the heart was enlarged, it was reduced to normal size in one (V39) and in the other (V 45), already 29 years old, it became smaller. The T inversion in the chest leads always became less but was not abolished. The average size of the R wave in V1 was reduced from 22 to 12 mm. and of SI+RIII from 33 to 16 mm.

The first (V30) is now leading an active life in Malaya: it is surprising that with such a high gradient (158 mm.) his heart had not become large, and equally that his R.V. strain had diminished so much with a residual gradient of 78 mm., but this may have regressed since. The second (V39) leads an active life with a heart that is now normal in size, and the third (V43) leads a quiet life in a

TABLE III

ACYANOTIC PATIENTS WHERE THE GRADIENT WAS REDUCED TO UNDER 40 MM. WITH GOOD EFFECT

Case No.	Sex and age	Reduction in systolic gradient*	Reversal in T inv. in leads	Reduction of R in V1	Reduction of SI +RIII	Reduction in cardio-thoracic ratio
V 86	F 14	102 to 39	V4–V2	17 to 8	62 to 18	Normal
V 88	M 11	130 to 34	V5–V2	24 to 14	30 to 22	55 to 52
V 116	M 21	155 to 34	V4–V2	24 to 1	42 to 34	Normal
V 120	M 19	145 to 17	V3–V1	28 to 2	42 to 22	Normal
V 127	M 12	110 to 2	V5–V2	26 to 5	33 to 14	57 to 52
V 133	F 5	(120 to 32)	V5–V2	17 to 4	28 to 18	63 to 57
V 134	M 13	(115 to 21)	V3–V1	23 to 3	22 to 16	Normal
V 139	M 16	101 to (37)*	V3–V1	27 to 12	34 to 6	Normal
Average (8)		122 to 27	V4–V1(2)	23 to 6	37 to 19	—
Patients with less R.V. Strain before Operation						
V 64	F 19	140 to 38	Normal	5 to 3	21 to 14	Normal
V 79	M 14	84 to (22)*	Normal	5 to 3	21 to 20	Normal
V 82	M 7	100 to 25	V1	25 to 11	31 to 22	Normal
V 83	F 19	114 to 32	V1	15 to 4	24 to 8	Normal
V 89	F 12	90 to 31	Normal	14 to 8	24 to 14	Normal
V 100	M 12	75 to 28	Normal	18 to 10	19 to 16	Normal
V 101	M 12	124 to (25)*	Normal	11 to 7	9 to 4	Normal
V 118	F 20	103 to 14	V1	19 to 4	33 to 15	Normal
V 140	F 14	97 to (36)*	Normal	2 to 2	18 to 13	58 to 55†
V 141	M 22	100 to (30)	V1	27 to 9	22 to 16	Normal
Average (10)		103 to 28	—	14 to 6	22 to 14	—

* See note to Table II. † After one year only.

bank and plays golf. The fourth leads a more active life and has had her first baby without any set-back: her paroxysmal auricular fibrillation has become established—an uncommon complication of pulmonary stenosis—but she is less troubled by this, controlled with digitalis, than she was before. The fifth (V108) is disappointing because the surgeon had become much more experienced: he is improved but cannot lead a normal life, mainly because his gradient is still much too high though his age of 33 years may also be a factor.

Another 9 patients with results that were not so good, though they were greatly improved, are shown in the lower part of Table IV. The average gradient was reduced from 113 to 42 mm. but it was often about 40 instead of about 30 as in the more successful cases. The T inversion was generally reduced but not abolished. R in V1 was reduced from 20 to 10 mm. and the sum of SI+RIII from 33 to 25 mm.

It is obvious that these nine patients were older, all but three being 23 or more, and the importance of this will be discussed later. The first three did not fall far short of those with the best results, but they were not quite so good, probably because the gradient had been reduced less. The failure in the fourth (V69) must be due to the production of pulmonary regurgitation for though the gradient had been reduced to 10 mm. there was no relief of her R.V. strain and the heart became larger—the only case in the series where this happened—so that in the long run she is unlikely to benefit. In one other (V121) a slighter degree of pulmonary regurgitation prevented the heart size decreasing as much as it should have. A pulmonary diastolic murmur was heard in three others, but has not so far prevented a good result.

