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A DECADE OF CARDIAC SURGERY*

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The present stream of cardiology is so broad that no physician or surgeon can claim to have mastered all its reaches. Since the simplest cardiac operation requires a knowledge of anatomy, physiology, pathology, and pharmacology, the anaesthetist and surgeon must be members of a team, the leadership of which must inevitably change from time to time.

Ten years ago surgeons thought they were entering a period of relaxation after three new technical procedures, initially difficult, had been mastered. Gross and Hubbard (1939) had established the need for and method of closing the ductus arteriosus, and Gross (1945) and Crafoord and Nylin (1945) had successfully operated on coarctation of the aorta. Blalock, having described with Helen Taussig (1945) his operation for increasing the blood flow to the lungs in congenital cyanotic heart disease, could record three years later the results of 610 operations performed for congenital cyanotic heart disease in the same year that the real surgery of the heart valves was initiated. Sellors (1948) and Brock (1949) performed the first direct operations on the stenosed pulmonary valve; Bailey, Brock, and Harken all operated successfully for mitral stenosis and opened the most successful chapter in the treatment of disability due to this disease since William Withering introduced digitalis.

The profession which had slept so long, nearly 25 years after Souttar's solitary successful effort to explore the mitral valve, suddenly awoke to the possibilities of surgery in this common disease. The time was ripe for a great surge forward: Forssmann's (1929) introduction of a cardiac catheter into the human heart had been applied by Cournand in America and MacMichael in this country to the study of pulmonary blood flows and pressures and of pulmonary hypertension: the haemodynamics of the circulation could be studied before and after operations on the mitral valve. But it must not be forgotten that the pioneer work of Brock, Bailey, and Harken was based on their obstinate belief in the surgical principle of relieving obstruction.

The rude shattering of the opinion that disease of the heart muscle accounted mainly for the symptoms in mitral stenosis has revived cardiology and encouraged the study, by direct observation in the theatre, the radiological department, and the laboratory, of many cardiac disorders.

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I.—THE EVOLUTION OF SOME ESTABLISHED OPERATIONS

(a) Constrictive Pericarditis

By 1948 a working knowledge of this condition existed and many pericardiectomies had relieved the strangled heart and improved the diastolic filling of both ventricles. Most of us would regard the pericardiectomy of ten years ago as inadequate by present standards; attention has been paid not only to an anterior decortication of the ventricles but to liberating the posterior surface of the left ventricle and at times of the atria. Catheter studies usually demonstrate pulmonary hypertension of the type often seen in mitral stenosis, but the impairment of right ventricular filling by the disease process masks this clinically so that dyspnoea is not a severe symptom except in advanced, neglected cases. It is equally important to recognize the group with signs and findings on cardiac catheterization reminiscent of those of tricuspid stenosis, for extensive pericardiectomy over the right atrium and ventricle is necessary in this event.

The main changes have been: (1) the earlier recourse to surgery even in the presence of active tuberculosis, streptomycin being the efficient watchdog of the infective side of the process; and (2) the tendency to carry on the clearing of the heart more and more to the left and to use an approach consisting of a bilateral thoracotomy with transverse division of the sternum. By this exposure a really adequate liberation of the heart in all areas is possible and safe. In ill patients presented late for surgery a less radical operation through a left antero-lateral transpleural approach is used.

(b) Persistent Ductus Arteriosus

By 1947 the diagnosis and surgical treatment of the uncomplicated ductus was established and few problems seemed to be left; but discussions have since ranged around the ideal age for operation, whether ligation or division is indicated (I practise division, as it fulfils surgical precepts; it is obligatory for the broad ductus), and the procedures to be employed when pulmonary hypertension has developed.

Age for Operation.—Increasingly more infants with heart failure due to a wide persistent ductus are being operated upon; dyspnoea, repeated lung infections, enlargement of the heart, with electrocardiographic

changes in infants who do not thrive from birth onwards, are the signposts indicating operation as a matter of urgency. In the symptomless group, the age of 3 to 4 years is a satisfactory time for surgery, as the technique of the operation is simple at that age, there is no interference with schooling, and the risk of pulmonary hypertension or of subacute bacterial infection is largely prevented.

It is curious that Maude Abbott's (1937) statistics, which showed that 48 of 242 deaths from a persistent ductus occurred in the first year of life, have received so little attention. The diagnosis at this age is not easy on clinical grounds alone; infants without cyanosis admitted in heart failure, with an enlarged heart with a systolic murmur only, may be suffering from coarctation of the aorta, ventricular septal defect, common atrio-ventricular canal, or a persistent ductus. Under medical treatment the infants with a ductus may convert this systolic murmur into a typical machinery one, but by no means always. In these infants, who may be only a few weeks old, cine-angiocardiology is safer than aortography in establishing the diagnosis. (Dr. R. Astley, my radiological colleague, kindly allowed me to show a film which illustrates the diagnostic points in left-to-right shunts in infants.)

In the 12 infants I have operated upon, the ductus has always been large and the typical lung biopsy appearance has revealed what Edwards (1955) regards as the foetal type of smaller pulmonary artery; these vessels show muscular hypertrophy and excess of elastic tissue. This "foetal" appearance is seen in other left-to-right shunts such as atrial septal defects that have caused pulmonary hypertension (Heath and Whitaker, 1957) but often show severe destructive changes when the shunt is of some duration.

