THE SURGICAL SIGNIFICANCE OF PULMONARY HYPERTENSION*

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PULMONARY HYPERTENSION with or without increased pulmonary blood flow is an outstanding feature in a large group of patients who have congenital heart disease. The anatomical deformities which produce increased pressure in the pulmonary artery are varied. However, with the exception of rare malformations such as congenital mitral stenosis and congenital ideopathic pulmonary hypertension, most of these deformities have in common a large communication between the pulmonary and systemic circulations. In addition, the lungs uniformly reveal varying degrees of luminal narrowing of the muscular pulmonary arteries. Recently some evidence has appeared to support the contention that these pulmonary vascular changes are not congenital in origin but are the result of increased pulmonary artery pressure and blood flow and are progressive.[5, 20] Therefore, if this is the case, early operation should be employed when possible to relieve the hypertension and thus prevent the progression of pulmonary artery changes.

During fetal life, the smaller muscular pulmonary arteries have a relatively thick wall and narrow lumen due primarily to hypertrophy of the medial musculature (Fig. 1A). A high resistance to blood flow results[2, 11] and probably represents the mechanism by which a proportionate blood flow is maintained in the pulmonary and systemic circulations during fetal life. The high resistance continues after birth, but by the time the infant is six months of age the medial thickening has disappeared, the smaller arteries have become dilated, and the resistance to blood flow is low (Fig. 1B). If a congenital cardiac malformation is present in which the two circulations are united, then the high pulmonary vascular resistance may continue and changes in the smaller pulmonary arteries may persist and progress. The medial hypertrophy may increase and, in addition, fibrosis of the intima may appear and result in further narrowing of the lumen of the vessels. It seems likely that cyanosis and disability which so often occur in patients with the Eisenmenger's complex around the age of puberty may be the result of these changes. A second course that the pulmonary vascular resistance may possibly follow is to increase only slightly and become stable so that a balance between the systemic and pulmonary resistance and blood flow results. This balance may be achieved in another manner when minimal pulmonary stenosis is present, and this apparently occurred in the patient reported by Civin and Edwards[5] who had "stenosis of the ostium infundibuli associated with biventricular origin of the aorta" and who died at the age of 47 from carcinoma of the bladder. His pulmonary

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vessels appeared essentially normal. The third possible course is that the pulmonary resistance may gradually diminish after birth and result in an increasing pulmonary blood flow and cardiac failure.

Among the first reports concerning pulmonary vascular changes was that by Stewart and Crawford.[21] They studied the lungs in a 60-year-old man with the Eisenmenger's complex and decided that the changes in the pulmonary arteries were due to syphilis. Old and Russell[18] found both medial hypertrophy and intimal fibrosis of the smaller pulmonary arteries along with acute perivascular inflammatory changes in the lungs of an 11-year-old boy with the Eisenmenger's complex. In reviewing these cases, Civin and Edwards[5] suggested another pathogenesis for the changes in the smaller pulmonary arteries. They noted that the pulmonary vessels in an 11-month-old infant with the Eisenmenger's complex were characterized by medial hypertrophy, a normal intima and narrow lumen and resembled closely those vessels found in the normal fetus. Edwards and Chamberlain[8] reported the case of an eight-year-old boy with cor triloculare biatriatum and subaortic stenosis. The muscular arteries showed not only medial hypertrophy but also intimal fibrosis which caused complete obliteration of some of the arteries. These findings, along with other similar findings, have led Edwards and his associates to consider the medial hypertrophy as a continuation of the fetal vascular state, and the intimal fibrosis a result of persistent pulmonary hypertension.

Our studies have, in general, borne out the findings of Edwards and his associates.[5, 8] We have obtained biopsies of the lung and direct pressures in the pulmonary and systemic circulations by means of a strain gauge manometer from most patients during operation and have attempted to correlate pulmonary arterial changes with the pulmonary artery pressures, age of the patient, and nature of the malformation.

