PULMONARY VALVOTOMY AND INFUNDIBULECTOMY

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Obstruction to the outflow of the right ventricle may be at the pulmonary valve, the infundibular region, or both, and may be associated with defects in the septa. The normal and pathological anatomy of this area has been fully described by Brock (1957), and various surgical techniques have been suggested and practised for dividing the valve or relieving the infundibular stenosis.

(1) Transventricular approach using a valvotome and splitter to open the valve and a punch to remove the infundibular thickening—with intact circulation (Sellors, 1948; Brock, 1948).

(2) Transarterial approach using a valvotome to cut the valve—with intact circulation (Potts *et al.*, 1950; Søndergaard, 1952; Pettersen, 1954).

(3) Open transarterial approach to the pulmonary valve with circulatory occlusion under hypothermia (Swan and Blount, 1956).

(4) Open transarterial or transventricular approach to the valve and infundibular region using a cardio-pulmonary by-pass.

Since 1954, 92 operations on the pulmonary valve and infundibulum have been performed at the Royal Liverpool Children's Hospital and Broadgreen Hospital, and the experience with these forms the basis of the subsequent observations. In the first 16 cases attempts were made to divide the valve through the ventricle or the pulmonary artery by means of a valvotome and stretcher. Although a complete division of the valve is possible by these methods, the disadvantage of either approach appeared to be that the valve is usually only partially divided and then stretched without further splitting. Manometric readings at this stage are somewhat difficult to interpret, and no confirmation of the resultant size of the opening was obtainable, either by sight or by finger palpation. The final result was often disappointing. In cases of pure pulmonary stenosis the right ventricular strain was often only partially relieved, and in cases with an associated ventricular septal defect and hypoplasia of the valve and pulmonary artery (tetrad of Fallot) the technical difficulties of dividing a miniature valve completely made the operation somewhat hazardous.

This blind approach to the pulmonary valve was abandoned in favour of the direct visual exposure through the pulmonary artery and this has been used in 61 cases. Not only can the valve be seen directly and be accurately divided to the valve ring, but the finger can be passed through it into the right ventricle to ensure that there is no true infundibular stenosis. If such a stenosis is found, it can then be approached through the divided valve and the amount of material punched out controlled by finger palpation. Although this approach to an infundibular stenosis cannot be considered ideal, it is less disturbing to the heart than a transventricular approach and has the advantage that a tactile check of the residual opening can be made. There is little doubt that if the presence of an infundibular stenosis is demonstrated or suspected at the pre-operative catheterization, its complete removal can be guaranteed only by a direct visual approach. The time required for this together with any plastic repair on the outflow tract of the right ventricle demands, at present, the use of a cardiopulmonary by-pass. It has been argued that in pulmonary valve stenosis, the evidence obtained at pre-operative catheterization can not always guarantee that some degree of fibrotic infundibular stenosis or a small ventricular septal defect will not be found, and

in centres where a cardiac-pulmonary by-pass is in routine daily use, virtually all patients with a pulmonary valve stenosis are operated upon by this means (Gross, 1958; Lillehei, 1958). Nevertheless, increasing experience in the interpretation of catheter readings, selective angiocardiograms, and electrocardiograms now usually makes possible the correct anatomical diagnosis of an uncomplicated pulmonary valve stenosis, so that it seems hardly justified in such cases to substitute for the simple transarterial approach an elaborate and time-consuming technical procedure to undertake its division. There is, however, a group of cases with the pressures in the right and in the left ventricles approximately the same, so that a small ventricular septal defect may not be demonstrated, and in such cases the use of a cardiac-pulmonary by-pass would seem to be indicated.

Selection of Cases for Operation

Pulmonary stenosis with intact ventricular septum presents as four clinical groups.

(a) Infants or very young children showing dyspnœa or cardiac failure. They are occasionally cyanosed due to the severe peripheral anoxæmia secondary to the reduced cardiac output or to reversal of flow through a patent foramen ovale. In such children a leathery type of valve is found, either alone or associated with a tubular type of infundibular stenosis. The whole outflow tract of the right ventricle, the pulmonary valve, and the pulmonary trunk are usually hypoplastic.

When a systolic murmur has been discovered incidentally in an asymptomatic infant and the subsequent investigation reveals the presence of pulmonary stenosis, operation is carried out at this stage only if the R.V. pressure is over 100 mm. Hg. The dangers of waiting until the infant has reached the age of five or so are not great, providing that there are no symptoms and the electrocardiogram is not developing signs of right ventricular strain. The operation is technically easier to perform at about the age of five years than at a few months old.

(b) The child in whom a cardiac murmur has been discovered by the family physician or at a routine school medical examination. Such children may complain of some dyspnœa, but often appear to be asymptomatic, although on close questioning they or their parents often admit that they are mildly disabled and unable to compete with their companions.