These infants had severe lung symptoms with heart failure of varying degrees and transient cyanosis in five. The rapid restoration to health of the nine survivors suggests that, if pulmonary hypertension existed, it abated even when cyanosis had been present. This picture is very different from that seen in older children and adults with hypertension. If the flow of blood is balanced or has been reversed as a result of a steady increase in right ventricular pressure—the "atypical ductus" with a systolic murmur—the surgical problem is difficult. If the shunt is reversed to produce classical differential cyanosis, surgical closure will not reverse the changes in the irretrievably ruined lung vessels. In the only patient with this type of ductus on whom I have operated death followed 24 hours later. The pathological details of this case were published (Brewer, 1955). There was widespread occlusion of the pulmonary arteries by fibrous tissue, and many arteriovenous communications were noted. The real problem concerns those patients with a balanced or near-balanced shunt with pulmonary hypertension.

Ductal Occlusion in the Presence of Pulmonary Hypertension

Surgery can help some patients with hypertension. Such have large hearts, a systolic murmur, respiratory symptoms, and easy fatigability. Ziegler (1955) accurately delineates two types, and our experience confirms his grouping.

1. *Ductus Arteriosus with Moderate or Marked Pulmonary Arterial Hypertension and Increased Pulmonary Blood Flow.*—Here there is a capillary or post-capillary hypertension diagnosed by finding an elevated pulmonary "wedge" pressure by cardiac catheterization. The electro-

cardiograph often shows right ventricular hypertrophy and pulmonary hypertension of a predominantly diastolic type; urgent division of the ductus, which will be large, is indicated and the changes in the lung vasculature are reversible.

2. *Ductus Arteriosus with Marked Pulmonary Arterial Hypertension and Normal or Decreased Pulmonary Blood Flow.*—Because of permanent damage in the pulmonary arterial tree at the pre-capillary level the "wedge" pressure will not be raised, and this finding in a patient with right ventricular hypertrophy and a high pulmonary artery pressure is certain evidence of increased pulmonary artery resistance; radiologically the lung shows decreased pulmonary vascularity and the electrocardiograph invariably denotes severe right ventricular hypertrophy: the patient may be permanently cyanosed. Surgical occlusion is contra-indicated.

Whenever operation is carried out on a ductus with a systolic murmur direct pressures are taken in the aorta and the pulmonary artery before the ductus is clamped and immediately after the clamping: if the pressure rises in the pulmonary artery in adults, the operation should be abandoned; in children, however, the clamp is left on for 15 minutes; if the right ventricle continues to behave well the ductus can be divided: such children usually have a difficult convalescence for the first few days but then recover steadily.

Much misunderstanding results from the statement that pulmonary hypertension contraindicates surgery in the treatment of left-to-right shunts such as ductus arteriosus or atrial or ventricular septal defects; what really is meant is that surgery is valueless when the pre-capillary vasculature has deteriorated so disastrously under an attitude of "wait and see" that the patient has entered the stage when reversal or balancing of the shunt is associated with marked pulmonary arterial hypertension but a decreasing pulmonary blood flow into the left atrium.

The Complicated Ductus

Operations on a typical uncomplicated ductus carry a low mortality rate. In my own series of 180 operations 141 were of this type, and there has been one sudden death two weeks after operation, when the patient was at home. The remaining 39 patients were complicated in various ways and the mortality rate was high, with 10 deaths (Table I).

TABLE I.—Results of Surgery in 39 Complicated Cases

	No.	Deaths	Ages
Infants with cardiac failure	12	3	1-23 months
Associated defects (V.S.D., A.S.D.,* coarctation, congenital mitral stenosis)	7	0	3-10 years
Cardiac failure or pulmonary hypertension	12	3	(4, 4, 6, 6, 11, 12, 23, 24, 38, 45, 47, 55)
Infected	8	4	(8, 11, 13, 17, 27, 30, 31)

* V.S.D. = Ventricular septal defect. A.S.D. = Atrial septal defect.

The "cardiac failure" deaths included three infants with severe pre-operative failure: one was an infant of 21 months who died seven days after surgery; a false aneurysm developed and ruptured into the left lung—an example of staphylococcal infection. A boy of 6 with great cardiac enlargement had been thought to have a ventricular septal defect for several years; the murmur was systolic, and there was right ventricular hypertrophy and pulmonary hypertension. The ductus was clamped for 15 minutes, and, as the right ventricle behaved well, the ductus was divided; he died the next day. Necropsy revealed an unsuspected gross mitral regurgitation due to fibroelastosis; there were advanced changes in the pulmonary artery, and the vascular obstruction was clearly pre-capillary. Another death was that of a woman of 24 with differential cyanosis, to whom reference has already been made—a further example of pre-capillary hypertension and really inoperable. The sixth death was in a man of 45 with increasing dyspnoea who at

operation had severe degenerative arterial changes: a tear occurred in the aorta which proved fatal.

Of the four fatal cases of subacute bacterial endocarditis one had a mycotic aneurysm of the left lung in addition to gross infection at the site of the ductus. The second was a girl of 17 with heart failure in addition to the infection; she had a large ductus which I ligated (it should have been divided): recurrence followed, and two further attempts were made to close this ductus, at the last of which fatal haemorrhage occurred. The third was a child of 8 who, in addition to the infected ductus, had syringomyelia and tuberosclerosis. The last case, a boy of 11, had gross infection of the pulmonary artery and was an operative fatality.

Division of the Ductus in the Presence of Associated Anomalies

If a ductus is associated with a post-ductal coarctation of the aorta there can be no doubt that surgery at an early age to correct both defects is indicated: the delivery of the extra blood from an aorta in which the pressure is abnormally high increases the risk of early pulmonary hypertension. A persistent ductus is said to be present in 10% of patients with coarctation of the aorta.