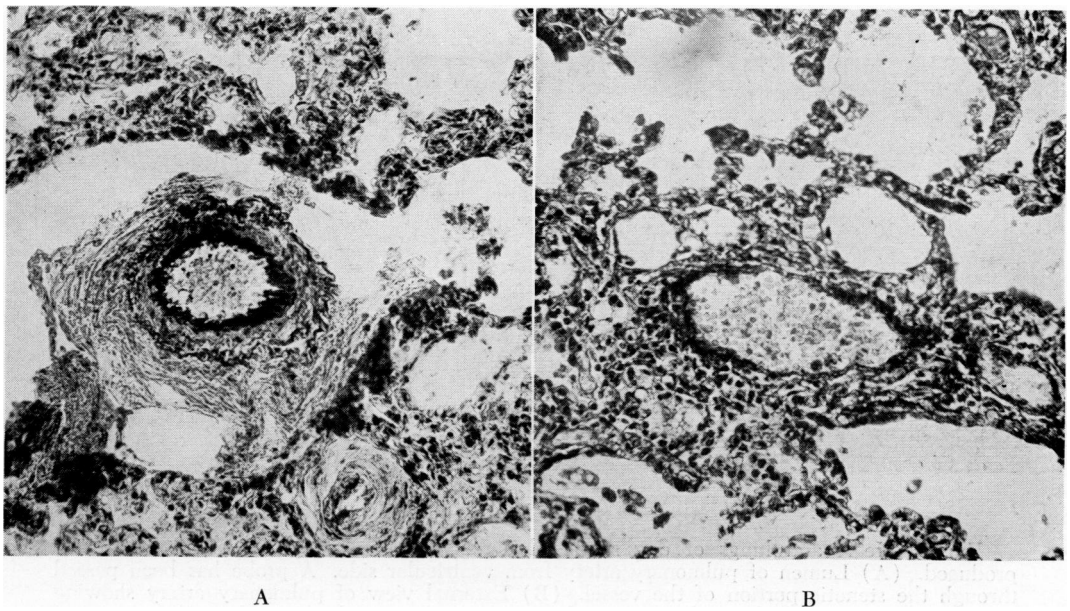
INTRACARDIAC COMMUNICATION BETWEEN SYSTEMIC AND PULMONARY CIRCULATIONS

A significant group of patients with pulmonary hypertension is that in which the communication between the systemic and pulmonary circulations is intracardiac. This group includes patients who have a single ventricle without pulmonic stenosis, large ventricular septal defects, and the Eisenmenger's complex. In each of these abnormalities the heart functions physiologically as a single ventricle in that there is a common ventricular ejectile force. Using the common ventricular ejectile force as the criterion, true truncus arteriosus may also be included in this group.

At the present time there is no satisfactory surgical procedure for treatment of these deformities. Correction of the septal defect is logical and has been attempted, but will probably not be practical until the extracorporeal pump can be used satisfactorily. It has been suggested by Civin and Edwards[5] that pulmonary hypertension and blood flow might be diminished by surgically creating pulmonary stenosis in these patients and thus affording protection to the small pulmonary arteries. The case which they reported lent support to this suggestion.

Blalock[3] narrowed the main pulmonary artery in two patients who did not survive. He[4] discussed the usefulness of such a procedure and questioned its advisability in view of the already present narrowing of the smaller pulmonary arteries. He thought that it was a point which should be determined. Goldberg and associates[10] also discussed the possibility of creating pulmonary stenosis and thought that while the pulmonary artery pressure might be reduced and the pulmonary arterioles protected the strain upon the right ventricle would still be present. They de-

cided that such a procedure would not be beneficial. It seemed to us that creating pulmonic stenosis, thus placing the point of high resistance to blood flow at the stenosis and not in the smaller muscular pulmonary arteries, should be beneficial. Pulmonary blood flow might or might not be diminished, depending upon the degree of pulmonary vascular change already present, and alterations of systemic blood flow would depend directly upon the change in pulmonary flow.



A B

FIG. 1.—(A) Small muscular artery from normal infant who died ten hours after birth. The lumen is small because of medial hypertrophy. (B) Small muscular artery from normal child two and a half years old. The lumen is large and the media is thin.

Experimental Data. Most previous attempts to produce pulmonary stenosis in the experimental animal employed a band about the main pulmonary artery[9, 12, 19] which frequently resulted in erosion of the wall of the vessel. Hufnagel and his associates,[13] however, utilized a partial occlusion clamp in a large series of dogs and were able to remove a segment of the vessel wall and narrow the pulmonary artery by as much as 80 per cent of its original diameter. We employed a similar method to excise a portion of the vessel wall but also used a band of reactive polyethylene film and cotton tape about this area, because we thought that over a period of time the pulmonary artery might dilate at the point of narrowing if such a band were not employed. Clatworthy[6] and his associates used such a method in producing experimental coarctation of the aorta. We narrowed the pulmonary artery in five dogs by this procedure and they were sacrificed at from two weeks to eight months after operation. In the dogs sacrificed at eight months, approximately 80 per cent of the artery was occluded (Fig. 2A). Considerable tissue reaction was present in the region of the reactive polyethylene band (Fig. 2B). There was slight dilatation of the artery proximal to the point of narrowing and moderate poststenotic dilatation beyond this point. Pressures taken directly in the pulmonary artery before the animal was sacrificed were much higher proximal to the stenosis than distal to it.

In applying this procedure to patients, there was no way to estimate the amount of stenosis which should be produced. From the observations of Mann and his associates,[15] we decided that the artery should be narrowed by at least two-thirds of its original diameter in order to reduce the pulmonary blood flow by 40 or 45 per cent. We thought that the degree of acute narrowing that the patient could tolerate might not be sufficient to achieve the optimum reduction in pulmonary artery pressure and blood flow and thought that the reactive polyethylene might cause further narrowing of the vessel. As to whether or not this degree of narrowing is sufficient will require further studies over a period of time.

