CARDIAC SURGERY FOR THE CYANOTIC INFANT*

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Surgical treatment for cyanotic congenital heart disease evolved in the Johns Hopkins Hospital when the combined skill and understanding of Drs Alfred Blalock and Helen Taussig culminated in the building of an artificial ductus for a patient with Fallot's tetralogy.[1] This procedure, the creation of a Blalock-Taussig anastomosis, is still the basis of most palliative surgery for Fallot's tetralogy, the commonest cyanotic congenital heart disease.[2]

TYPES OF LESION

Fallot's Tetralogy

Treatment for this anomaly may be either palliative or curative, depending upon the age of the patient and the severity of the disease. We have operated upon patients below the age of one year for total correction of Fallot's tetralogy but have abandoned this policy in favour of palliative procedures because of a lower mortality rate with the use of palliation in the infant group.

Five infants under the age of one year were operated upon for complete correction of Fallot's tetralogy, 3 of these operations being successful (mortality 40%). Twenty-five palliative operations have been performed on patients for Fallot's tetralogy and 4 of these patients died (mortality 16%). In the majority of these palliative operations an anastomosis has been fashioned between the subclavian artery and either the right or left pulmonary arteries, i.e. the Blalock-Taussig procedure. Because of the difficulties associated with a previous pulmonary-systemic shunt of this type at a subsequent operation done under cardiopulmonary bypass, and because the Blalock-Taussig operation is not always successful in infants with a small subclavian artery, a number of alternative procedures have been employed for the palliation of these cyanotic infants who would not otherwise survive to a suitable age for total correction.

The Potts operation[3] was developed as an alternative procedure and consists of anastomosing the left pulmonary artery to the descending aorta by a side-to-side anastomosis, thereby enabling a larger shunt to be created than would be possible with a Blalock-Taussig operation. The facility with which this operation could be performed was due principally, in the early days, to the development of a special clamp, which is now not often used as newer instruments have been designed which are simpler and safer to use. A shunt created between the ascending aorta and the right pulmonary artery also has many advantages.[4-6] It is now widely used in infants too small for a Blalock-Taussig operation and it is relatively easily performed even in these small patients. It can be closed through the opened aorta at the subsequent total correction without the tedious and hazardous dissection often necessary for the closure of a Blalock-Taussig or Potts shunt.

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The chief disadvantage, as with a Potts anastomosis, is that it is possible to make the shunt a little too large and cause flooding of the lungs, or left ventricular failure. Infundibular resection would seem to be an ideal procedure, as it relieves the pulmonary stenosis and increases flow through the pulmonary artery, which, if hypoplastic, should then develop, making the second-stage operation simply a matter of closure of the ventricular septal defect. Unfortunately this is not always the case. The infundibular resection can be performed as originally described by Brock,[7] a blind procedure performed with a transventricular punch, and a pulmonary valvotomy may be performed via this route, if necessary, at the same time. The infundibular stenosis may be present not only in the line of the punch in the outflow tract of the right ventricle, but often below the crista beyond the access of the punch, and therefore may be missed when using a blind procedure.

Infundibular resection may be performed as an open procedure under temporary occlusion of the superior and inferior venae cavae or on cardiopulmonary bypass. These open techniques will allow a more careful and complete relief of the pulmonary stenosis. If, however, the stenosis is almost entirely infundibular and the pulmonary artery and pulmonary valve ring are reasonably well developed, radical relief of the pulmonary stenosis can allow an appreciable reversal of the shunt through the large ventricular septal defect with consequent flooding of the lungs, a not uncommon complication following the Brock procedure.

A ventriculotomy performed on a critically ill infant, on the other hand, can cause right ventricular failure if the stenosis is inadequately relieved, and the crippled right ventricle is still faced with the work of pumping against systemic resistance. However, if the correct amount of relief is achieved, this is an excellent operation, and adequate assessment of the degree of relief may be made by using intra-operative dye dilution curves to supplement surgical judgement.[8]

Recently, because our experience in the use of cardiopulmonary bypass in infants has been encouraging,[9] we have become more aggressive in the use of total corrective procedures in younger children and this attitude has extended to Fallot's tetralogy. In the presence of severe infundibular stenosis the assessment of the adequacy of development of the pulmonary artery may be difficult in some cases, and after an adequate resection of the infundibular stenosis an artery which was previously considered inadequate may expand with the resultant increase in blood flow sufficient to allow closure of the ventricular septal defect without embarrassment to the right ventricle. In most cases, however, it is possible to evaluate the development of the pulmonary artery with considerable accuracy by angiography, and

we now consider a case of Fallot's tetralogy amenable to total correction if the pulmonary artery is adequately developed, irrespective of the age of the patient.