In these children we have adopted the policy that if there is a right ventricular pressure of more than 60 mm. Hg, operation should be advised, for the stenosis must be considerable to produce these pressure changes, and the chance of the span of life being shortened is high. Serial electrocardiograms that show a progressive climbing of the R wave are a clear indication that operation should be undertaken, and S–T depression suggests some urgency.

When the catheter studies show a valvar stenosis or an infundibular diaphragm (indicating the probable presence of a subvalvar chamber) there is little hesitation in recommending operation by the method described. When, however, the findings suggest a long infundibular stenosis then the operation is better performed with a cardio-pulmonary by-pass.

(c) The young adult who has reached this age because no surgical procedure has been possible until the last few years. He may have considerable symptoms, cardiac enlargement, and a large pressure gradient across the valve, and is clearly a candidate for relief of the stenosis. Nevertheless the strained, irritable myocardium make the operation technically more hazardous, and the postoperative course may be less straightforward.

(d) A few adults who have survived to an age of 50 or 60 with a large heart and generally some aneurysmal dilatation of the pulmonary artery. The state of the myocardium makes valvotomy truly dangerous here, and the decision about advising operation may well be difficult.

When *an atrial septal defect is present* there may be some difficulty in deciding how much true pulmonary stenosis exists and how much the gradient across the valve is due to increased blood flow. With an atrial septal defect having a large left-to-right shunt, a gradient of up to 50 mm. across a normal valve may well occur. In findings such as this closure of the atrial septal defect is indicated in the first instance. If a significant gradient across the pulmonary valve persists and a systolic thrill is still present over the pulmonary valve then exploration of the valve should be done. The radiological appearance of the vasculature of the lung fields is a valuable guide to the presence

of true pulmonary stenosis in these patients. Normal or diminished vascular markings with a gradient of 50 mm. or more across the pulmonary valve would strongly indicate enough stenosis to require surgical relief. This can be carried out conveniently at the same time as the suture of the atrial septal defect. In some with high ventricular pressure the shunt through the atrial septal defect may be reversed so that there is cyanosis, and then the first procedure is to undertake pulmonary valvotomy: suture of the atrial septal defect can be undertaken at the same time or as a second operation. The cardiac condition after pulmonary valvotomy in these intermittently cyanosed patients may well suggest that suture of the atrial septal defect would be wiser at a later stage.

In *the presence of a ventricular septal defect* with or without overriding of the aorta, the direct treatment of the pulmonary stenosis has to be considered with care. If the pulmonary valve ring is of the same size as that of the aorta and the valve is widely opened, the patient is left with a ventricular septal defect allowing a large left-to-right shunt and the danger of developing pulmonary hypertension. Only a partial opening of the pulmonary valve, which may be very difficult to assess, or a complete structural repair with the help of a cardio-pulmonary by-pass must be done. Where there is much disproportion between the aorta and pulmonary valve rings and a ventricular septal defect, as is found in most patients with Fallot's tetralogy, a full opening of the pulmonary valve or an infundibular obstruction is permissible and indeed advisable. In the presence of a long tubular infundibular stenosis, Blalock's systemic-pulmonary anastomosis may well be considered the safer procedure to adopt, particularly in a young, severely cyanosed child whose condition demands early relief. While an internal reconstruction of the normal anatomy must be the ultimate aim in patients with Fallot's tetralogy, yet in some the lack of development of the outflow tract of the right ventricle and the pulmonary valve might well prevent the opening up of this region to a level that is physiologically satisfactory.

How thin the wall of a narrowed outflow tract of the right ventricle can be made without subsequent aneurysm formation is not yet clear. Inserts of compressed Ivalon sponge into the infundibular wall or across the valve ring have been suggested (Kirklin *et al.*, 1959) to enlarge the lumen, but the ultimate fate of such material is undecided. Certainly a resulting pulmonary valvular regurgitation of any severe degree, while generally of little immediate consequence, should be viewed with concern as to the long-term effect on the right ventricle.

The Operation

A transarterial approach to the pulmonary valve with circulatory occlusion has generally been performed under hypothermia, but this adjunct does not appear to be necessary. Provided full oxygenation of the tissues by some degree of hyperventilation is produced immediately before the circulatory arrest, a period of three minutes is available for the division of the valve without hypothermia. In order that full utilization can be made of this time a complete preparation up to the stage of valve exposure is made before the circulation is interrupted. No difficulty has been found in dividing the valve satisfactorily in this time, but if an infundibular stenosis is present as well, a longer period may be required. This can be obtained by reclamping the incision in the pulmonary artery at the end of three minutes, and releasing the caval tourniquets. The normal circulation is allowed to continue for five minutes, and then the cardiac inflow is again arrested and a further three minutes is available for dealing with the obstruction in the right ventricular outflow tract. This can be repeated a third time if necessary.