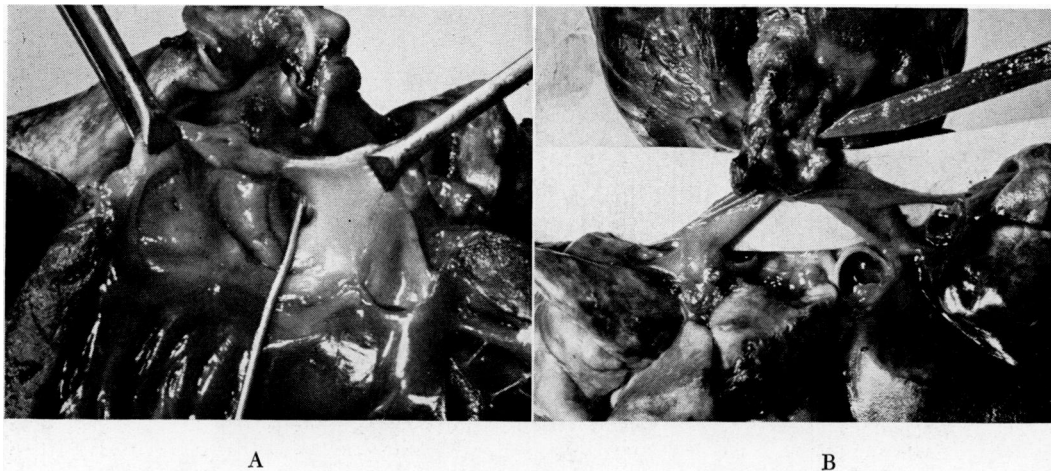


FIG. 2.—Heart and lungs of dog sacrificed eight months after pulmonary stenosis was produced. (A) Lumen of pulmonary artery from ventricular side. A probe has been passed through the stenotic portion of the vessel. (B) External view of pulmonary artery showing marked tissue reaction about the narrowed portion of the vessel. Note the enlargement of the right and left pulmonary arteries distal to the stenosis.

Surgical Technic. We have used a procedure similar to that outlined above to produce pulmonic stenosis in patients. The patient is placed supine on the operating table with the left shoulder and left side of the chest slightly elevated. The chest is entered through an anterolateral incision in the second or third left intercostal space. The pericardium is opened over the course of the main pulmonary artery from the outflow tract of the right ventricle to the reflection of pericardium on the distal portion of the artery. It may be necessary to further incise the pericardium both medially and laterally to afford further exposure. The pericardium between the aorta and pulmonary artery is incised, the areolar tissue is divided, and the main pulmonary artery is mobilized (Figs. 3 and 4). The partial occlusion clamp is applied to the mid-portion of the main pulmonary artery and a continuous mattress suture of arterial silk is placed in the portion of the vessel occluded by the clamp (Fig. 5). The occluded portion is then excised, and a continuous over and over suture of arterial silk is placed along the cut edge to afford further hemostasis (Fig. 6). The clamp is then removed, and a band of reactive polyethylene film and cotton tape is sutured around the artery at this point (Fig. 7). Streptomycin and penicillin are placed in this area. The pericardium is closed loosely. The chest is closed and intrapleural catheter drainage is instituted.

Clinical Data. We have explored five patients with the intention of surgically producing pulmonary stenosis.

Case 1.—This patient was an infant of four and a half months, who had appeared normal at birth. Progressive tachypnea was noted during the first few days of life. At the age of 10 weeks he was hospitalized because of failure to gain weight properly and shortly thereafter developed frank cardiac failure with cough, rapid respiration, and orthopnea. There was a loud blowing systolic murmur maximal in the third and fourth left intercostal space near the sternum. Roentgenologic examination revealed generalized cardiac enlargement and extremely vascular pulsating lung fields. The electrocardiograph was bizarre. A diagnosis of single ventricle without pulmonary stenosis was made. In spite of intensive medical therapy his failure progressed, and it seemed that death would occur soon unless something could be done to reduce the excessive pulmonary blood flow. On July 11, 1951, exploration was carried out through the second left anterior intercostal space, and a markedly enlarged pulmonary artery and relatively small aorta were found. The pulmonary artery was narrowed to approximately one-third of its original size by the method which we had used in dogs. About three weeks after operation definite improvement was noted; he began to gain weight normally; and cardiac failure was not evident. Digitalis was discontinued three months after operation. He has continued to improve, although his rate of gain in weight has diminished during the past several months. Otherwise his development has been essentially normal. At present, he is 1 year old and has grown considerably in height, has teeth, and has learned to stand and walk. Biopsies of the lung and pressure studies were not obtained on this patient because of his precarious condition throughout the operation. This case has been reported in detail previously.[16]