The age of choice for total correction is still probably 5 - 9 years, but if surgery is indicated before this age because of the severity of the disease, a palliative operation is performed only if the pulmonary artery is inadequately developed. Our operation of choice for palliation is the Blalock-Taussig procedure, as this has stood the test of time. However, if the degree of pulmonary artery development is on the borderline of adequacy, i.e. approximately one-quarter the diameter of the aorta, then our approach would be to perform an infundibular resection on cardiopulmonary bypass, and if sufficient relief of the stenosis could be achieved, the ventricular septal defect would be closed. If relief of the stenosis is inadequate, on the other hand, the defect would be left open to be closed at a second operation when the pulmonary artery had enlarged.

Transposition

The second most common cardiac lesion causing cyanosis in infancy is transposition of the great vessels.[10] This disease is, however, the commonest cause of death from heart disease in infancy, only 14% of untreated cases surviving to the age of 6 months.[11] Complete transposition of the great vessels is very rarely associated with extracardiac anomalies, and operations are now available to restore these children to a virtually normal life, and which carry a very acceptable operative mortality rate in experienced hands. Complete transposition is defined as a heart with 2 atria and 2 ventricles, normal atrioventricular valves, normal pulmonary and systemic veins, and with the pulmonary artery arising entirely from the left ventricle and the aorta entirely from the right ventricle.[12] This is the commonest type of transposition.

The fundamental haemodynamic difference between transposition and a normal heart is the independence of the pulmonary and systemic circulations in transposition (Fig. 1). The only way in which oxygenated blood can

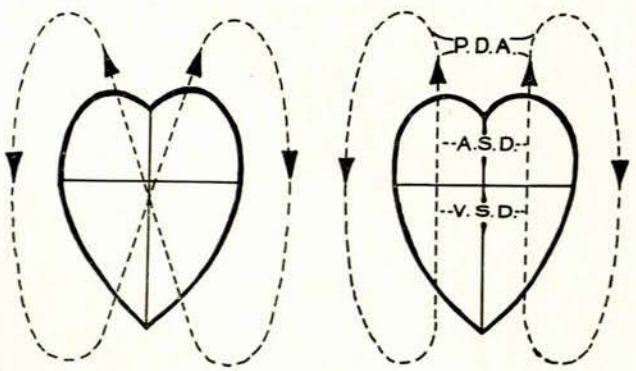

Fig. 1. Transposition of the great vessels (right) compared with normal heart (left).

enter the systemic circulation is by a process of mixing between these two circulations which must be naturally bi-directional and equal, and can occur only through a ductus arteriosus, an atrial septal defect, a ventricular septal defect or through collateral vessels. When the ductus closes, if no septal defect is present, the infant deteriorates rapidly and dies within days or even hours, despite medical therapy, unless surgical relief is available.

If adequate mixing is present after closure of the ductus, generally through a ventricular septal defect, the infant usually develops an excessive pulmonary blood flow some months later as the pulmonary vascular resistance falls with the normal process of development of the pulmonary vasculature, and death usually results within a few months of birth unless a pulmonary stenosis protects the lungs. Some infants with complex malformations, particularly interruption of the aortic arch, die within a few days of birth and surgery is of little avail in this small group of transpositions.

A number of palliative techniques have been developed to tide these infants over this critical phase, the most widely used of which is an operation developed by the late Dr Alfred Blalock in conjunction with Dr Rollo Hanlon at the Johns Hopkins Hospital.[13] This operation entails the creation of an atrial septal defect by an ingenious technique to assist in the mixing between the two circulations. The disadvantage of this operation is that the superior pulmonary veins are occluded for some minutes, and to prevent the upper lobe from becoming overloaded with blood, the pulmonary artery to this lobe must also be occluded. In infants under 3 months of age, this technique carries a high risk even in experienced hands, and alternative techniques may be preferable. Our practice is to create an atrial septal defect under hypothermia with the venous inflow to the heart temporarily occluded with caval snares (Fig. 2).