After occlusion of the venæ cavæ the pressure in the systemic circulation falls in 20 seconds to between 10–15 mm. Hg where it balances up with the raised venous pressure. Fifteen seconds after the venous occlusion the electroencephalogram shows that the cerebral activity has ceased: that is more rapid than would be expected with anoxia and is almost certainly due to cerebral vascular congestion. After three minutes of the superior vena caval obstruction, it does not return to normal until the circulation has been re-established for at least five minutes (Fig. 1).

Technique (Fig. 2). Anæsthesia is induced with a barbiturate combined with a muscle relaxant and supplemented by nitrous oxide and oxygen. Ventilation must at all times be well maintained in order to prevent any fall in the pH level, and an adequate respiratory exchange without any drawback to the surgeon is

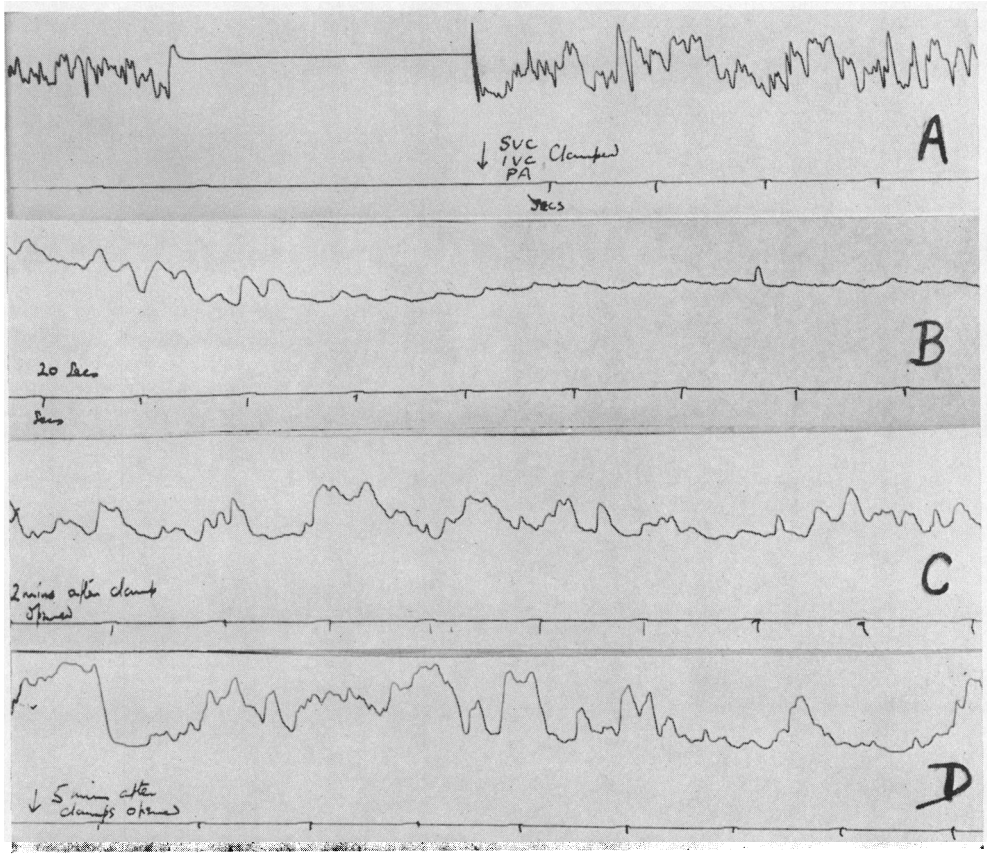

FIG. 1.—Electroencephalographic studies during circulatory occlusion under normothermic conditions. (A) Occlusion of the venæ cavæ. (B) At 20 sec. the waves have practically disappeared. (C) At two minutes after recirculation increased cerebral activity. (D) At five minutes the wave formation is near normal.

obtained by hand pressure of the bag at a rate somewhat higher than that of normal respiration (Rees, 1958).

Earlier a transverse submammary incision across the front of the chest with division of the sternum was used. The chest was entered through the second interspace on the right and the third interspace on the left with an oblique division of the sternum between these two spaces. This incision is somewhat higher than that usually described for full exposure of the heart, but it is necessary in order to get a good exposure of the pulmonary valve from above and to manipulate with comfort the instruments cutting the valve and punching out the infundibulum. Furthermore, in ventricles with very high pressure and in adults with an infundibular diaphragm and a large subvalvar chamber, the pulmonary artery may run directly backwards, so that every possible bit of room superiorly is needed to obtain a good exposure of the valve.

More recently, however, a median sternotomy has been employed. This has given an adequate exposure of the pulmonary artery and from the post-operative point of view has given rise to less discomfort and, resulted in fewer respiratory difficulties and complications. The substernal tissues are freed and the sternal ends retracted with a rib-spreader. The thymus gland is turned upwards as far as the innominate vein and can be stitched out of the way by passing a suture through it. The pericardium is opened vertically and sutured to the edge of the wound to keep the lungs out of the field of operation.