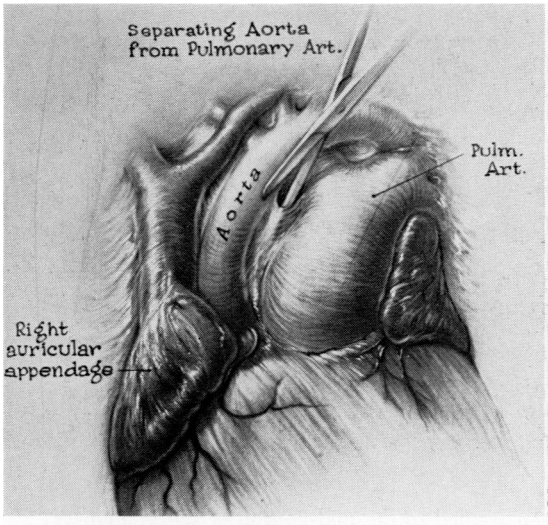


FIG. 3

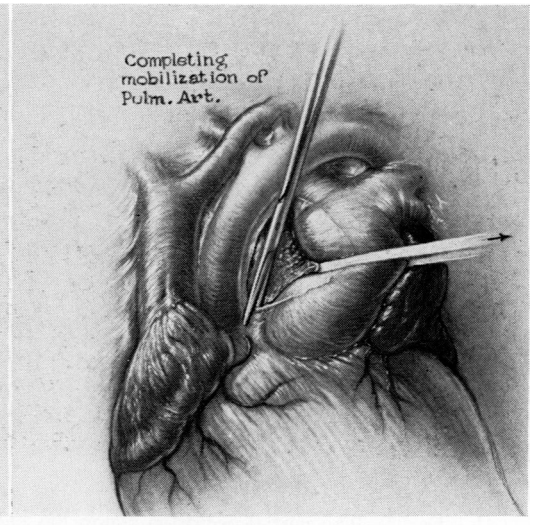


FIG. 4

FIG. 3.—Drawing of operative exposure for the production of pulmonary stenosis, illustrating division of the pericardium between the enlarged pulmonary artery and small aorta.

FIG. 4.—A tape has been passed about the pulmonary artery and further mobilization is carried out.

Case 2.—This 15-year-old boy was born prematurely. A heart murmur was heard at the age of 4 months. Cyanosis and exertional dyspnea were noted shortly afterward. Although dyspnea has continued and progressed, he was able to lead a moderately active life. Physical examination revealed him to be very underdeveloped and undernourished and to have mild cyanosis of the lips and nails. There was no clubbing of the fingers. Blood pressure was 116/60. The point of maximal impulse was in the sixth left intercostal space in the anterior axillary line. A systolic drill was felt in the suprasternal notch and along the left sternal border. There was a long, moderately loud, harsh systolic murmur maximal in the fourth left intercostal space. There was an apical mid-diastolic rumble. A blowing diastolic murmur was heard in the third intercostal space at the left ster-

nal border. The second heart sound at the base was accentuated and split. Femoral and brachial pulses were equal. No liver enlargement was present. On roentgenologic examination the lung fields appeared excessively vascular but rather quiet. In the right anterior oblique position, the main pulmonary artery appeared much enlarged. Both ventricles and the left auricle appeared greatly enlarged. Electrocardiographic examination showed combined heart hypertrophy. Cardiac catheterization revealed a ventricular pressure of 106/0 to –5. The catheter entered the descending aorta where the pressure was 106/50. Samples of blood from the ventricle and aorta were identical in color. In retrospect, the catheter probably entered the aorta through the pulmonary artery and patent ductus. Direct aortography demonstrated no dye in the lung fields. Thus it was felt that a patent ductus arteriosus could be ruled out and a diagnosis of single ventricle without pulmonary stenosis was made. Because the patient was becoming progressively worse, exploration was carried out through an incision in the left third anterior intercostal space. The lung was extremely red and beefy and was much firmer than normal. Upon opening the pericardium over the main pulmonary artery, one could see that it was tremendously enlarged and tense, measuring approximately 5 cm. in diameter and appearing to extend directly into the aorta. A much smaller aorta, however, could be palpated proximally in the usual position and large right and left pulmonary arteries rose from the main pulmonary artery in approximately the normal position. It was thus decided that we were dealing with a large patent ductus arteriosus, aortic stenosis, and a single ventricle or very large ventricular septal defect. Because of the obvious pulmonary vascular changes and because it was felt that it might be hazardous to attempt to close this patent ductus or produce pulmonary stenosis in the right and left pulmonary arteries, nothing was done. The patient made an uneventful recovery. Biopsy of the lung revealed that the muscular arteries showed marked narrowing due to medial hypertrophy and intimal fibrosis and many were completely obliterated.