Results have been good, with 10 operations performed and 2 deaths, giving us a mortality rate of 20%. This technique has some disadvantages: firstly, air may enter the right ventricle and hence the aorta unless the procedure is performed with care, and it is possible also to excise too much of the atrial septum and create a leak in the atrial wall. If a ventricular septal defect is present, our practice is to band the pulmonary artery and create an artificial pulmonary stenosis to protect the lungs. Alternative techniques of creating an atrial septal defect have been developed to avoid the necessity of clamping the pulmonary artery: two of these are interesting, although they have not been used in our clinic so far. The first was developed by Senning,[14] and consists of a dissection of the interatrial groove and the positioning of traction sutures in the septum to enable a clamp to be applied to this area without occlusion of the pulmonary artery or veins. Secondly, Alvares[15] introduces an instrument through the superior pulmonary vein which elevates the atrial septum and enables it to be clamped in common with the free wall of the right atrium, thereby avoiding occlusion of the pulmonary artery or veins. The atrial septum may also be ruptured by the use of a special balloon catheter.[16] This last-mentioned technique may well replace surgical palliation except in those cases which require pulmonary artery banding.

We have used intermittent positive-pressure respiration postoperatively in a large number of infants undergoing cardiac surgery and we regard the use of this technique as particularly valuable in cases of transposition. Patients with this anomaly who have survived infancy are then considered for a corrective operation. A programme is at

present under way for the total correction of transposition in our hospitals, using the technique described by Dr W. Mustard of Toronto.[17] This is the procedure of choice for correction of this condition today, and it involves the insertion of a patch of pericardium into the two atria in such a way as to shunt the pulmonary venous blood into the right ventricle and hence to the aorta, and to deflect the systemic venous blood on the opposite side of this patch into the left ventricle for circulation to the lungs. The circulation is thus restored haemodynamically to normal, and short-term follow-up of these cases has proved the excellent results.