The pulmonary artery is examined and the character of the jet and thrill is studied. A harsh thrill in the neighbourhood of the valve ring and a forceful jet combined with a post-stenotic dilatation is characteristic of a valvar stenosis; a more subdued thrill, arising apparently below the valve ring, with a more diffuse jet and less enlargement of the pulmonary artery suggests an infundibular stenosis. The two conditions

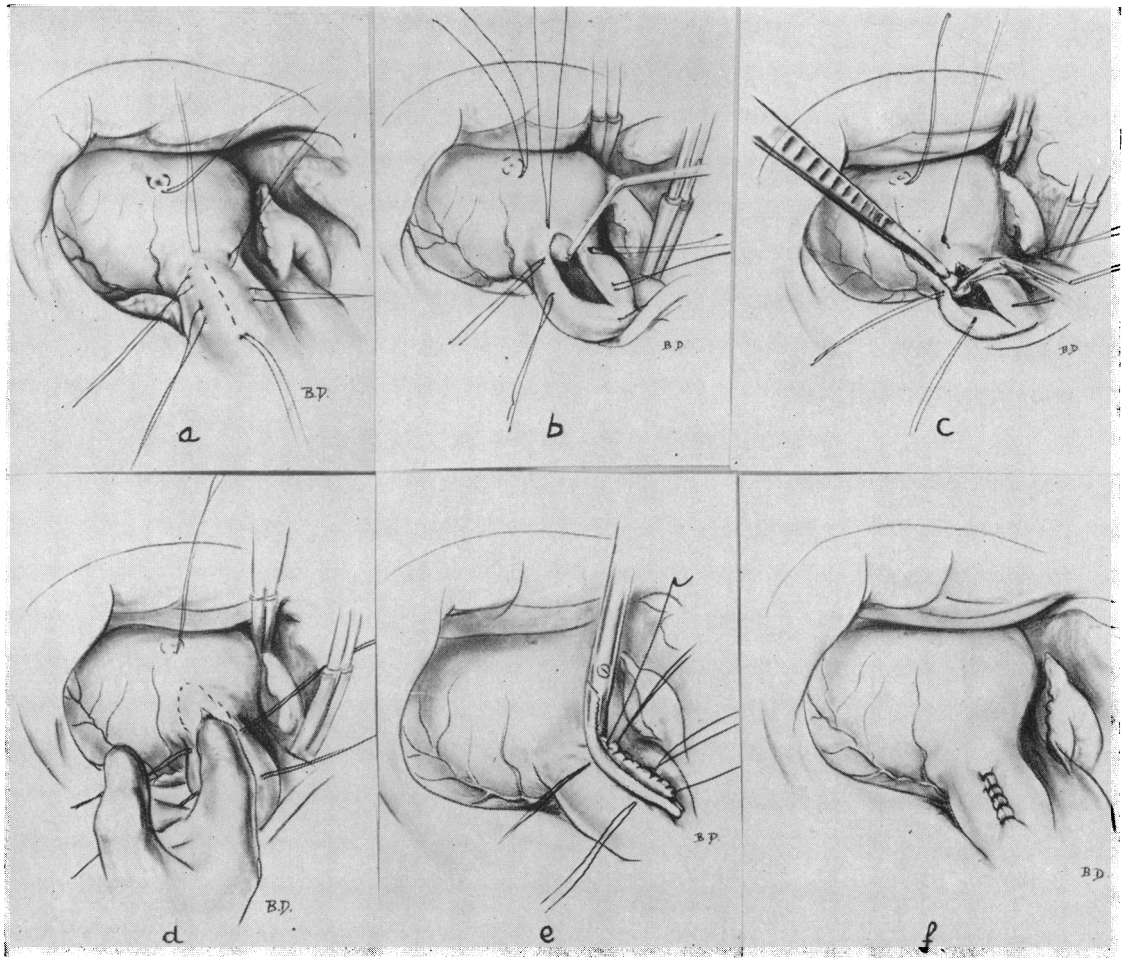

FIG. 2.—Operation of transarterial pulmonary valvotomy. (a) Line of incision in pulmonary artery. (b) The stenosed valve is exposed. (c) The valve is cut into a bicuspid structure. (d) A digital check is made to ensure that there is no residual organic stenosis in the outflow tract. (e) The incision in the artery is clamped and sutured. (f) Final appearance.

may be present at the same time. Occasionally the ostium in the pulmonary valve is obliquely situated and the jet strikes one side of the pulmonary artery producing a unilateral bulge in this position. Palpation of the outflow tract of the right ventricle is again informative. A high pressure contractile ventricular wall up to the valve ring is in favour of a valvar stenosis. A thick ventricular wall below the valve ring with little pulsation suggests a tubular infundibular stenosis, and the presence of a low pressure infundibular chamber is confirmation of a diaphragm-like stenosis below it.