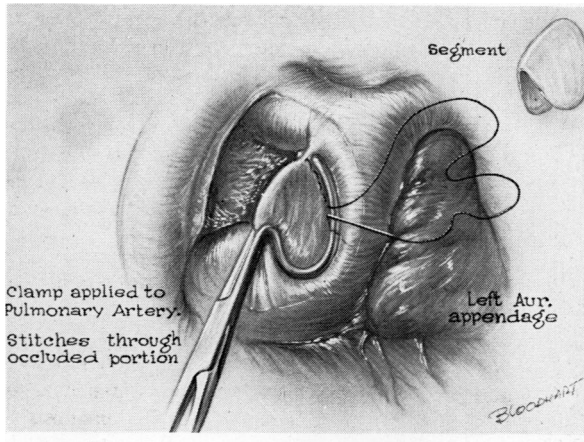


FIG. 5

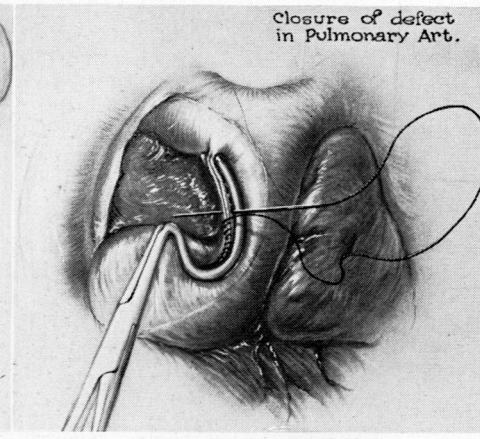


FIG. 6

FIG. 5.—The partial occlusion clamp has been applied to the mid-portion of the pulmonary artery and a continuous mattress suture is being placed in the portion of the vessel occluded by the clamp. The segment to be excised is in the upper right corner.

FIG. 6.—The segment of vessel wall within the occluding clamp has been excised and a continuous over-and-over hemostatic suture is being placed along the cut edge. (By permission of Surgery, Gynecology and Obstetrics.)

Case 3.—This 9-month-old infant was the result of a normal full-term delivery. During the neonatal period he took his feedings well. He gained weight rapidly and showed no evidence of cyanosis. At no time was a murmur heard. At the age of five and a half months, however, during an acute upper respiratory infection, he became quite blue upon crying and lost consciousness for several seconds. One other similar attack was noted. After this time he became progressively more cyanotic even at rest, and cyanosis was accentuated by crying and exercise. Physical examination revealed a well-developed, well-nourished child with slight cyanosis and no clubbing of the fingers or toes. The heart was not enlarged. There were no thrills and no murmurs. The liver could not be palpated.

Pulsations in the upper and lower extremities were equal. On roentgenologic examination the heart was enlarged and had an accentuated boot shape with a pronounced shelf in the right anterior oblique view. The pulmonary arteries did not appear to be enlarged. The region off the main pulmonary artery was concave. The aortic arch was prominent and was on the left side. Electrocardiograph revealed marked right axis deviation and right ventricular hypertrophy. Cardiac catheterization and intravascular opaque studies were not performed. When initially seen, it was felt that this infant had pulmonary atresia and that the onset of cyanosis was concomitant with closure of a patent ductus arteriosus. Typical attacks of paroxysmal dyspnea with marked cyanosis occasionally accompanied by loss of consciousness developed, and because these attacks increased rapidly in number and severity, it was decided that an operation should be performed. On January 26, 1952, the left side of the chest was entered through the left anterior third intercostal space. An enlarged tense pulmonary artery was found. It was narrowed to about one-third its former size by the technic previously described. Pressure tracings showed a diminished pulmonary artery pressure distal to the stenosis. At the end of the procedure the child appeared moderately cyanotic, but cardiac action was fairly good. The child died, however, about 6 hours after operation, probably from prolonged cerebral anoxia and edema. Postmortem examination revealed a functional two-chambered heart with mitral atresia and a rudimentary left ventricle. A large pulmonary artery and aorta arose from the right ventricle. Biopsy of the lung revealed medial hypertrophy of the muscular pulmonary arteries.

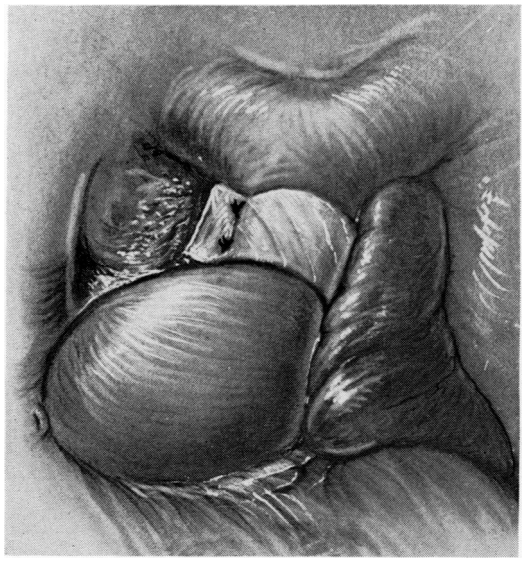


FIG. 7.—Drawing showing the band made of reactive polyethylene film and cotton tape which has been sutured about the area of narrowing in the main pulmonary artery. (By permission of Surgery, Gynecology and Obstetrics.)