It is in combination with other cardiac abnormalities, such as septal defects, that ductal occlusion, though helpful, is clearly not the full solution. After studying sizes of hearts before and after ductal occlusion on many patients it was noted that the size decreased in all but five: these all had associated septal defects, and, although the children are well, their future cannot be regarded without anxiety, and the possibility of their being operated on to close the defects by open cardiectomy is being considered. If infants with severe symptoms and a proved ductus have an associated septal defect, closure of the ductus alone may be life-saving.

In two children a large ductus has been associated with congenital mitral stenosis. These have been described (Bower *et al.*, 1953). One child who was in severe respiratory distress survived mitral valvotomy and is still alive and well four years later, though far from cured. At the operation pressures were taken in the aorta and pulmonary artery before and after temporary clamping of the ductus; this occlusion caused a steep rise in pulmonary artery pressure. The left atrium was then explored and a congenitally tight mitral stenosis opened: the pressures in the pulmonary artery, however, still showed a rise when the ductus was temporarily occluded; it was not divided, as it clearly served a function in lowering the pressure in the lung vessels. The second child who was operated upon died: extensive changes in the heart characteristic of fibro-elastosis were found at necropsy.

(c) Coarctation of the Aorta

In the management of classical coarctation of the aorta (the post-ductal or adult type) opinion has steadily veered towards the surgical view that good relief of the aortic obstruction will lower the blood pressure and prevent the more disastrous complications of this condition. No one, however conservative, doubts the malignancy of coarctation in most patients, and no one is ignorant of the fact that a few survive to a good age. Maude Abbott (Hamilton and Abbott, 1928) found that in 71% of 200 necropsy cases the patients had died before the age of 40. Reifenstein *et al.* (1947) found that 61% of his 104 patients suffered the same fate; in my own experience I have not seen any patients over the age of 40 without considerable symptoms, of which exertional dyspnoea has been the outstanding one. As the operation has been in wide use only since 1950 it is impossible to say whether it will prolong life. Since the mortality rate has been steadily lowered most cardiologists regard the risks of the natural course as being higher than those of surgery. During the developing stages of any major operation not only is technique hesitant but bad-risk patients are submitted.

In my own small series of 51 operations there have been five deaths: those of an infant, a girl of 17 with a large ductus who died at a second-stage operation in a technically mismanaged case, two young men (deaths being due to haemorrhage, one post-operatively, attributable to my technical imperfections), and a man of 50 with large intercostal aneurysms, uncontrollable haemorrhage occurring from the rupture of an aneurysm of the bronchial artery.

Gross (1953) reported that in his first 270 operations there were 15 deaths in the first 100 but only two in the last 100. Since operation is being advocated increasingly at ages between 6 and 10 (d'Abreu and Parsons, 1956) the mortality rate is falling sharply, the surgical procedure being simple in children and the convalescence rapid. Operation in childhood and early adolescence, when the aortic tissues are free from degenerative changes, seems to be the best way of avoiding complications such as subacute bacterial infection, the development of intercostal aneurysms (I have seen these at the age of 16), dissecting and non-dissecting aneurysms of the aorta, heart failure, and the effects of hypertension such as cerebral haemorrhage, often due to the rupture of berry aneurysms at the base of the brain.

Effect of Surgical Excision and Anastomosis on the Hypertension

If an anastomosis of good calibre is obtained, a fall in blood pressure in the arms and a development of good pulsation in the lower limb vessels will follow; the fall of brachial artery pressure may not be down to the normal of corresponding age groups (Cleland, 1955), but its lowering must surely be better than the acceptance by the patient of a hypertension that usually rises with the years. In children the falls in pressure are more satisfactory and far more immediate than in adults, though, as in them, the fall continues over the 18 months following operation.

In a boy of 14 with very large collaterals the result was bad, although I thought the anastomosis was a good one. Two years later aortography showed, in fact, narrowing at the anastomosis site; I reoperated on him, excised the strictured area, and inserted an aortic graft; this was followed by satisfactory lowering of the blood pressure.

In infants cardiac failure occurs quite often; in five years at the Birmingham Children's Hospital, Parsons (1955) found 30 deaths in infancy. With adequate medical treatment the infant may be tided over the failure, and, as Gross maintains, surgery can then be postponed. If, however, the condition continues to deteriorate surgery should be employed; disappointment may follow the operation, which is a simple one in infants, but, in my experience, has enabled four out of five infants to survive. Unfortunately fibro-elastosis is not an unusual concomitant. A coarctation with a ventricular septal defect has been resected in two, with survival.

The Lesser Circulation in Coarctation

Parsons in following up children after resection of coarctation has been struck by the constant insistence of the parents and children themselves that breathlessness has been abolished: this in spite of the fact that pre-operatively no mention had been made of dyspnoea. Recently Donald and Taylor, in Birmingham, have investigated the haemodynamics of the circulation before and after surgery, and their results will be published shortly. They have found evidence that a raised pulmonary capillary pressure in coarctation before operation has fallen to normal when measured six months or more after excision of the coarctation. It is also clear on purely clinical grounds that many children with pure coarctation have unexpected right ventricular strain.

Relief of Symptoms after Excision of Coarctation

Cleland *et al.* (1956), in reporting fully on 37 patients after operation, found them all in good physical condition with no recurrence of their symptoms. In 44 of my own patients, adequately followed up, I have found the same. In

children, symptoms are by no means infrequent. Parsons on following up 11 children found that 5 with pre-operative headache, 8 with abnormal feelings of exhaustion after exercise, and 2 with intermittent claudication had complete relief after surgery in addition to the abolition of dyspnoea, already mentioned.

At the moment, surgery is indicated in coarctation of the aorta in the early years of life (5-16), when a low mortality rate can be expected: the objection that the aorta will not enlarge with the growth of the patient has not been confirmed by laboratory experiments or by aortography done years after the resection in this group of patients.