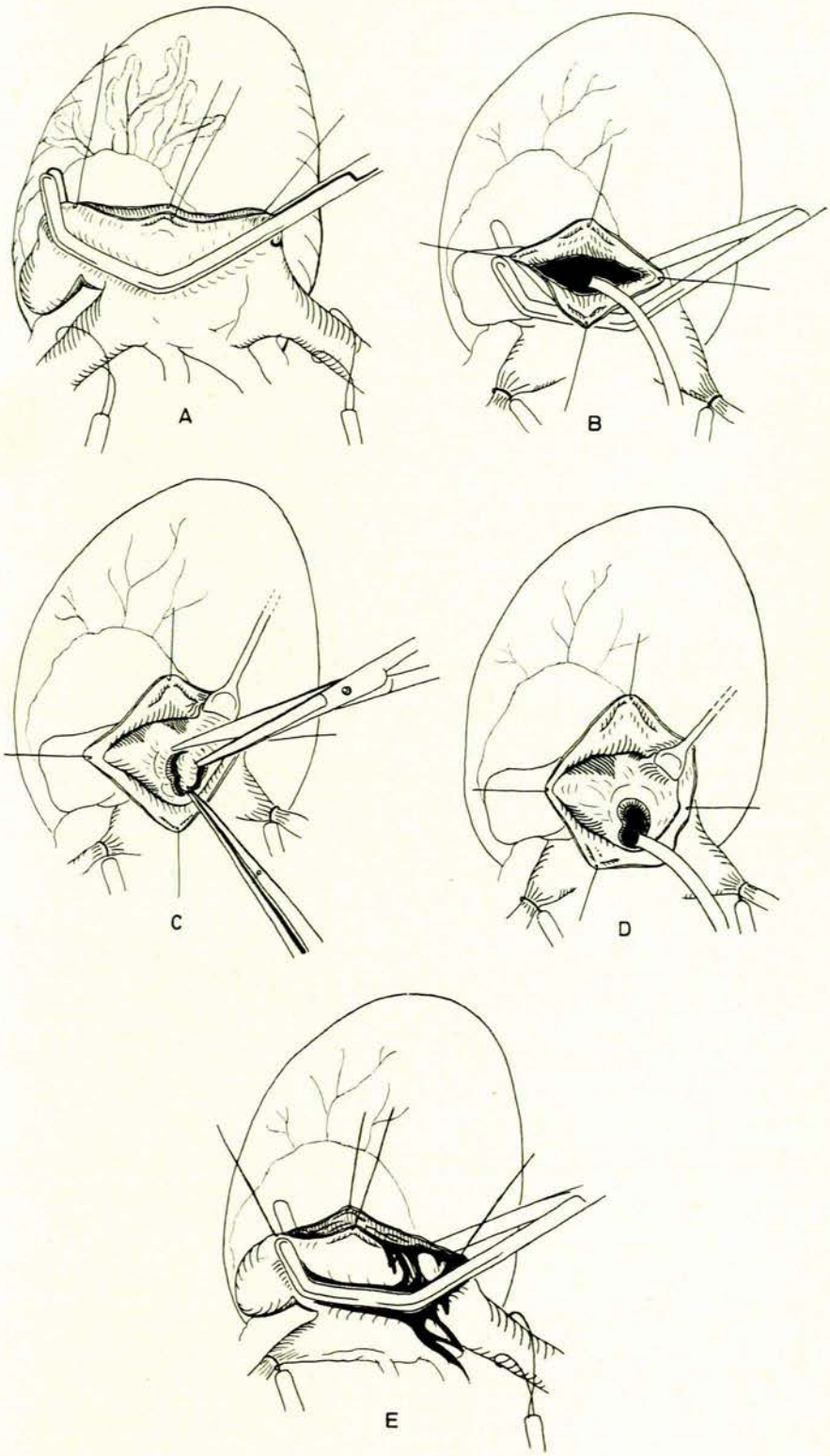

Fig. 2. Atrial septectomy. A: Clamp applied, atrium opened B: Cavae occluded, clamp released. C: Septum excised. D: Atrial septal defect created. E: Air excluded, clamp re-applied.

The hospital mortality for the Mustard operation is now under 15% in the more experienced centres undertaking this type of surgery.[18-20] In one-third of the cases a ventricular septal defect is present[21] and this can be closed by the usual technique of patch insertion, except that it is often possible and very desirable that this should be performed through the tricuspid valve, thereby avoiding a ventriculotomy and the subsequent damage to the right ventricle. It will be appreciated that this right ventricle will be the systemic ventricle after operative correction, and the technique of atrial approach is employed by most surgeons performing these corrections, in order to protect this ventricle.

A ventricular septal defect is often associated with some degree of sub-pulmonary stenosis in the left ventricle, and if this is mild as assessed at catheterization by pressure studies and angiography, it can be ignored; in fact a mild stenosis may be of some advantage to the patient by protecting the lungs from excessive blood flow and delaying the development of pulmonary hypertensive vascular disease which is prone to occur at a young age in this condition. If, however, the pulmonary stenosis is more than mild, it represents a formidable problem as it is rather inaccessible in the posteriorly situated left ventricle, and difficult to reach via the posteriorly positioned pulmonary artery, and if the stenosis is severe enough to require the insertion of an outflow tract patch, it is not possible to insert this adequately because of the consequent damage to the coronary artery crossing in this region. If the sub-pulmonary stenosis is very severe, it may lead to cardiac failure in infancy because of inadequate pulmonary blood flow, and

some form of systemic-pulmonary arterial shunt is indicated.

Dr Mustard's preference in these cases is for the Glenn procedure[22] or cavo-pulmonary anastomosis, and at the subsequent total correction the Mustard procedure is modified to shunt only the inferior vena-caval return across to the mitral valve and the superior vena-caval return is left undisturbed to continue draining into the right lung. Thus even these rather severe cases may be corrected in some measure and enabled to lead a normal life. Complete transposition of the great vessels can now quite rightly be classified in the group of cyanotic congenital cardiac defects eminently suitable for surgical correction.