The remaining five were all 25 years old or more, and this was probably one reason why they did not get better results. In the first two (V97 and 93) the improvement in R.V. strain was much

TABLE IV

ACYANOTIC PATIENTS WITH ONLY MODERATE IMPROVEMENT

Case No.	Sex and age	Reduction in systolic gradient	Reversal of T inv. in leads	Reduction of R in V1	Reduction of SI +RIII	Reduction in cardio-thoracic ratio
V 30	M 12	158 to 78	V3 V2	16 to 12	41 to 26	Normal
V 39	F 10	140 —	V4	28 to 30	52 to 25	63 to 49
V 43	M 18	130 to 60	V3 V2	31 to 14	18 to 10	Normal
V 45	F 29	98m to 30m†	V4	17 to 7	36 to 12	68 to 63
V 108	M 33	173 to 80	V3 V2	20 to 7	16 to 9	Normal
Average (5)		165 to 78	—	22 to 12	33 to 16	
V 56	M 23	98 to 48	V4 V3 V2	31 to 20	32 to 24	Normal
V 70	M 13	124 to 43	V2 V1	30 to 0	40 to 31	Normal
V 121	F 10	105 to 42	V3 V2	20 to 8	46 to 31	59 to 57‡
V 69	F 17	75 to 10	None	18 to 5	21 to 18	53 to 56‡
V 97	F 33	124 to (46)*	V4 V5	14 to 4	22 to 14	69 to 54
V 93	F 42	145 to (42)*	V4	9 to 4	30 to 21	59 to 54
V 80	F 25	109 to 45	None	8 to 1	—	Normal
V 105	F 25	135 to (65)*	V6 V5	14 to 10	37 to 27	Normal
V 92	M 25	100 to 39	None	34 to 34	36 to 37	Normal
Average (9)		113 to 42	—	20 to 10	33 to 25	—

* See note to Table II. † = mean pressures.
‡ These two patients developed pulmonary regurgitation.

less than usual. In the third (V80) the gradient was still 45 mm. and the T inversion in V1 and V2 did not change. The fourth and fifth are the most disappointing for they had signs of severe R.V. strain that did not improve much. In the last (V92) with a gradient of only 39 mm. it is difficult not to think that his age had led to some irreversible changes. This accounts for 39 of the 43 patients. Operation was a failure in the one boy described and three, including the boy who spent much of his time in a sanatorium and died there, are excluded as our data are not sufficiently complete.

REDUCTION IN THE SIZE OF THE HEART

Symptoms and a general increase in the size of the heart, as opposed to hypertrophy of the right ventricle, are late developments of severe stenosis. Probably because of this, they are easy to relieve and a successful operation, even if it leaves some residual gradient, always relieves the symptoms and results in the heart becoming smaller and often of normal size.

The 10 cyanotic patients with general cardiac enlargement (cardiothoracic ratio above 52 per cent) are shown in Table V. The heart has always become smaller and generally normal or nearly normal in size. The average cardiothoracic ratio had been reduced from 60·1 to 53·3 per cent after four years and the decrease seemed to be progressive. The reduction was by more than one-tenth of the original diameter, and by nearly one-sixth in the last six cases where the heart had been greatly enlarged. The heart that is now the largest (c.t.r. 57% in V84) has failed to regress further because the patient developed some pulmonary regurgitation, but this was not enough to prevent it becoming smaller.

Similarly, all the acyanotic patients with a large heart are shown in Table V, the two who developed pulmonary regurgitation being shown separately below. In one where there was free regurgitation the heart became larger and in the second it did not become much smaller. In the other ten it improved as much as in the cyanotic cases, its average diameter having been reduced by one-tenth. In one patient the heart, though smaller, was still very large (V45; c.t.r. 68 to 63%) but her age was already 29 years and her gradient was still considerable. Even age does not prevent great reduction

TABLE V

REDUCTION OF HEART SIZE AFTER VALVOTOMY IN SIMPLE PULMONARY STENOSIS

Case No.	Sex and age	Cardiothoracic ratio (percentage)				
		Pre-op.	1 yr.	2 yr.	4 yr.	6 yr. or more
		Cyanotic patients				
V 40	F 5	56	56	56	55	53
V 41	M 11	58	51	50	49	50
V 49	M 8	56	53	53	53	52
V 71	F 26	54	52	52	52	53
V 73	F 19	64	59	57	55	54
V 74	M 5	64	60	52	51	48
V 84	M 4	66	64	60	57	—
V 94	M 4	68	61	58	54	—
V 114	F 4	65	54	54	53	—
V 138	F 3	60	53	54	—	—
Average		60·1	56·4	54·7	53·7	(52·5)
		Acyanotic patients				
V 39	F 10	63	56	54	52	49
V 45	F 29	68	63	61	63	63
V HS	M 8	56	52	52	54	54
V 75	F 6	63	58	58	57	—
V 88	M 11	55	53	53	52	52
V 93	F 42	59	57	56	54	54
V 97	F 33	69	55	54	54	—
V 127	M 12	57	54	52	—	—
V 133	F 5	63	58	57	—	—
V 140	F 14	58	55	—	—	—
Average		61·2	56·1	55·2	55·1	(54·8)
		Acyanotic patients with pulmonary regurgitation				
V 69	F 17	53	57	56	55	56
V 121	F 10	59	62	59	57	—