Better anaesthesia with the use of hypotension produced by trimetaphan camphorsulphonate ("arfonad") for short periods during the excision and the anastomosis, the use of Potts's small-toothed aortic clamps, and Brom's approximating device have removed many technical difficulties. In all large centres the easy access to dry-frozen homografts has provided an extra source of confidence, though their use is rarely required in children and young adolescents; they have a wider place in adults whose complications, such as rigidity of the aorta and aneurysmal formations, occasionally make their use imperative, and they must be available in the theatre at every operation.

(d) Mitral Stenosis

By clinical and physiological measurements a well-performed operation on a valve with a critical degree of stenosis (1 cm.) relieves the dyspnoea and improves the haemodynamic picture of the circulation, especially on the pulmonary side. Since the operation has been practised widely for less than ten years the effect on the expectation of life cannot be assessed, but the quality of many lives has been dramatically altered.

From a clinical follow-up of the first 300 patients personally operated upon (Table II) the results are excellent in those with pure mitral stenosis, well compensated and in

TABLE II.—Results of 300 Mitral Valvotomies

Normal rhythm:			Fibrillation:		
Cases	166		Cases	134	
Deaths	5 (3%)		Deaths	10 (7.5%)	
Age	Cases	Deaths	Age	Cases	Deaths
10-19	11	0	40-49	85	8
20-29	59	1	50-59	19	3
30-39	126	3			

Eight deaths occurred among the first 100 patients, five among the second, and two among the third.

normal rhythm with pulmonary hypertension; they are good in similar patients with atrial fibrillation. The poorest results are in fibrillation with gross pulmonary hypertension and congestive failure. But it must be remembered that in this last, unpromising group startling results are occasionally obtained, and they should not be rejected lightly as candidates for surgery. If there are permanent severe changes in the smaller pre-capillary vessels the results, as discussed earlier in relation to the ductus arteriosus, will be bad, as the obstruction is no longer confined to the left atrium but is largely in the wrecked pulmonary artery system.

Most of the published studies of patients three or more years after operation concern those done in the early years of mitral surgery when the valvotomies were less thorough than those of to-day; none the less, all reports are remarkably consistent, with successful results of between 75 and 80%. In all centres patients are coming in small numbers with "re-stenosis" having taken place. I have had to re-operate on five patients, whose primary valvotomies were done three to six years ago. Although my own operation note on these showed that I was satisfied at the time with the valvotomy, to-day such an operation would not be regarded as really sufficient. As in all operations, experience leads to more thorough procedures, and this is so in mitral surgery. Re-stenosis occurs particularly when the valve mobility is poor, however good the split in the commissures. Re-stenosis is certainly a problem, but I doubt if it will be a

large one provided the original operation is thorough and a valve with mobile cusps is left after the splitting has taken place.

In the follow-up the bigger the size of the reopened valve the better has been the result; the poorest results, apart from grade IV patients, have been with heavily calcified valves, or where a funnel-shaped type of left atrium has led down to a stenosed orifice surrounded by cusps with shortened, thickened chordae tendineae.

The 300 patients were not all suffering from pure mitral stenosis, but it has been regarded as the predominant lesion: there were 15 hospital deaths, a mortality rate of 5%; in the last 100 cases there were two deaths, both fibrillators and both over the age of 40. It is a comfort to be able to tell prospective candidates for surgery in the age group 20-39 that the mortality risk is under 2% and that if they are not fibrillating it is under 1%.

Optimal Time for Surgery

Many patients are still being referred for surgery after the best time has passed. In the present series 11 of the 15 deaths were in patients over the age of 40. Surgery should be considered in all patients with progressive symptoms. When doubt exists about the severity of the symptoms (often underrated by a patient used to dyspnoea), if cardiac catheterization shows evidence of right ventricular overwork, a fixed cardiac output, a raised pulmonary artery and wedge pressure, and increased ventilation and high oxygen uptake, then surgery is indicated. From a clinical assessment of these 300 patients, of the surviving 285 very good results have been obtained in 70%, great improvement in 10%, and the remainder (20%) have deteriorated or died, mainly from progressive cardiac failure. These results are very similar to those reported by Turner and Fraser (1956) in a progress report on the first 250 valvotomies performed in Logan's clinic in Edinburgh, by Mounsey (1957) on the results of 100 from the London Hospital, and in many other reports throughout the world.

Post-operative Changes in Circulatory Haemodynamics

Many studies of pre- and post-operative states have been published; I am quoting only from the studies of Donald and his colleagues (1957), because I am more conversant with their work and because their complete studies have not been widely read and are possibly unique in their thoroughness. In a study of 24 patients with clinically satisfactory results the striking changes were in the lungs. Ventilation at rest and on exercise was greatly reduced in most; the resting oxygen uptakes fell to normal in all but one, and this indicates the decreased work done on breathing. The mean pulmonary arterial pressure at rest fell after operation in all except two, but remained abnormally high on exercise. The pulmonary capillary wedge pressure was lowered in all; this, together with the decrease in ventilatory work and the loss of Kerley's lines (probably due to lymphatic fluid around the pulmonary veins), points to a relief in the post-capillary pressure in the lung vessels. The wedge pressure, however, still becomes elevated on exercise even in patients without clinical disability. The work of the right ventricle was greatly reduced to within normal limits. All these changes were present with no great increase in the cardiac output.

Changes in Technique

Reduction in the amounts of anaesthetic and relaxant drugs used, and the immediate correction of hypotension at any stage of the operation by small doses of nor-adrenaline run in through a separate intravenous infusion set, have much increased operative safety.