Case 4.—This 11-month-old twin appeared normal at birth but had feeding difficulties all of her life. At the age of 10 months a generalized convulsion accompanied by cyanosis occurred, and a heart murmur was noted at that time. The cyanosis persisted. Physical findings, cardiac catheterization, and angiocardiography were interpreted to be consistent with the diagnosis of single ventricle without pulmonic stenosis. At operation increased pulmonary artery pressure was not found, thus pulmonic stenosis was not created. Her recovery was uneventful.

Case 5.—This 5-year-old boy appeared normal at birth. At the age of 3 months he had a generalized convulsion which was followed by cyanosis. Since 3 months of age he has had moderate cyanosis upon exertion and exertional dyspnea. As an infant he had pneumonia 3 times. A diagnosis of ventricular septal defect was made at the age of one year. Physical examination revealed that he was undernourished and underdeveloped and was slightly cyanotic about the lips and nail beds. Blood pressure in both arms was 160/100 and in both legs was 95/80. There was a corresponding pulse difference in the upper and lower extremities. The heart was enlarged to the left. A blowing systolic murmur could be heard maximal at the apex and close to the sternum in the third left intercostal space. P-2 was markedly accentuated, split, and louder than A-2. No collateral circulation could be palpated over the upper portion of the body. Roentgenologic examination revealed moderate vascularity of the lung fields and definitely enlarged pulsating pulmonary arteries. Both ventricles, especially the right one, seemed enlarged in all views. The aortic knob could not be seen. Following barium swallow, poststenotic dilatation of the aorta was demonstrated in the left anterior oblique position. Electrocardiographic examination showed pronounced right axis deviation and incomplete right bundle branch block. During cardiac catheterization, pressures recorded from the right ventricle were 145/0 to –6 and in the pulmonary artery pressure was 150/70. Oxygen studies revealed a significant rise in oxygen content on passing from the right auricle to the right ventricle and pulmonary artery. Direct aortography revealed no communication between the aorta and

main pulmonary artery but demonstrated coarctation of the aorta just distal to the left subclavian artery. A diagnosis was made of coarctation of the aorta and a large ventricular defect, although an aortic pulmonary septal defect could not be ruled out. On January 28, 1952, an exploration was carried out through the left posterolateral fourth intercostal space. Systolic pressures measured in the main pulmonary artery and aorta proximal to the coarctation were both 140/102. These pressures are probably low because the capacity of the strain gauge we were using was exceeded. Pressure in the aorta distal to the coarctation was 89/80 (Fig. 8A). The coarctation was excised and the pressures in the aorta and pulmonary artery were again found to be equal although much lower than previously. The pulmonary artery was then narrowed to about 40 per cent of its original diameter, and the pressure in it distal to the stenosis was about 10 mm. of mercury lower than that proximal to it (Fig. 8B). A biopsy of the lung taken at this time showed luminal narrowing of the small muscular arteries (Fig. 9) due to medial hypertrophy and some intimal fibrosis. This luminal narrowing was more marked than it was in any other patient except Case 2. He was discharged from the hospital 14 days after operation. Slight cyanosis continued for about 2 months and