A check of the pressure gradients across the stenotic area is made by inserting a Mason's malleable metal catheter into the right ventricle just below the site where the stenosis is judged to be, a fine silk purse-string having been sutured into the ventricle to control any bleeding from it. The catheter is passed upwards into the pulmonary artery and it is then directed downwards well into the ventricle so that no secondary stenosis is missed. Pressure tracings are taken during insertion and withdrawal and these can be compared with the tracings made at the preliminary cardiac catheterization. This metal catheter is particularly useful in judging the nature of the obstruction and the size of the ostium, as it is rigid enough to transmit tactile sensations to the fingers.

The superior and inferior venæ cavæ are exposed intra-pericardially and rubber catheters passed round

them. Pieces of rubber tubing are passed over the two ends of each of the catheters and are clamped after drawing the catheter through them when obliteration of the vessels is required. If a left-sided superior vena cava is present, control of this vessel will also be required. A trial compression of the cavæ for about one minute is now performed and the outflow from the right ventricle into the pulmonary artery is studied. In the absence of a left-to-right shunt, the pressure in the pulmonary artery falls in 10–15 seconds to near zero and the coarse thrill disappears. The right ventricle collapses. With an associated atrial or ventricular septal defect, the pulmonary artery pressure only falls slowly, and in the presence of such a shunt more blood may be lost at the time of relief of the stenosis. The caval inflow is now re-established by releasing the tourniquets.

Stay sutures of 000 silk are inserted into the pulmonary artery for a distance of 3 cm. upwards from the valve ring, and a lateral clamp applied to the artery pinching up the portion of the vessel wall controlled by the stay sutures. It may well be advisable to try three or four different clamps for it is important that this clamp fits comfortably and can be re-applied without difficulty. We have found Pott's spoon-shaped clamp to give the best control in most cases. Care must be taken, when this clamp is applied or at subsequent application, that the coronary artery which is running laterally just below the valve ring is not compressed or included. The portion of the pulmonary artery within the clamp is incised for some 2·5–3 cm., and a stay suture put through each edge of the artery so that the lumen will be held open after release of the clamp.

This completes the preparation for exposure of the valve and the anæsthetist hyperventilates the lungs to ensure maximal tissue oxidation. The caval tourniquets are tightened and the right and left and pulmonary circulation allowed to empty for 30 seconds. The main pulmonary artery distal to the lateral clamp is occluded with a Crafoord clamp. The lateral clamp on the pulmonary artery is then removed and the sucker inserted to the valve to keep it clear of blood. Very little blood should be lost and a completely clear view of the valve should be obtained. The valve is picked up with a tissue forceps and two opposite cuts made with scissors down from the meatus to the valve ring. Dividing the diaphragm into a bicuspid valve appears to give greater freedom from regurgitation than if a tricuspid opening is made, as frequently the valve is so stretched and elongated by the ventricular hypertension that there is danger of one of the artificially produced segments turning inside out, as they have not the formed structure of normal cusps. Severe pulmonary regurgitation, while not productive of any immediate symptoms, is likely to be associated with progressive right ventricular enlargement in the future. Provided the division in the valve is made to the periphery the functional opening appears to be entirely satisfactory. In infants the valve is surprisingly tough and may cut like ligamentous tissue.

The forefinger is passed through the divided valve to check that the division has been as complete as possible. The finger is advanced into the ventricle to examine the outflow tract and to exclude the presence of an additional infundibular stenosis. If this is present then the thickened wall or diaphragm will require removal with a punch. A true infundibular stenosis is felt as a fibrotic thickening with some obstruction to the finger. When, however, the finger is intermittently gripped by the hypertrophied muscle, and the lateral angiogram has demonstrated a good opening of the area in late diastole, no further removal of tissue appears to be indicated. A maximum of three minutes is allowed for the whole procedure. This is quite adequate to deal with a diaphragmatic valve but not always with an infundibular stenosis completely. The stay sutures are elevated and the lateral clamp is re-applied on the pulmonary artery; the distal transverse clamp on the pulmonary artery is loosened; and the tourniquet on the superior vena cava is released first, when the heart will start to beat strongly, often with some tachycardia. The inferior vena caval tourniquet is only released gradually, as there is a tendency to dilate the right ventricle if all the blood dammed up on the venous side is allowed to rush into the heart. Pulmonary hyperventilation is maintained for two or three minutes and the tachycardia rapidly settles down. The pulmonary artery incision can then be sutured with a continuous 000 silk and the stay sutures tied across to support the incision; but if a further procedure is necessary on the stenosis, the circulation should be allowed to continue for five minutes. At the end of this time, the inflow can be re-arrested, the clamp removed from the incision in the pulmonary artery and the operation carried a further stage. The whole procedure can be repeated if necessary, and when the outflow tract of the right ventricle is free of obstruction to finger palpation the artery is finally sutured. In the diaphragmatic type of infundibular stenosis, it may be more convenient to insert the punch forceps through a purse-string controlled incision in the infundibular chamber and guide the forceps with the finger passed through the incision in the pulmonary artery.