Increasing insistence on obtaining a really wide valve opening has meant that more instrumental valvotomies are being done if a purely digital commissurotomy is inadequate. Dubost (1955) has had excellent results by using a dilator

which is placed in the mitral orifice through the atrial appendage; Logan has, I believe, made this procedure safer and more effective by introducing a dilator through a tiny stab wound in the left ventricle: with the finger of the right hand in the left atrium the dilator is guided from below to lie accurately in the valve orifice so that it can be opened using bimanual control; it produces excellent splitting of both commissures. My own practice now is to attempt to divide the commissures with a Vernon Thompson finger-ring knife. If this fails I proceed to Logan's method. The latter method is of especial value when a large organized intra-atrial thrombus prevents the use of the atrial appendage for digital entry into the heart; the little finger is then introduced through a pulmonary vein or a small incision in the atrial wall, guarded by a purse-string suture, and the dilator passed through a left ventricular incision to be guided into place by contact with the little finger above the valve.

Management of Patients with Intra-atrial Clots

Patients with the indications for valvotomy who have had previous embolic episodes should on the whole be subjected to operation; in this series 30 patients with previous embolisms have undergone valvotomy with one post-operative embolism. The main cause for anxiety in a mitral valvotomy is the risk of post-operative embolisms; this risk is almost but not quite confined to fibrillators. At operation the atrial appendage should be opened before the atrial clamp is applied firmly, so that the gush of blood through the lips of the incision will wash away loose clots; temporary clamping of the branches of the aortic arch before and during any manipulations within the atrium may be indicated, and Barrett (personal communication) has found this to be extremely effective; I have, however, had two cerebral embolisms after very careful occlusion of the innominate and left carotid artery and can give no considered opinion on the value of the procedure, nor on the use of anticoagulant therapy which has been used in most of the fibrillators in this series.

When a large organized clot is present in the atrium it may be possible to remove it, but access to the mitral valve may have to be made around or under it via incisions in the atrial wall or through a pulmonary vein. A ball thrombus can be removed by a separate incision in the atrial wall through which it is levered out into and through the incision in the atrial appendage. The removal of these massive clots may possibly be better undertaken by the use of open cardiac surgery.

(e) Aortic Stenosis

In the past ten years the surgical relief of aortic stenosis has lagged behind that of mitral stenosis. In mitral stenosis relief can be afforded long before the patients are bad operative risks, however severe the symptoms. This is not so with aortic stenosis; deterioration when it comes is sudden, indicating a left ventricle in sad trouble; to await these symptoms is to find a patient with a short expectancy of living. In addition to this sudden clinical deterioration the recognized heavy calcification in many of these valves and the risk of producing incompetence have been factors inducing caution. Bailey (1955) pointed out that aortic valvotomy in a patient who also had established mitral stenosis is a far safer procedure when carried out concurrently with mitral valvotomy than in patients with pure aortic stenosis, since the mitral stenosis has protected the muscle of the left ventricle. If the gradient of pressure across the aortic valve is 50 mm. Hg or over with associated mitral stenosis, the aortic valve can safely be tackled at the same operation. Similarly, if a stenosed aortic valve with this sort of gradient can be opened without producing incompetence and before the left ventricular muscle has been overtaxed, the mortality will be below 10%.

In recent years new methods have enabled the cardiologist to know exactly the gradient across the aortic valve: for example by left atrial and left ventricular catheterization effected by passing a fine catheter through a cannula introduced into the left atrium through a bronchoscope (Allison

and Linden, 1953), by direct transthoracic atrial puncture (Björk, 1954), and by direct percutaneous left ventricular puncture (Brock, 1956). The last method is safe and can be carried out with a needle of moderately large bore, which cuts down damping effects. By this method surprisingly high pressures are disclosed in left ventricles even in children. Patients with classical aortic stenosis and a systemic blood pressure of over 120 may have a left ventricular pressure of 250–300; in one child of 12 with apparently minimal symptoms, though these included a genuine attack of coronary pain, a ventricular pressure of 250 was found, which after valvotomy fell to 140; more and more patients are being presented for surgery.

The technique of aortic valvotomy is a controversial subject. Bailey developed the transaortic approach, a patch of pericardium or plastic material being sutured to the lips of an incision in the ascending aorta; through this pouch digital and instrumental relief of the obstruction can be carried out, probably more accurately than through a ventricular incision into which is introduced a sound and a dilator. The transaortic method is more difficult technically than the use of a Brock dilator through the left ventricle. This instrument, properly used, need not produce incompetence, as the commissures, here as in the mitral valve, tend to split along the natural line of pathological fusion. The heavily calcified valve presents a problem of great difficulty, and operation in this type will naturally carry a greater risk of incompetence than operation on a valve with only fibrous fusion.

I have found satisfactory direct-vision surgery through an incision in the aorta under hypothermia with the venous inflow to the heart occluded and the aorta clamped off above the incision site (to prevent air embolism). I believe it is the safest method of dealing with the calcified valve. The important point is to think of surgical relief before the patient has degenerated into a severe surgical risk. At the moment a mortality risk of 5% in good-risk patients can be offered; if, as should be done on occasion, cardiac cripples with large left ventricles and anginal pain are accepted, a mortality rate of 40–50% is the rule.

(f) The Tricuspid Valve

Isolated tricuspid stenosis is rare; incompetence, usually functional, with mitral stenosis is not uncommon: tricuspid atresia can be diagnosed accurately by modern methods and can be dealt with through the right atrium. It is not such an easy valve to open as the mitral valve because of its three cusps. If associated with mitral stenosis it is often wiser to deal with the mitral valve and await the result of this and a further catheter assessment of the haemodynamics before embarking on the tricuspid valve.