as shown by Cases V93 and V97, though in the latter some of the reduction was due to her persistent ductus having been closed at the same time that she had valvotomy.

IMPROVEMENT IN THE ELECTROCARDIOGRAM

These changes can be summarized as follows for 57 patients (18 cyanotic and 39 acyanotic), omitting the one who did not benefit and the six with less complete data. No significant T wave inversion remained in 37: in 14 of these it had never been much and in 23 it had been severe, extending across the right chest leads to V4 or further. In 20 others, however, these signs still remained, though if they had been severe they became less than they had been.

When the changes in R.V. preponderance in these groups are compared, the differences are not very striking though they are in the direction that would be expected. The average height of the R wave in V1 was reduced to a third or less in those with the best results (from 27 to 8 mm. in those with R.V. strain and from 15 to 5 mm. in those where there had been less strain), and to less than half (from 23 to 10 mm.) in those who were only improved. Similarly, the average sum of SI and

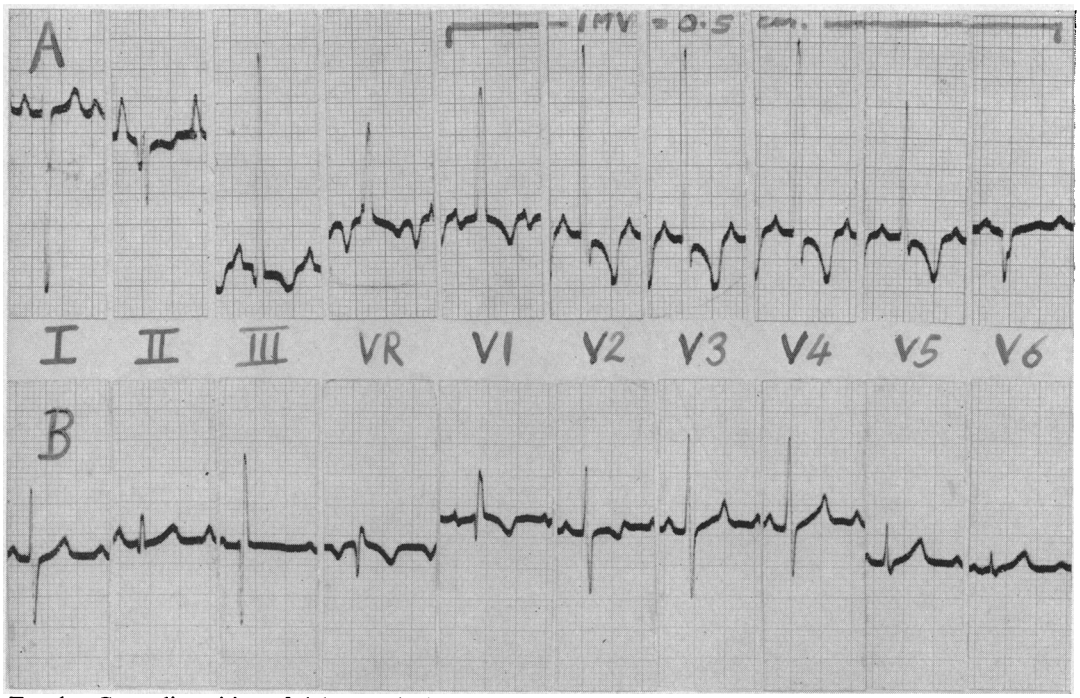

FIG. 1.—Great dimunition of right ventricular preponderance and strain and of a large pointed P II after pulmonary valvotomy. (A) Before operation. (B) Three years after: R.A.D. is 10+14 instead of 27+35; R in V1 is 7 instead of 40 mm.; and T inversion has disappeared in V3, V4, and V5 and almost so in V2. In (A) the standardization of V1–V6 is half normal. Case V94, aged 3 years.