Double Outlet Right Ventricle

A group of congenital lesions somewhat resembling complete transposition is the group usually referred to as double outlet right ventricle, in which the aorta is transposed but the pulmonary artery is not, so that both vessels arise entirely from the right ventricle and the only outlet for the left ventricle is through a ventricular septal defect. This defect may be below the crista supraventricularis, as in the common type, or above the crista, in which case the anomaly is usually referred to as the Taussig-Bing complex. Pulmonary stenosis may also occur, in which case the lung fields on X-ray will be oligaemic as in tetralogy of Fallot and the differentiation from this condition can usually be made only at cardiac catheterization. All three varieties will usually be cyanotic, but the correction of the common type without pulmonary stenosis can be accomplished, provided the septal defect is not restrictive and provided this defect is closed with a patch which creates an adequate outflow for the left ventricle into the aorta in such a way as to avoid encroaching upon the right ventricular outflow tract. The superadded lesion of pulmonary stenosis which is always infundibular in type not only makes the operative correction more difficult, but, because of the amount of damage suffered by the right ventricle from resection of the stenosis, the function of the right ventricle may also be embarrassed postoperatively. The correction of the Taussig-Bing complex requires the closure of the ventricular septal defect in such a way that the left ventricular blood passes into the pulmonary artery. A patch to shunt the blood across to the aorta would obstruct the passage of blood from the right ventricle into the pulmonary artery in this condition, and thus closure of the ventricular septal defect in the above manner will create a situation of complete transposition of the great vessels. This transposition is now corrected by the insertion of a pericardial baffle to provide an atrial switch of the two streams of blood as in the Mustard operation.[23]

We have successfully corrected one double outlet right ventricle, but failed in another case complicated by a pulmonary stenosis and a large persistent ductus arteriosus.

Total Anomalous Pulmonary Venous Connection

A less common condition which causes cyanosis and severe cardiac failure in infancy is total anomalous pulmonary venous connection. In this condition all the pulmonary venous blood enters the right atrium, where it mixes with the systemic venous blood and passes through an atrial communication to the left heart, resulting in desaturation of the arterial blood and cyanosis. When the ductus closes, the only path for blood into the left heart is through an atrial septal defect which, if inadequate in size, leads to the rapidly fatal onset of cardiac failure in a manner identical with a case of complete transposition of the great vessels. If the atrial septal defect is adequate the infant will survive closure of the ductus, but if insufficient blood enters the left heart the left ventricle may remain poorly developed relative to the right ventricle. Also, if extracardiac obstruction is present in the anomalous venous drainage of the lungs, pulmonary venous congestion may develop.

The anomalous pulmonary venous drainage is usually to a common pulmonary vein which lies behind the heart and connects with a systemic vein in the superior vena-caval system, the inferior vena-caval system, or with the right atrium directly. Thus we classify this condition into supracardiac, cardiac and infracardiac types, the incidence of the three types being conveniently in this descending order of frequency. Major associated cardiac malformations are present in one-third of cases, being commonest in the infracardiac type.[24] At cardiac catheterization—which is imperative in order to make a detailed diagnosis of the condition—the adequacy of development of the left ventricle can be assessed, and if this is considered inadequate to carry the systemic circulation, then an atrial septal defect should be created, as in transposition, to relieve the obstruction to flow and to enable the left heart to develop. If the left ventricle is adequate, on the other hand, our choice is total correction even in the infant group, on total cardiopulmonary bypass. These operations entail the shunting of blood from the anomalous pulmonary vein to the left atrium, closure of the atrial septal defect, and ligation of the distal part of the anomalous vein, if necessary.

We have attempted total correction of 6 cases of total anomalous pulmonary venous connection, 4 of which have been completely successful, one being in an infant of 6 months. We have employed a technique of open heart surgery for these cases in which we cooled the patients to a nasopharyngeal temperature of 20°C, turned off the heart-lung machine for some minutes to define the anatomy clearly in an open and non-beating heart, and then restarted the heart-lung machine to rewarm the patient after the more delicate part of the intracardiac procedure had been completed. This brief period of circulatory arrest at profound hypothermia is well tolerated by cyanotic infants. The majority of cases of total anomalous pulmonary venous connection, therefore, are amenable to surgical correction by a one-stage or two-stage operation.

Pulmonary Atresia

A condition which causes death in infancy as commonly as does total anomalous pulmonary venous connection is pulmonary atresia. This may occur with an intact ventricular septum, in which case closure of the ductus arteriosus will precipitate a crisis as it does in the two previous conditions, the major source of blood supply to the lungs in this case having become obliterated. It may also occur in association with a ventricular septal defect, in which case the condition is usually known as extreme tetralogy of Fallot, or pseudo-truncus arteriosus because

of the similarity of the haemodynamics in this condition to that of a type 4 truncus arteriosus (Fig. 3). When pulmonary atresia occurs with an intact septum, the degree of development of the right ventricle varies from case to case, and may be normal in cases generally associated with tricuspid incompetence due to a malformation of the tricuspid valve as found in Ebstein's anomaly, or the right ventricle may be hypoplastic with a hypoplastic tricuspid valve. The right-to-left shunt occurs across the atrial septum, usually through a foramen ovale defect.