Pressure readings are taken from the ventricle as before. The flow into the pulmonary artery is now a diffuse surge, the pressure in the artery is raised, and the right ventricular pressure has fallen. A soft systolic

thrill usually persists. As discussed subsequently complete elimination of the gradient across the stenosis may not be obtainable at this stage, but if the opening is satisfactory to sight and by palpation, then the long-term result should be good.

The small hole in the ventricle that was used for the pressure readings may require a suture, but it is preferable, if possible, to remove the suture and keep a pad on it for a few minutes to permit spontaneous closure. The pericardium is partially closed. Drainage of both sides of the chest is undertaken when a bilateral thoracotomy is used, but with a median sternotomy usually the right side only is drained after the right mediastinal pleura has been opened widely: if the left mediastinal pleura has been accidentally opened to any degree a left-sided drain also is inserted. The patient should not be returned to the ward before consciousness is fully restored.

Post-operative Course

An oxygen tent is imperative for these patients as they frequently show cyanosis in the first 24 hours after operation. The cause of this is not clear but the cyanosis appears to be peripheral in type. It is not uncommon for signs of hypovolæmia to be noted with a fall in blood pressure and tachycardia some 3–6 hours after the operation. The explanation for this may well be that, although a complete replacement of the known blood loss has been made, the opening up of the pulmonary vascular bed, following the more direct communication with the right ventricle, results in a relative general circulatory oligæmia. The condition certainly responds dramatically to a further blood transfusion. It has now become our custom to continue the transfusion in the post-operative stage and to give more than the total collected in the drainage bottles. The administration of an additional 10 per cent of the calculated blood volume of the patient should compensate for the original pulmonary oligæmia.

The drainage tubes are removed in 24–48 hours, and in association with this there is one important complication common to all bilateral chest operations. If any air leak into the chest occurs at the time of tube removal, or if the tube incision is not effectively sealed afterwards, bilateral pneumothorax will occur. This is difficult to diagnose clinically if only moderate in amount, as the breath sounds appear equal on both sides and there is no tracheal or cardiac displacement. The patient may develop dyspnœa, some cyanosis, and tachycardia, for no apparent reason until a chest X-ray reveals the cause. If these symptoms develop, even in the middle of the night, it is important that a chest X-ray be considered.

The relation of coccal infection to these operations is of significance. After a valvotomy, and in particular an infundibulectomy, a considerable area of the internal heart wall is left uncovered by endothelium for some days or even weeks, and is thus particularly susceptible to develop vegetations if any form of bacteræmia is present. It is advisable to delay operation if there has been any recent throat or skin infection, and any form of obvious sepsis should be completely cured. The healing of the transverse chest incision in the midline of the sternum may sometimes give trouble. If wound separation occurs in this area it may expose the sutures that have been inserted through the bone and a secondary infected discharging sinus will develop. The sinus will not heal until the sutures are removed and this entails dragging the suture material through the marrow cavity of the sternum. In view of the free communication of this cavity with the circulation, any organisms on the suture can be responsible for a bacteræmia and possible endocarditis. Such a train of events occurred in one case in this series following the removal of a transternal suture some weeks after an infundibulectomy. A staphylococcal septicæmia followed and responded only intermittently to antibiotics: death occurred three months later, and autopsy showed the infundibular region to be covered with vegetations. We have since abandoned the use of any trans-sternal suturing, and the median sternotomy now employed can be well controlled by peristernal sutures of chromic catgut.

Results

Operation has been performed on 92 patients with obstruction to the outflow tract of the right ventricle: 77 had a pulmonary valvotomy, 16 by the transventricular route and 61 by the open transarterial route, and in five of these an infundibulectomy was considered necessary and carried out at the same time. The other 15 had resection of an infundibular stenosis either by the transventricular route or through a subvalvular chamber. Two patients had an atrial septal defect closed at the same operation, and one had a ligation of a patent ductus arteriosus. The age groups are shown in Table I.