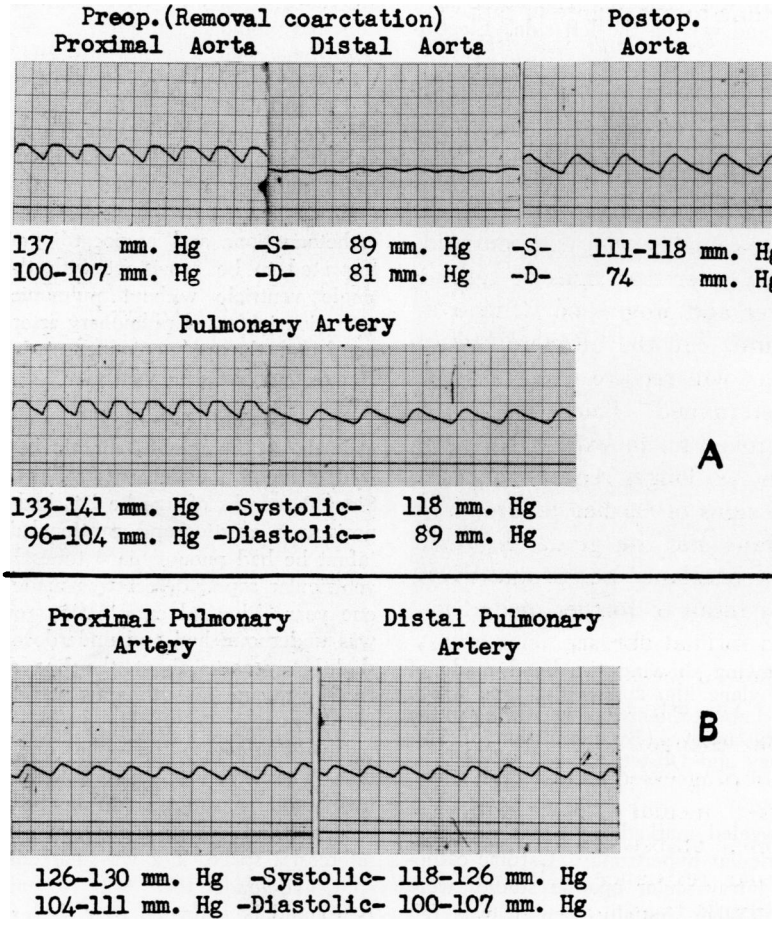


FIG. 8.—(A) Direct pressures made at operation in Case 5. The pressures in the aorta and pulmonary artery were similar before the coarctation was excised. The capacity of the strain gauge being used was exceeded. The pressure in the aorta distal to the coarctation is much lower than that proximal to it. After the coarctation was excised the pressures in the aorta and pulmonary artery are lower but still equal.

B. Pressure studies of the main pulmonary artery proximal and distal to the surgically produced stenosis. An immediate marked drop in the pressure distally does not occur because the high peripheral pulmonary artery resistance is present.

then gradually disappeared. His color remained excellent during a severe respiratory infection which occurred recently. Before operation cyanosis was much more marked during such episodes.

Comment. In attempting to classify these patients according to the degree of pulmonary resistance, it seems that the first and third case probably fall into the group in which the pulmonary resistance gradually diminishes after birth, resulting in an increasing pulmonary blood flow and cardiac failure. Both of these patients at birth appeared to be reasonably well compensated, and it was only later that signs of cardiac failure appeared and progressed. Only over a period of time, can the ultimate benefit the first patient will receive from the procedure be determined. Thus far he has definitely improved to the extent that he is gaining weight, no longer requires digitalis and shows no signs of cardiac failure. The second case falls into the group in which the pulmonary resistance has progressively increased as a result of further medial hypertrophy and intimal fibrosis. The biopsy of his lungs showed these changes to an extreme degree. The fifth case also falls into this group, but changes in his pulmonary arteries had not progressed to such a degree. He had marked medial hypertrophy and moderate intimal fibrosis and a high pulmonary vascular resistance. This case is admittedly difficult to evaluate because of the co-existence of two cardiovascular deformities. One might argue that relieving the coarctation alone would have achieved similar results if pulmonic stenosis had not been created. Relieving the coarctation, however, would be expected to increase the right to left shunt by decreasing the systemic resistance. An increased cyanosis would, therefore, be expected, but this was not observed. The pressure in the pulmonary artery and aorta were equal after the coarctation was excised, indicating a large communication between the two circulations. This would seem to justify the creation of pulmonary stenosis. A marked drop in pulmonary artery pressure distal to the stenosis was not expected to occur immediately because of the high peripheral pulmonary resistance. The fact that cyanosis disappeared about two months after operation might indicate that the small muscular arteries of the pulmonary vascular bed were becoming larger with a resulting decrease in pulmonary resistance and an increase in pulmonary blood flow.

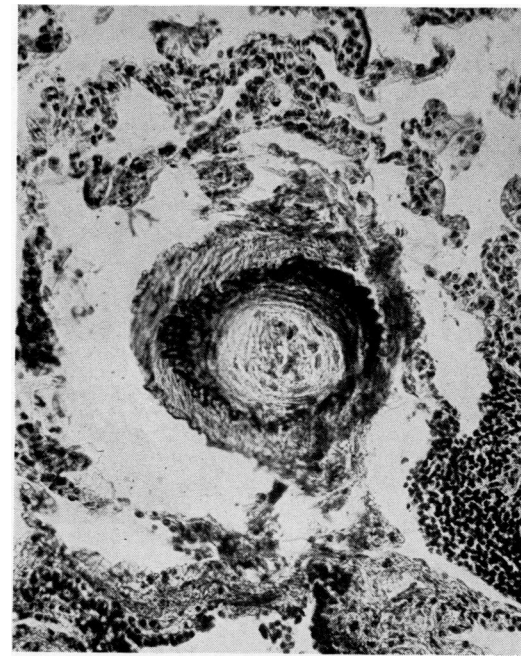


FIG. 9.—Photomicrograph of small muscular pulmonary artery from Case 5, a five-year-old boy with a large interventricular septal defect and coarctation of the aorta. There is marked medial thickening as well as intimal fibrosis causing great narrowing of the lumen.