If at angiography the right ventricle appears adequate in size, and this is confirmed by obvious tricuspid incompetence, the atretic pulmonary valve can be incised and the obstruction relieved. The atretic valve is usually the sole obstruction to outflow from the right ventricle and can be located without difficulty through the opened pulmonary artery, but a pulmonary valvotomy performed in a case with an inadequate right ventricle is of no avail, as this chamber cannot cope with the load of the systemic venous return. The best approach to these cases with inadequate right ventricles is the construction of a systemic-to-pulmonary-artery shunt and the creation of an artificial atrial septal defect, if necessary, to allow sufficient blood to reach the left heart. If the ventricular septum contains a defect, as it does in cases of extreme tetralogy of Fallot, then closure of the ductus arteriosus is generally not as catastrophic as when the septum is intact, as this defect offers an adequate channel for blood through the heart, and these cases may occasionally survive to childhood with the lungs being supplied by dilated bronchial arteries. If not, a systemic pulmonary artery shunt will generally tide them over to an age when total correction may be entertained.

This was done successfully in two of our patients. Pulmonary valvotomy was performed on 3 occasions, being successful only once. The inevitable pulmonary incompetence resulting from the incision of a valve as deformed as in these cases appears to be well tolerated for some years, as shown by our serial catheterization studies of cases of tetralogy with pulmonary incompetence created at the time of total correction, but it is obviously preferable to provide a competent pulmonary valve if possible. In this situation it has proved suitable to use a homograft aortic valve, and if necessary a portion of ascending aorta may be used to replace a hypoplastic pulmonary artery. Many cases of pulmonary atresia and pseudo-truncus arteriosus can now be considered operable by either a single or a two-stage operation.