Evidence of mitral stenosis with oedema but without real lung symptoms or a plethoric lung should lead to suspicion, especially if the oedema persists after a good mitral valvotomy: vigorous pulsation in the neck, with cyanosis, a large right atrium, and a lower diastolic murmur at the lower end of the sternum, suggest the diagnosis. The cardiac catheter will show characteristic pressure changes.

Changes in Attitude to the Heart

The success of operations on the ductus, the coarcted aorta, mitral stenosis, and in congenital cyanotic heart disease have shown that severely crippled hearts can stand up to long interventions under good anaesthesia. Anaesthesia has become lighter and lighter, with minimal doses of the drugs required to give relaxation and unconsciousness. Hyperventilation with full oxygenation prevents acidosis.

Firm manipulation of the heart without untoward results has convinced us, perhaps belatedly, of the truths taught us in physiology that the heart muscle is powerful, adaptable, and elastic; it will stand tourniquets applied to its inflow and outflow great vessels under hypothermia or with an extracorporeal circulation; when arrested chemically by

the potassium citrate method of Melrose (1953) its metabolism is so damped down that open surgery can be carried out for periods of well over 20 minutes. It will even recover after gross air embolisms into the coronary arteries.

The modern treatment of cardiac arrest is established. The direct transthoracic approach alone provides sufficient access for cardiac resuscitation in which the two main essentials are full lung oxygenation and manual massage sufficient to provide an easily palpable pulse in the carotids. Whether the heart is in complete asystole or in ventricular fibrillation the circulation to the brain must be maintained by manual compression for several minutes before recourse is made to drugs or to undertaking defibrillation. The method of defibrillating the heart by one or more powerful electric shocks is now effective, and no hospital to-day can be without its defibrillator. Of the drugs used, direct intracardiac adrenaline and calcium chloride are the most valuable.

Exposure of the Heart.—For procedures such as blind mitral, aortic, pulmonary, or tricuspid valvotomy, good exposure can be obtained through one pleural cavity (Fig. 1). In the last few years, however, increasing use has been made of bilateral thoracotomy with transverse section of the sternum. This exposure is necessary for open cardiomy under hypothermia or to establish an extracorporeal circula-

FIG. 1.—Exposure of the heart through left transpleural approach. This exposure is adequate for mitral valvotomy, blind pulmonary valvotomy, and blind aortic valvotomy. It is inadequate for open cardiac surgery.

FIG. 2.—Closure of atrial septal defect under direct vision. The heart has been exposed by a bilateral anterior thoracotomy with transverse division of the sternum. The superior and inferior venae cavae have been occluded by tapes passed through rubber tubing. The aorta and the pulmonary artery have been occluded by a clamp passing through the transverse sinus posteriorly. The right atrium has been opened and the septal defect is being sutured.

tion, and with the heart so exposed all areas can be examined fully (Fig. 2).

II.—DISSATISFACTION WITH BLIND PROCEDURES

At operation for mitral stenosis a careful assessment of the valve cusps, the size of the valve orifice, and the state of the chordae tendineae and their attachments can be made. It is difficult to imagine the discarding of this "blind" operation for open cardiomy in mitral disease. Attention is being focused on the possibility of open surgery in mitral incompetence which, it seems to many of us, only very careful plastic surgery can correct.

In addition to thousands of successful mitral valvotomies and many aortic valvotomies, relief of pulmonary valvular and infundibular stenosis, and the blind occlusion of atrial septal defects, have been achieved. It is with special reference to open surgery in pulmonary stenosis and atrial septal defects that I wish to speak. In his Simpson Smith Memorial Lecture of 1949 and in his latest book, Brock (1957) has described fully the anatomy of obstruction to the outflow track of the right ventricle; by resecting tissues causing obstruction to the infundibulum of this ventricle and by division and dilatation of a stenosed pulmonary valve by ingeniously designed instruments he proved that the pressure across these areas of congenital obstruction could be altered drastically; the results have continued to be good. In pure pulmonary valvular stenosis without ventricular septal defects most to-day would agree that evidence of right ventricular strain is an urgent indication for surgery. All cardiac surgeons have done this operation blindly; many have been disappointed to find months later that, though catheter evidence shows a decrease in right ventricular pressures and an increase in that in the pulmonary artery, the right ventricle shows persistence of hypertrophy; for this reason many of us prefer open valvotomy through the pulmonary artery, first performed by Swan (Swan *et al.*, 1953). This can be done safely under hypothermia at a temperature of 29–30° C., but naturally requires a wider thoracotomy than in Brock's operation.

Atrial Septal Defects

The frequency of this anomaly, at times associated with aberrant pulmonary veins draining into the right atrium and with pulmonary stenosis, and the usual clinical deterioration of the patient between 25 and 40, make the problem of surgical correction an important one. Campbell *et al.* (1957), after a full review of 100 patients, think the prognosis is rather worse than in ductus arteriosus. Reasonably good closure has been produced by sewing part of the redundant invaginated atrial wall to the edges of the defect, the suturing procedure being guided by a finger introduced into the right atrial appendage (Bailey *et al.*, 1953; Edwards *et al.*, 1955) or by the Sondergaard (1955) operation, in which a circumferential suture, accurately placed, approximates the anterior to the posterior wall of the defect. Another method, that of Gross (Gross *et al.*, 1952), consists in the use of a "well" sutured to an incision in the atrial wall through which, by digital contact, the defect is sutured or closed by the sewing in of a patch of plastic material: this method has been used extensively and safely by Kirklin, of the Mayo Clinic.