TABLE I

AGE INCIDENCE OF PATIENTS

	With intact ventricular septum				With ventricular septal defect (Fallot type)			
Number	59 (28 male, 31 female)				33 (20 male, 13 female)			
Age years	TVV	OTAV	OTAV and Inf.	TV Inf.	TVV	OTAV	OTAV and Inf.	TV or TC Inf.
0–1	—	2	—	—	1(+)	—	—	2(+)
1–2	—	1	—	—	1	1	—	—
2–3	—	2(+)	—	—	—	2	—	1
3–4	1	1	—	—	—	—	1	—
4–5	—	1	—	—	3(+)	—	—	2
5–9	5(+)	13	—	2	2	4(+)	1	3(+)
10–14	—	16	1	2	1	2	2	2(+)
15–19	2	4	—	—	—	—	—	—
20–29	—	6	—	—	—	1(+)	—	1
Total	8	46	1	4	8	10	4	11
Deaths	1	1	—	—	2	2	—	3

TVV—Transventricular Valvotomy.
OTAV—Open Transarterial Valvotomy.
Inf.—Infundibulectomy through the opened valve.
TV or TC Inf.—Transventricular or Transchamber Infundibulectomy.
(+) Death.

Nine patients died either during the operation or soon after. Three of these were infants under the age of four months (two urgent infundibulectomies for Fallot's tetralogy and one urgent transarterial valvotomy for pure valvar stenosis). Seven of the nine died with cardiac failure within 48 hours of the operation, no other cause being apparent at autopsy. One patient, a girl of twenty with an associated ventricular septal defect, developed progressive dyspnœa and tachycardia, apparently from the production of two large a left-to-right shunt, perhaps with some rise of pulmonary arterial pressure, and died twelve days later. The ninth died of Staphylococcal septicæmia three months later, the apparent cause being the removal of unabsorbable transternal sutures in the base of a suppurating wound.

Sixty-one patients had an open transarterial valvotomy without hypothermia with three deaths, two with cardiac failure (one on the table and one within 48 hours) and one with the situation just described. In no patient in the whole series was there any suggestion of cerebral damage.

It is difficult to assess the clinical results of these operations. Many of the children had minimal symptoms before, even though the right ventricular pressure in some was 150–200 mm. Hg, but their parents noted increased exercise tolerance after. In children with valvar stenosis with intact septum in whom the valve has been opened under direct vision, the child might be expected to be able to live a full and active life. In cases of Fallot's tetralogy the subsequent result was variable depending essentially upon the relative size of the pulmonary artery and aorta, and while some patients are now very satisfactory, others are still somewhat cyanosed with limited activities. In adults, some improvement in the dyspnœa is quite clear, but restoration to full normal activity, including strenuous exercise, is slower.

The results after "infundibulectomy" were less satisfactory than those after valvotomy and there is little doubt that a cardio-pulmonary by-pass is required to give the time for a really adequate relief of the obstruction to the outflow tract of the right ventricle.

It is too soon to say how far the electrocardiograms of the patients with an intact septum who have had an open pulmonary valvotomy will improve, for the time taken for the regression of the right ventricular muscle hypertrophy is unknown. The electrocardiograms of 20 cases of

uncomplicated pulmonary valvular stenosis submitted to open transarterial valvotomy in this series and followed up for a period of one to four years have been examined by Professor John Hay and Dr. Olive Scott: 17 of the 20 showed evidence of R.V. hypertrophy in the pre-operative records and after valvotomy. (a) Nine developed an rsr′ or rsR′ pattern in V3R and V1, (b) one showed splintering of the upstroke of the R wave, (c) three showed a decrease in the height of the R wave alone, and (d) four showed no change in the height of the R wave. Three of these patients have not been re-catheterized, and one has a RV pressure of 60 mm. Hg at re-catheterization at six months. Six of the 17 had evidence of R.V. strain (S–T depression with deep inversion of T wavein V3R and V1) as well as hypertrophy and this strain pattern disappeared in five of them.

Of the remaining three, one had an rsr′ pattern before valvotomy and afterwards an rS complex in V3R and V1, one had an rsr′ pattern before valvotomy and this persisted after it, and one had a normal record before operation (R.V. pressure 96/0, P.A. pressure 13/7) and this has remained normal.

A systolic bruit is still audible over the pulmonary valve in all patients, but is soft and very different from the previous harsh murmur.

In a few patients a short pulmonary diastolic bruit is now audible indicating a degree of pulmonary regurgitation. The pulmonary component of the second heart sound has usually become louder. Radiologically the pulmonary vascular shadows become fuller, but the shadow due to the post-stenotic dilatation of the pulmonary artery alters little, at any rate for the few years that we have followed these patients.

Discussion

The ultimate object of the operation in the presence of the intact septum is to abolish the pressure gradient between the right ventricle and the pulmonary trunk, thus indicating that the right ventricular obstruction has been relieved. If little or no regurgitation at the valve has been produced then the future prognosis should be good. Many patients in whom an apparently complete opening of the pulmonary valve and outflow tract has been obtained under visual and tactile control have still retained a gradient between the ventricle and artery of some 50–80 mm. Hg at the end of the operation. This, on the face of it, appears disconcerting and would suggest that further removal of some of the wall of the infundibulum should have been undertaken. No fibrotic obstruction was palpable in such cases but the finger was heavily gripped by the hypertrophied infundibulum during the late phase of systole, and this was particularly noticeable when the right ventricular pressure was very high. A study of the position where the pressure gradient changes shows that before valvotomy it is at the level of the valve and after valvotomy it is lower down at the commencement of the outflow tract of the ventricle.