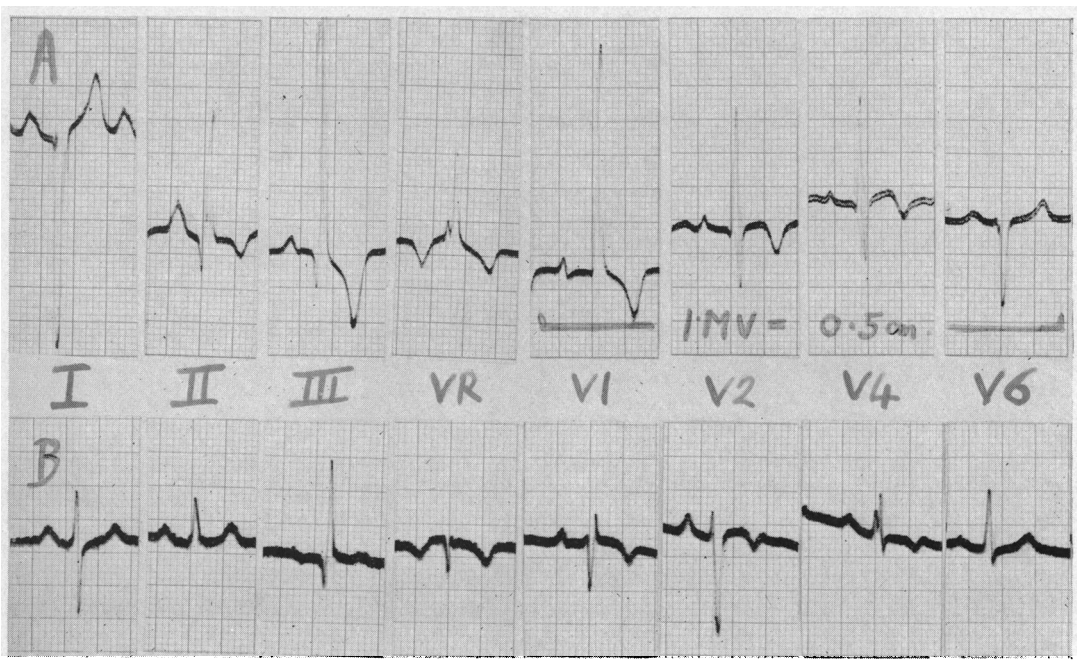

FIG. 2.—Great improvement in R.V. preponderance that started in the first year after operation, and in T wave inversion mainly between the third and fifth years after operation. The gradient had been reduced from 112 to 14 mm. (A) Before operation. (B) Eight years after. In (A) the standardization of V1–V6 is half normal. Case V41, aged 11.

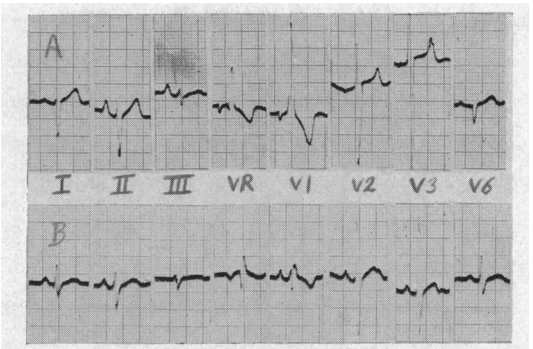

FIG. 3.—Great improvement in R.V. preponderance and in less widespread T wave inversion, mainly within the first year after operation. (A) Before operation. (B) Five years after. Case V90, aged 18.