These methods, which are by no means discarded, have the usual drawbacks of blind surgery, and closure under direct vision under hypothermia is surgically more satisfying. None of the methods is applicable to that variation of atrial septal defect known as "the ostium primum defect" or "the persistent common atrio-ventricular canal." In this complicated anomaly there is a deficiency low in the atrial septum which involves also the top of the ventricular septum and is accompanied often by a cleft, incompetent mitral valve and sometimes by an incompetent tricuspid valve. Such a condition, which can be diagnosed accurately by correct interpretation of the E.C.G. and catheter findings, can be corrected only by open cardiomy with an extracorporeal

circulation, as the time required for the plastic repair much exceeds that provided by hypothermia. Besides blind repair is futile if the anatomy of the abnormality as seen at open surgery or necropsy is remembered.

Surgical Closure of the Ostium Secundum Defect under Hypothermia

Only a few technical points can be mentioned here. The operation should be done before the persistent large ventricular output has caused right-sided heart failure or fixed pulmonary hypertension, and long before the onset of cyanosis (in the absence of pulmonic stenosis) has indicated a reversal of the shunt. The operation is done before symptoms are clamant. In a young patient the beneficial effects of closure can be seen while the patient is still on the operating table, and the obvious diminution in size of the right atrium and the right ventricle is one of the dramatic sights of cardiac surgery.

Bedford *et al.* (1957) and Sellick (1957) have published a lucid account of their technique, surgical and anaesthetic, in the closure of 40 atrial septal defects with two deaths, and this is largely based on the work of Swan (Swan *et al.*, 1953). Of the three methods of producing hypothermia, by venovenous cooling (Brock *et al.*, 1956), by the blanket method (Inglis *et al.*, 1954), or by the method of immersion in a cold bath, they prefer the latter. I have used the blanket method and the cold bath, and find both satisfactory; the blanket method is less awkward and requires fewer people in the theatre for its management, but the rate of cooling is a little slower than by cold-bath immersion. As the temperature continues to drop as soon as the bilateral thoracotomy has been done, the operation can be started with the temperature between 30 and 31° C.

First the caval vessels are prepared for their temporary occlusion; it is important, however careful the pre-operative angiocardiographic and catheter studies have been, to look for two important associated abnormalities: (1) anomalous pulmonary veins draining into the superior vena cava or into the right atrium, and (2) supernumerary caval vessels. In one patient of 12 two superior venae cavae were seen, the left one as usual draining into the coronary sinus; and two inferior venae cavae, both fortunately draining into the right atrium. Sometimes the inferior vena cava, or an accompanying vessel, may drain wholly or partially into the left atrium. If a left superior vena cava is overlooked and not temporarily occluded during the cardiomyotomy a great volume of blood will flow into the coronary sinus and obscure vision.

Before the circulation into and out of the heart is occluded the right atrium is explored digitally to confirm the diagnosis. If the right ventricular pulmonary outflow tract or the pulmonary artery provides any appearance suggestive of stenosis, pressures should be taken in the right ventricle and in the pulmonary artery to estimate the gradient. Usually this diagnosis will have been made by pre-operative catheter or angiocardiographic studies. Should the stenosis be significant it is dealt with by open pulmonary valvotomy before the atrium itself is opened.

If an ostium secundum is present, the finger is withdrawn from the atrium, which is clamped; the circulation is then occluded by applying temporary compression to the caval vessels and the disappearance of the carotid pulsation is awaited: the aorta and pulmonary artery are then occluded with one large clamp, and the right atrium is widely opened by enlarging the previous incision made for the digital exploration. The blood having been rapidly sucked from the atrium, the defect, usually 2–5 cm. in length, sometimes with small secondary deficiencies, appears as a long slit which can be sutured with 000 silk (Fig. 2). Two sutures are used, each starting at the end of the defect; before these are tied together the anaesthetist exerts pressure on the lungs to drive blood on into the left atrium, which forces air from that chamber to the surface and out of the left side of the heart. This is further assisted by pouring into it

saline, under which the sutures are then tied to each other; the temporary clamping of the inferior vena cava is released, and when the right atrium is full of blood the incision in its wall is held in a clamp and the occlusion of the superior vena cava relaxed. When the heart is full of blood the clamp on the aorta and pulmonary artery is opened; usually the heart, which has been beating regularly throughout apart from frequent fibrillation of the right atrium, returns to normal rhythm. Should the ventricle fibrillate, massage is employed before defibrillation is undertaken: the condition of the heart will often improve if warm saline is poured over it to raise the local temperature. The incision in the atrium is then closed by suture.

Criticism has been made of the use of a simple suture of the defect, and recurrence has been regarded as probable. At open operation, however, the walls of the defect come together without any tension, and I believe rapid adherence is the rule; time will show whether this assumption is correct: experienced surgeons such as Kirklin believe that the incorporation of plastic material is helpful.

The ease of right atrial cardiomyotomy can be made use of for the open surgery of the stenosed tricuspid valve, and, as Chin and Ross (1957) have shown, for the removal of a myxoma of the left atrium by an approach through the atrial septum.

Open Cardiomyotomy with Extracorporeal Circulation

Probably more time is being applied to this problem than to any other branch of surgery. The brilliant results that have followed the use of the Blalock-Taussig operations of anastomosing a systemic to a pulmonary artery, or of the Potts procedure in which the aorta is anastomosed side to side to the pulmonary artery, are undoubted; but, although after over ten years of follow-up most of the patients are satisfactory, the addition of an extra defect to the tetralogy has been accompanied in many cases by a steady increase in heart size. Brock's original direct attack on the infundibular or valvular stenosis in these patients led the way to a more physiological solution of the problems of pulmonary oligoemia, but he himself always felt that the closure of the right-to-left shunt was the next essential step. Lillehei (Lillehei *et al.*, 1955) first achieved this by using cross-circulation from a human donor and then by the use of the bubble-oxygenator in combination with a venous and arterial "sigmamotor" pump.