The mechanism of this phenomenon appears to be that in the presence of a valvar stenosis, although the infundibulum has taken part in the general muscle hypertrophy in the right ventricle, it can still be momentarily dilated by the high systolic pressure in the ventricle as it contracts to force blood through the stenosed orifice. The ventricular wave of contraction starts in the septum and works its way around the apex up to the base of the heart, and thus while the apex of the ventricle is contracting the outflow tract is relaxed and is kept open by the build up of pressure behind the valvar diaphragm. After relief of the valvar stenosis the blood can get away into the low resistance pulmonary circulation so quickly that no such build-up is possible and the hypertrophied infundibulum becomes itself a muscular obstruction. Following relief of the mechanical obstruction by valvotomy, the possibility of a slow but progressive diminution in this functional obstruction associated with the regression of the ventricular muscle hypertrophy should be envisaged. That this in fact takes place in some cases has been suggested by the electrocardiographic changes occurring in the months subsequent to the valvotomy. Re-catheterization studies in patients presenting this phenomenon confirms these observations. This has been shown by Johnson

TABLE II

PRESSURES BEFORE AND AFTER OPERATION

	Age (years)	Pre-operative		Post-operative		Re-catheterization		Time
		RV	PA	RV	PA	RV	PA	
M.R.	15	120/0	8/3	50/0	22/16	40/0	22/8	1 yr.
C.N.	9	108/0	13/5	Raised but damped		24/2	16/3	1 yr.
B.L.	11	180/0	14/12	50/10	30/20	35/0	24/0	1 yr.
E.J.	6	240/0	15/9	110/0	30/15	60/0	?	6 mo.
J.C.	15	186/0	17/6	90/0	24/6	45/0	26/5	5 mo.
S.B.	12	250/0	6/3	100/0	20/?	24/0	17/8	9 mo.

(1959) and Campbell (1959) also. If the lateral selective angiocardiogram shows that a full opening of the outflow tract occurs in diastole and early systole and no organic obstruction is palpable on passing the finger into the infundibulum, then even when some ventricular-arterial gradient is still present after valvotomy, no further procedure on the infundibulum is indicated.

By using the technique described no evidence of cerebral damage has been noted and, except for those that died during the operation, all patients have been fully awake and responsive when it was finished. It has not yet been established for how long circulatory occlusion can be tolerated by the brain at normal temperatures without evidence of damage. An important factor in preventing damage would appear to be an instantaneous re-establishment of a good cerebral circulation after the occlusion has ended. This occurs when the operation is done at normal temperatures.

Now that the successful reconstruction of the normal anatomy in cases of Fallot's tetralogy can be accomplished with reasonable safety (Kirklin *et al.*, 1959) with the use of a cardio-pulmonary by-pass, pulmonary valvotomy or infundibulectomy as a separate entity will certainly be practised less for such patients. As an emergency procedure in infants and young children, a Blalock's systemic-pulmonary anastomosis would appear to be adequate in most cases to carry them over to the age when a bypass can safely be used. Furthermore, the undertaking of a valvotomy or infundibulectomy in infancy is likely to make the subsequent full repair technically more difficult as a result of adhesions around the great vessels and within the pericardium.

SUMMARY

Observations are made on 92 cases of pulmonary valvotomy or infundibulectomy. The results with transventricular "blind" valvotomy in 16 cases were not considered satisfactory. The results of infundibulectomy were not fully satisfactory by transventricular or transarterial routes and such cases are better operated upon with the use of a cardiopulmonary bypass.

Transarterial open pulmonary valvotomy was performed on 61 patients at normal temperatures with three deaths, and a description of the technique is given.

If the gradient between the right ventricle and the pulmonary artery is not obliterated at the end of the operation, no further treatment for the infundibular obstruction is needed, provided the pre-operative lateral angiocardiogram demonstrated a fully opened outflow tract of the right ventricle and no fibrotic stricture is palpable. The gradient will fall during the succeeding months with the decrease in the infundibular muscular hypertrophy.

I am very grateful to Mr. John Bickford for permitting me to include the many patients on whom he has operated in this series. Most of the patients have been investigated and presented for surgery by Professor John Hay, Dr. Gordon Farquhar, Dr. Olive Scott, and Dr. W. S. Sutton. To them and to many other physicians and members of the team I am deeply indebted. To the skill in anæsthesia of Dr. G. Jackson Rees, Dr. Alan Stead, Dr. Noel Fenton and Professor T. Cecil Gray I pay tribute.

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