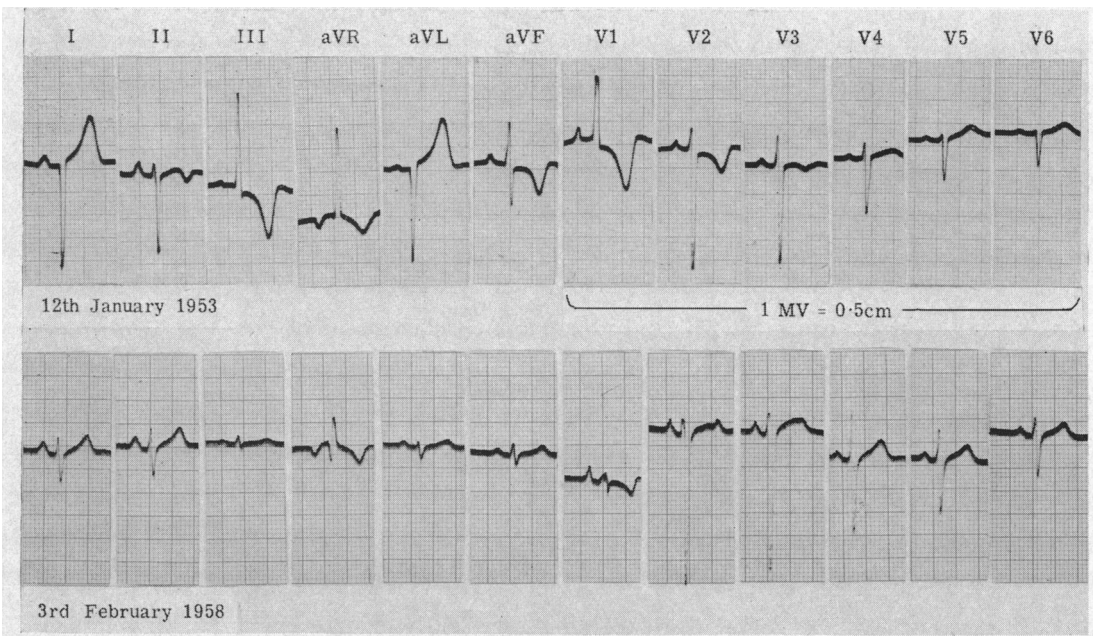

FIG. 4.—Virtual disappearance of gross R.V. preponderance and some strain after pulmonary valvotomy had reduced the gradient from 145 to 17 mm. (A) Before operation. (B) Five years after. In (A) the standardization of V1–V6 is half normal. Case V120, aged 19.

RIII was reduced from 40 to 20 mm. in those with the best results, from 23 to 13 mm. in those with less R.V. strain originally, and from 38 to 24 mm. in those that were only improved. The good results were more often in the young patients (see Table VI).

Striking improvement in both T wave inversion and R.V. preponderance often run parallel, but the former is abolished completely more readily than the latter. Improvement of both is illustrated in Fig. 1–3 here and in Fig. 2 and 6 of Campbell and Brock (1955), and improvement of R.V. preponderance in a boy of 19 who had less T-wave inversion in Fig. 4. Four of these patients have been recatheterized and the gradients had been reduced from an average of 127 mm. before operation to 14, 17, 30, and 12 mm. respectively. The figures were chosen without reference to this but have in fact selected patients whose operations were particularly successful. It is, however,