As far back as 1937 Gibbon, of Philadelphia, was publishing the results of his work on a heart-lung machine, and his constant attention to the problem through years of work has led to the designing of the Gibbon-Mayo pump oxygenator, with which Kirklin has performed hundreds of open cardiomyotomies with astonishing success. The time has come when most surgeons are reluctant to carry out an anastomotic operation for congenital cyanotic disease except under conditions of great urgency, as when the state of an infant or child is grossly deteriorating, in which case the surgical relief of the pulmonary obstruction with simultaneous closure of the ventricular defect is the ideal. The anastomotic operation still has a place in conditions such as tricuspid atresia with an absent or diminutive right ventricle.

Ductoplasty.—The problem of the very young child with cyanosis who is deteriorating is an anxiety to many of us; many die before they are old enough to be subjected to open cardiomyotomy or in centres where the extracorporeal circulation has not been established. If a Potts or a Blalock operation is done as an emergency measure a condition is established which may well make the later performance of open cardiomyotomy for correction of the defects difficult. In these circumstances it is permissible to use a human arterial graft to add a by-pass from the aorta to the pulmonary artery (this method was suggested and used by Keith Roberts in my department); later such a connexion can readily be disconnected, and the subclavian artery is available for use in setting up an extracorporeal circulation.

Machines Available

Many efficient machines are available. In spite of all criticisms the Gibbon-Mayo, the Melrose, and the Lillehei-de Wall systems can deliver adequate quantities of fully oxygenated blood to the patient with the heart and lung inflows and outflows cut off; haemolysis and defibrination are no longer problems, and metabolic acidosis in the patients will not develop if the use of the artificial circulation is scrupulously correct in all details. With the additional help of cardiac arrest produced by potassium citrate (Melrose), operations of up to 40 minutes and over can be carried out deliberately on a heart which, by reason of its arrest, has no need for metabolic changes; it behaves just as a limb does when its circulation is arrested by a tourniquet.

The startling advance made in several American clinics in the use of extracorporeal circulation should make us inquire into our own apparent slowness. I believe purely individual attempts to do this work will fail; not only is an adequate team required, but the work must be done in a reasonably sized department where the team engaged in the research work will be the one to perform in the operating theatre.

It is, I believe, the human factor that is now the important one and not the machines. Believing this, we decided, after seeing all the machines in action, that with our own limited resources the Lillehei-de Wall system would be the most suitable. Our immediate objective was to do our first work with the one object of getting dogs to survive from the outset, and, by spending a few months in the preliminary setting up of the apparatus, we have succeeded in achieving this. This small achievement (largely due to the efforts of my senior registrar, L. D. Abrams) is mentioned only because I think that in many clinics too many fresh ideas are being used before the experimenters have mastered the details of team-work. I only wish I could present results in patients.

The correct driving of the machine and the interpretation of the necessary monitoring (the electroencephalograph to tell us of the state of cerebral oxygenation, the recording of venous and arterial pressures, the exact knowledge of the total circulating fluid in the patient, and the pH of the blood) are essential.

Kirklin, Patrick, and Theye (1957) have described succinctly and clearly the requirements that must be fulfilled: "The maintenance of life by whole-body perfusion for one hour, during which time open cardiac operation is performed, can be accomplished at a very low risk provided all details are properly managed. While sporadically satisfactory results can be obtained otherwise, uniformly excellent results demand a thorough knowledge of the myriad of factors affecting the adequacy of the procedure, a carefully trained team, and proper equipment."

It is not over-caution which makes me say that it is easy to proffer a multitude of excuses for failure and defeatist views about the biological defects of the system in use. In the laboratory we have found that criticism which says that the blood volumes cannot be checked, that bleeding with the use of heparin is severe, that haemolysis is bound to occur and fibrinogen to be lost, and that acidosis is inevitable is readily rebutted. Refuting the theoretical objections to the bubble oxygenator and its modifications, it can be stated that blood can be kept fully oxygenated and carbon dioxide adequately eliminated, and that human blood when put through the oxygenator behaves always according to the classical pattern of the dissociation curve.

The problem of open cardiac surgery is by no means solved once the artificial circulation is in motion: the anatomical defects seen at open cardiectomy are so different from the diagrammatic representations or post-mortem appearances. The careful studies of Brock (1957) on pulmonary stenosis and the excellent descriptions of ventricular septal defects by Kirklin, Harshbarger, Donald, and

Edwards (1957) and Lillehei *et al.* (1957) are essential reading for any surgeon who even contemplates the repair of these malformations. The surgeon has returned to claim part of his heritage of surgical anatomy; for, however careful the study is in the post-mortem room or in the radiological department, the pathological anatomy of the living can shatter disconcertingly the armchair conception of the abnormality. Having seen such masters as Kirklin and Lillehei, I do not feel, however simple they made it appear, that this surgery will be easy for many a day.

Conclusion

I have attempted a brief summary of the progress in cardiac surgery in the last ten years. I have for reasons of time omitted much; the surgery of valvular incompetence and of cardiac ischaemia has not been discussed, as I believe the real advances in these fields have still to come, though much has been done. The treatment of cardiac tumours and cysts and of aneurysms of the great thoracic vessels is in itself a large field in which spectacular achievements have been made. I wish I could offer the real summit of this progress, the complete correction of the tetralogy of Fallot: my account breaks off at this exciting stage. As I disentangle myself from the coils of the cardiac catheter, the magic of the electrocardiograph, and the complexities of the circulation I know I am guilty of having avoided many issues. I take comfort in the words of my favourite essayist to his friend Coleridge, "Cultivate simplicity."

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