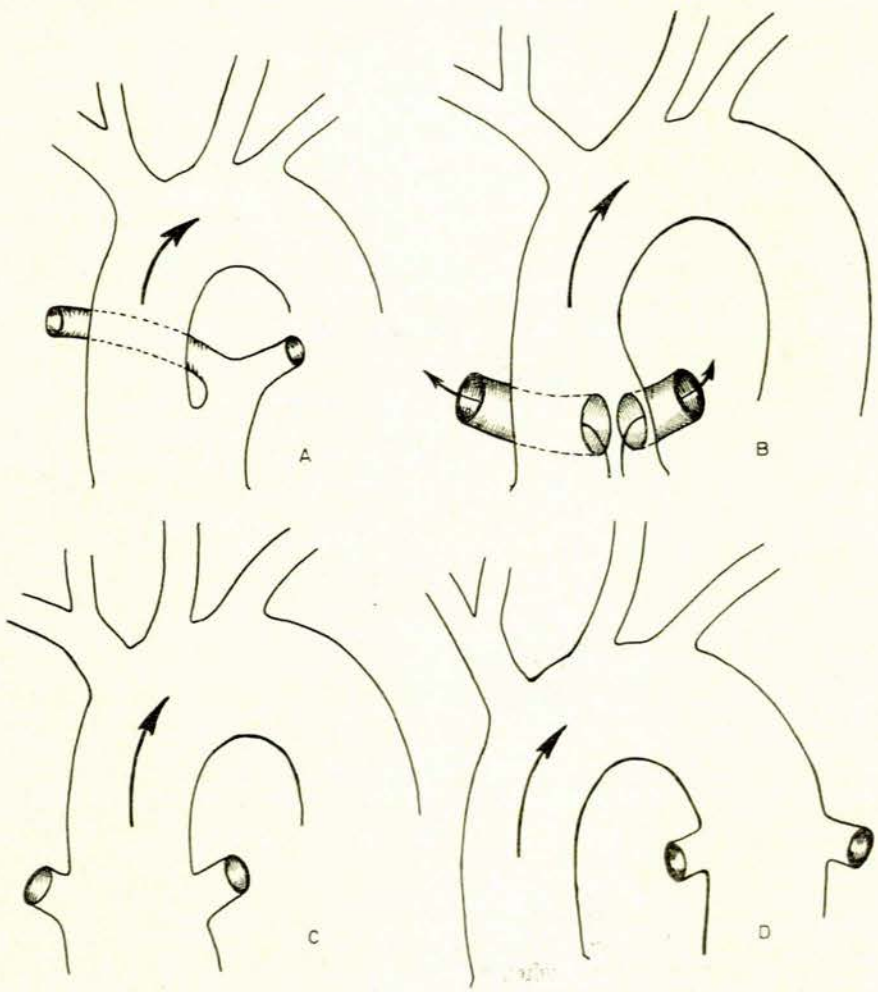

Fig. 3. Truncus arteriosus. A: Type I. B: Type II. C: Type III. D: Type IV.

Persistent Truncus Arteriosus

Persistent truncus arteriosus is a condition in which there has been a failure of partitioning of the primitive truncus arteriosus, so that only one major artery leaves the heart to supply blood to the aorta, coronary arteries and pulmonary arteries, and which contains only one semilunar valve. This entity is generally divided into 4 types, depending upon the origin of the pulmonary arteries (Fig. 3). In type 4 the pulmonary arterial supply from the descending aorta is thought to be derived from dilated bronchial arteries. A ventricular septal defect is invariably present and these cases are prone to develop hypertensive pulmonary vascular disease at any age unless there is restriction of pulmonary blood flow.

Because of crossing of the streams of blood there may be only minimal arterial desaturation and a high pulmonary blood flow in the absence of pulmonary stenosis may lead to a clinical misdiagnosis of simple ventricular septal defect. Thus, the less obstruction there is to pulmonary blood flow the less will be the cyanosis and the more prone will the patient be to develop pulmonary hypertensive vascular disease. Operative correction of this condition is possible, using a homograft ascending aorta and aortic valve to replace the pulmonary trunk.[25] An orifice is constructed in the outflow tract of the right ventricle after closure of the ventricular septal defect and the attached aortic leaflet of the mitral valve is used to facilitate the closure of the ventriculotomy and also to prevent development of a stenosis at this site. It is, of course, imperative to correct these lesions before pulmonary hypertensive vascular changes have become irreversible.

Tricuspid Atresia and Hypoplastic Right Ventricle

These two cyanotic congenital heart diseases are not yet amenable to surgical correction. The atretic tricuspid valve is represented by a pit in the floor of the right atrium and the entire venous return enters the left atrium through an interatrial communication and, along with the pulmonary venous blood, passes through the mitral valve to enter the left ventricle. Two types of this anomaly are encountered, one with transposition of the great arteries and usually without pulmonary stenosis, the other with pulmonary stenosis and normally orientated great vessels. A ventricular septal defect is usually present in both types. After closure of the ductus arteriosus, blood flow to the lungs may be restricted by a pulmonary stenosis or by a small restrictive ventricular septal defect. The interatrial communication may also restrict systemic venous flow and in the type with no restriction to pulmonary flow the lungs may become overloaded with blood and lead to congestive cardiac failure.

The available palliative procedures are, firstly, a systemic-to-pulmonary shunt for pulmonary oligaemia; secondly, an enlargement of a restrictive interatrial communication; and, finally, banding of a pulmonary artery carrying an excessive blood flow. Because of the inadequately developed right ventricle it is difficult to conceive of a completely corrective operation for this condition, and an attempt to achieve total correction in this disease unfortunately failed in December 1967, when the first heart transplant for this condition was unsuccessful.

SUMMARY

A brief outline of the types of congenital cyanotic heart disease which come under consideration for surgical treatment is given. Palliative and corrective operations are described for cases of Fallot's tetralogy, transposition of the great vessels, double outlet right ventricle, total anomalous pulmonary venous connection, pulmonary atresia, persistent truncus arteriosus, tricuspid atresia and hypoplastic right ventricle. Results in surgery for these cyanotic congenital heart diseases in the University of Cape Town teaching hospitals are presented.

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ADDENDUM

Since submission of this article for publication we have successfully corrected a case of transposition of the great vessels with sub-pulmonary infundibular stenosis in a 7-year-old boy by reconstruction of the left ventricular outflow tract with a dacron roof inserted via the right ventricle, and anastomosis of the divided end of the main pulmonary artery to the right ventricle with a segment of homograft aorta with aortic valve and aortic leaflet of the mitral valve, as described by Rastelli *et al.*[26]

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