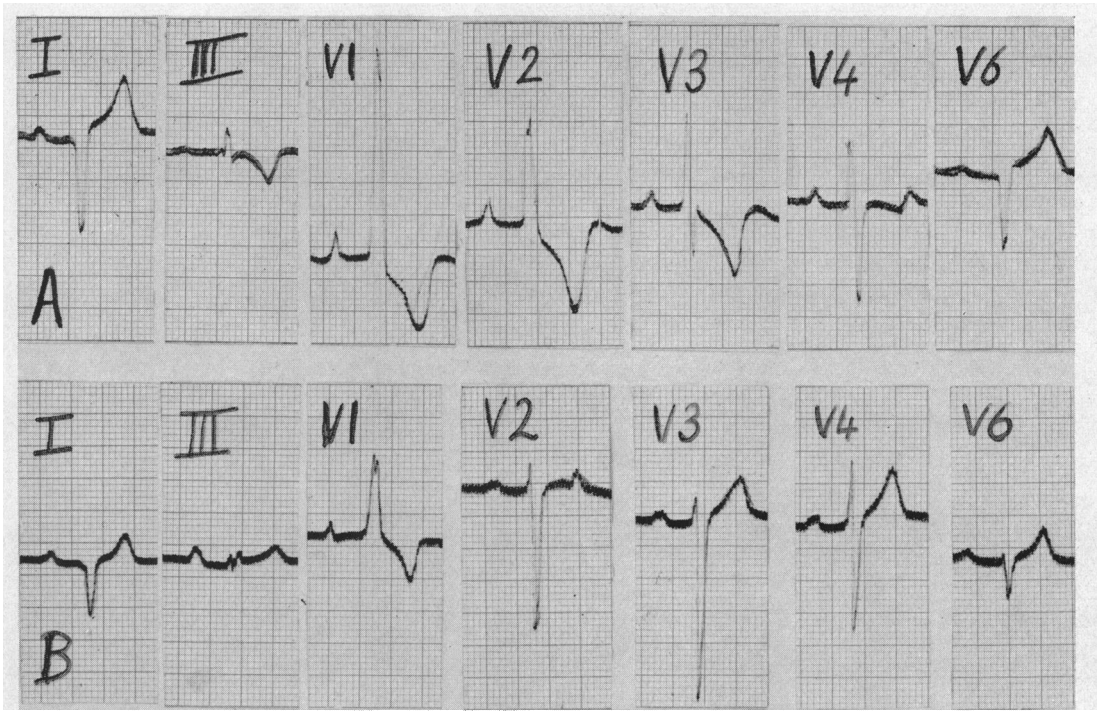

FIG. 5. Much diminution of R.V. preponderance and strain after pulmonary valvotomy, although the pulmonary systolic gradient was still 60 mm. (A) Before operation with deep T inversion to V3. (B) Seven years after, showing R in VI 13 instead of 31 mm., and much less strain. Case V43, aged 18.

possible to get great improvement with only a moderate reduction of the gradient. Most of the T inversion was abolished and the R.V. preponderance diminished in one boy (Fig. 5) although the gradient was still 60 mm., and the T inversion was greatly reduced in another (V30) although it was still 78 mm.

The rate at which this improvement takes place varies. T-wave inversion often develops or becomes much deeper about a week after right ventricular section, and progresses for two or three weeks (Brock and Campbell, 1950) and there may also be signs produced by pericardial effusion. A year or so after operation is a good time for judging the result for by then, and often by six months, these temporary post-operative changes will have disappeared. The improvement in T-wave inversion will mostly have taken place within a year (Fig. 3) but may continue during the next two or three years: Case V41 (Fig. 2), however, showed little at one year and improved greatly even after four years.

The signs of R.V. preponderance may improve more slowly though often within a year. A boy, aged 15 (V58), was chosen to illustrate improvement in T inversion, though after a year there was little change in his R.V. preponderance (Fig. 8, Campbell and Brock, 1955) but after three years R in V1 was 9 instead of 12 mm. and after seven years it was only 4 mm.: during this time the sum of SI+RIII improved gradually from 37 to 20 mm. The improvement in R.V. preponderance is more likely to continue for four years or so, sometimes because of the gradual regression of the infundibular obstruction. This was well shown in Case V127 where the gradient across the valve was reduced from 164 to 0 by valvotomy but replaced by an infundibular gradient of 92 that was reduced only to 62 mm. by infundibular resection: this too had disappeared completely when he was recatheterized $2\frac{1}{2}$ years after operation. Here much of the R.V. preponderance but less of the T inversion had disappeared after 15 months: after 30 months both had improved further (Fig. 5 of Johnson, 1959): they have not yet disappeared though it seems likely that they will, as he was only 12 years old at the time of operation. His T inversion had been observed becoming deeper and

spreading further across the chest leads for five years before I had an opportunity of advising operation. Torres *et al.* (1959) found that in mitral stenosis the signs of R.V. preponderance regressed in from three months to two years: this might be expected to be quicker for generally it has not been present for so long.

Other changes may be seen. Large P waves generally become smaller (see Fig. 1), sometimes even in cases that we regarded as improved only. Evans and McRae (1952) described plane- and wing-shaped S–T depression and late-rising and notched T waves as lesser cardiographic signs of coronary disease. They can be signs of right ventricular strain also and are found in many patients with pulmonary stenosis. They may be seen also after successful pulmonary valvotomy when previously there was deep T inversion (Fig. 1B, 4B, and 5B, generally in leads V2 and V3).

The Influence of Age

When a patient is only improved instead of being relieved, it may be because the operation has failed to reduce the pulmonary gradient adequately. Certainly some of these patients would have been better if it had been reduced still further, though there may be great improvement with a smaller heart and less R.V. strain, at least in young patients, even when the residual gradient is quite large.

Age might be important because the valve has become more rigid and the outflow tract more fixed with age or because the myocardial changes have become irreversible. I had surmised that the age might explain why the signs of R.V. strain sometimes persisted, but had not realized how strong the evidence for this was. It will be seen from Table VI that only two of those where severe R.V. strain had been abolished were over 20, but that half of those where it was only improved were over this age. Actually the only four patients with striking disappearance of the R.V. strain pattern over the age of 16 were 18, 19, 20, and 22 years of age, though three others aged 19, 20, and 21 had very good results. On the other hand, those where R.V. strain was present and was not successfully reduced included nine patients aged from 20 to 33 and one aged 42 years.

TABLE VI

Age of Patients with and without much Reduction of Right Ventricular Strain

Age in years	0 to 4	5 to 9	10 to 14	15 to 19	20 to 24	25 to 29	30 and over
T inversion reversed in V3 and V4 or more	3	7	5	6	2	—	—
Little or no R.V. strain	—	3	6	3	2	—	—
No change or only improved	1	2	3	4	3	4	3

It is not easy to disentagle the factors of age and of inadequate reduction of the gradient, for there are not enough older patients with a good reduction of the gradient and yet with persistent R.V. strain. It seems, however, that age makes successful reduction of the gradient more difficult (as might be expected) and that even when it is reduced there is less certainty of the signs of R.V. strain being reversed. The fact that the patients who did not lose their T inversion lost nearly as much of their R.V. preponderance as those who lost their T inversion is a further reason for thinking that the latter is sometimes due to irreversible changes and not always to failure to reduce the gradient.

We know that T-wave inversion sometimes represents functional changes because it can be reversed. Equally we know that many patients who come to necropsy have widespread but localized fibrosis in the muscle of the hypertrophied right ventricle, which must be irreversible. There is some evidence that these changes are common after 20 and uncommon before this age. Allanby and Campbell (1949) found these changes in all their cases with necropsy but five were between 17 and 29 and the sixth who was only 9 had an enormous heart and failure: the most

severe fibrosis was in two, aged 22 and 29. Marquis (1951) found it present in a patient of 27 but absent in three aged 5, 5, and 13, although they had deep T-wave inversion.

Clearly patients should be operated on before they are 17, or at the latest before they are 25, lest the T inversion has become irreversible because it is now due to fibrosis of the muscle of the right ventricle.

Closed and Open Operations

Most of these patients were operated on by the transventricular route, though some more recent ones have been done under hypothermia. Blount *et al.* (1954) reported 15 operated on in the usual way and 5 later ones operated on with a pulmonary arterial approach under hypothermia. The earlier series gives results similar to ours, with an average fall in the gradient from 152 to 43: the results were much better in those done by open operation, the average gradient falling from 97 to 5 mm., but too many of them developed pulmonary regurgitation, severe enough to lead to enlargement of the heart.

Of a later series of 38 patients operated on by this method with only two deaths (Blount *et al.*, 1957), 25 have been recatheterized since operation and the gradient was under 20 mm. in 17, and between 21 and 41 in the other 8 cases. Only in three of the earliest cases was any part of the pulmonary valve excised, but even so there were signs of pulmonary regurgitation in 8 of the later 38 patients. After three years this had not produced any harmful effect and a heart that had enlarged after operation had generally become somewhat smaller later: the pulmonary diastolic pressure was always over 8 mm. and did not seem lower than usual. They thought, therefore, that most pulmonary regurgitation was slight and unimportant, but our experience makes us think that it must be avoided to obtain a good lasting result: the slighter degrees of it do not produce obvious drawbacks in the first few years, but do militate against the heart returning to a normal size, and without this the operation cannot be regarded as a complete success. On the present evidence, it seems better to be left with a gradient of 20 or perhaps 30 mm. and no pulmonary regurgitation than with no gradient but with some degree of regurgitation.

This series does not prove that open operations with hypothermia have been more successful, because the few included were among the later operations which have mostly produced better results and lower gradients. This is also the experience of Crafoord (Hansen *et al.*, 1958) though he thought that the reported results by the transarterial route were generally better.

We have no experience of pulmonary valvotomy in infants but the severity of the stenosis in Cases V84, 94, 114, and 138, all cyanotic children aged 3 or 4, shows that it may be needed urgently at an early age. Rowe *et al.* (1958) reported the immediate results of open valvotomy in 21 children, aged between eight months and sixteen years, who had been recatheterized. Only one had died but the results were classed as good in only 9, as fair in 8, and as poor in 4: in many the gradients still seem to have been high. Operations seem, therefore, to be difficult in small infants but by three years of age we have found it possible to get excellent results.

Summary and Conclusions

We have followed up 64 patients (21 cyanotic and 43 acyanotic) for an average period of six years after valvotomy for severe pulmonary stenosis. These were the survivors of 76 who had been operated on by Sir Russell Brock in 1948–56. For patients who had not reached the stage of congestive heart failure, the operative mortality was under 6 per cent.

Only one patient failed to obtain any benefit and this was because his stenosis was not recognized as infundibular. One has died from tuberculosis though he was satisfactory as far as his heart was concerned. All the others were doing well but we have excluded five of them (mostly from oversea) because our data were not complete. We have tried to decide how many of the remaining 57 had been improved enough to be regarded as normal for most purposes, with a normal outlook for the future.

The results were so good in 35 (61%) of the 57, including similar proportions of acyanotic and

of cyanotic patients, that we think they nearly reach this high standard. They are able to lead normal lives and none has lost any of the improvement that was gained. The average systolic gradient across the pulmonary valve has been reduced from 111 to 28 mm. in the 27 where we have these measurements. In all the 14 where the heart was enlarged it became smaller, and in 11 much smaller. Where there was R.V. strain it was abolished or greatly reduced: R.V. preponderance also was reduced, e.g., the average size of the R wave in V1 was reduced from 22 to 7 mm. and the sum of SI+RIII from 33 to 17 mm. We think that these patients are likely to remain well for a long future. They have, of course, the risk of bacterial endocarditis, but none of them has suffered from this so far. Otherwise they can be regarded as nearly normal, though Johnson (personal communication) finds that the response to exercise is often abnormal even when the gradient has been nearly abolished. Perhaps the extra reduction of about 20 mm. in the gradient that would make them normal is more likely to be achieved with open operation with hypothermia, but this must not be at the expense of producing pulmonary regurgitation more often.

Another 22 patients (39%) were improved, often greatly but they still had significant pulmonary stenosis that may we think prove harmful in the future. In those where it was measured the average systolic gradient has been reduced from 132 to 55 mm. (against 111 to 28 mm. in the former group). In none of those with R.V. strain, as shown by T inversion in the right chest leads, was this abolished: it was, however, often improved and the R.V. preponderance was lessened nearly as much as in the first group (45 instead of 58%). The heart became smaller in 6 of the 8 where it was enlarged, in 3 much smaller, and in the other 2 we think this was prevented by the production of pulmonary regurgitation.

Most of the patients with the best results were under 16, and only four were over 20: on the other hand, nearly half of those who were only improved were over this age. One reason may be that good reduction of the gradient is more difficult because the valve and the outflow tract have become more rigid, but we think that sometimes it is because the fibrosis of the right ventricle has become irreversible. We have come to think, therefore, that patients should be operated on at an earlier age, as soon as convenient and always before they are 17, and that after 25 anything approaching a curative operation becomes much less likely.

We have come to think also that operation should be performed for patients with less severe stenosis. If there is no R.V. preponderance in the electrocardiogram, the gradient across the pulmonary valve must be slight. If this is still so when the patient is 20, it is unlikely that he will ever need an operation and he is probably one of the fortunate few who will get on well till the age of 50—a group that has been discussed by Campbell and Missen (1959). At the other extreme, T-wave inversion in the right chest leads, often to V3 or V4, nearly always indicates an R.V. systolic pressure of over 100 mm. and this certainly needs relief. The pressure may, however, be as high as this without the T inversion, and unless a decision can be taken on other grounds, most patients with simple pulmonary stenosis should have catheterization to decide if an operation is needed or is likely to be in the future.

A systolic gradient of 50 mm. across the pulmonary valve indicates, I think, the need for valvotomy. At first, with so many waiting, most of our patients had an R.V. systolic pressure of 100 mm. though Kirklin *et al.* (1953), Blount *et al.* (1954), and Brock (personal communication) thought that a pressure of 75 (or a gradient of 55 mm.) was enough to demand operation. Examination of this series shows that those with an average residual gradient of less than 30 mm. have done very well, but that those with one of over 50 mm. leave much to be desired. Gradients of 40 are more difficult to decide about. In one patient, a gradient of 39 mm. did not prevent an excellent result but another of 39 and several of between 42 and 45 mm. did seem to. I think that a systolic gradient of 45 mm. or in a child, where it might become higher as the child grew, one of 40 mm. is a reason for operation, especially as the stenosis may become more severe from the deposition of fibrin on the valve (Campbell and Missen, 1959) and as exercise increases it above this resting value. A study of these cases suggests that gradients of 25 to 30 mm. are not of much importance whether they are natural as in cases of very slight stenosis, or residual after surgical relief of a larger gradient.

In reporting what will probably be my last follow-up of a group of patients I would like to urge the great importance of continuing long-term studies for many years. There is no other way of obtaining the information that is necessary for giving the right advice to patients.

Once again, I should like to thank Sir Russell Brock for his initiative and skill in making this series possible, and for allowing me to assess the degree of improvement obtained. I have thanked Dr. Charles Baker and other colleagues who have allowed me to include some of their patients, and the registrars and research fellows who have contributed so much with the results of cardiac catheterization: to these I would now like to add Dr. Johnson whose paper on the regression of infundibular stenosis is published in this issue.

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