At the present time, we believe that pulmonary stenosis should be produced for the treatment of patients in whom a low pulmonary resistance and cardiac failure develop. If cardiac failure is present due to a low pulmonary vascular resistance, then placing a partial obstruction in the main pulmonary artery should not only reduce the pulmonary blood flow and pressure in the pulmonary artery distal to the stenosis,

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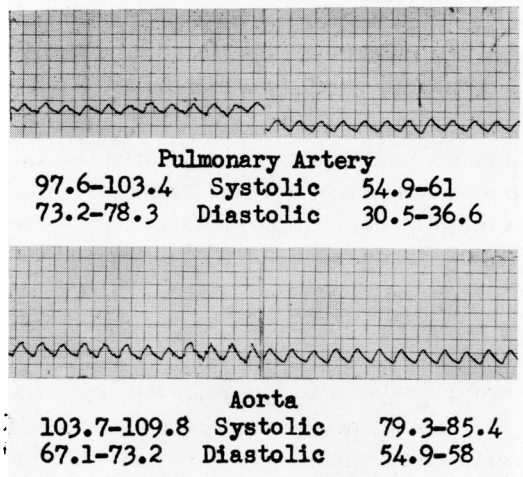
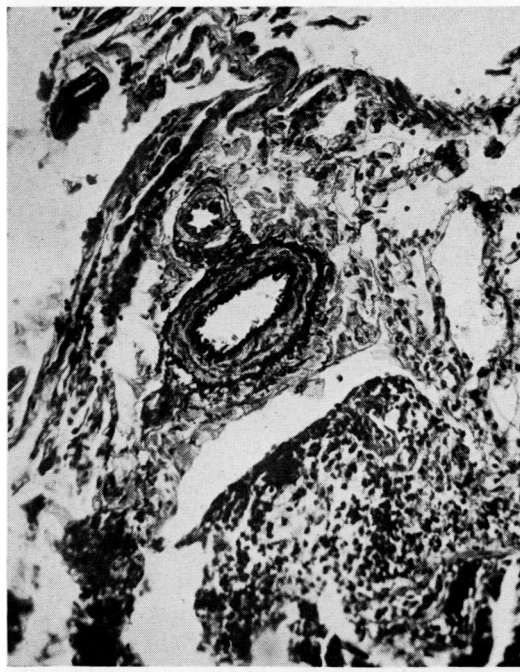


FIG. 10.—(A) Direct pressure measurements at operation in 13-month-old infant with atypical patent ductus arteriosus. The systolic pressure is higher in the aorta than in the pulmonary artery but the diastolic pressures are nearly equal. After closure of the ductus the pressure dropped generally. However, the pulse pressure in the aorta is reduced and the pressures in the pulmonary artery while reduced are still higher than normal.

B. Photomicrograph of small muscular pulmonary artery from above patient. Only hypertrophy of the media is present. This vessel is similar in appearance to that from the normal newborn infant in Figure 1A.

C. Photomicrograph of small muscular pulmonary artery from four-year-old child with small typical patent ductus arteriosus which did not produce pulmonary hypertension. The media is thin and the lumen is large.



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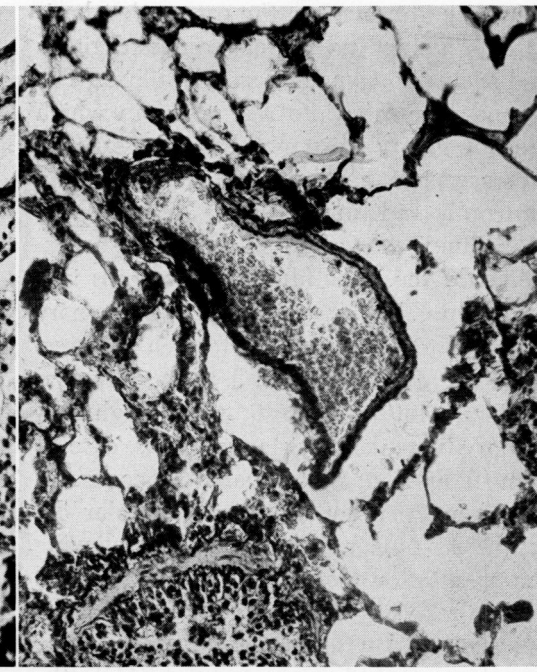


C

but it should correspondingly increase the systemic and coronary artery blood flow. In addition, pulmonary stenosis should also be produced in those cases where pulmonary vascular resistance is high due only to medial hypertrophy with or without a moderate amount of intimal fibrosis. It seems likely that if the pressure in the pulmonary artery is reduced, the muscular changes might be reversible. We do not feel that pulmonary stenosis should be produced in those patients where marked intimal fibrosis

is present until it can be demonstrated whether or not intimal fibrosis is a reversible process. This may be determined by catheterization some time after operation in patients having moderate fibrosis but could be demonstrated more satisfactorily if these changes could be produced in the experimental animal.

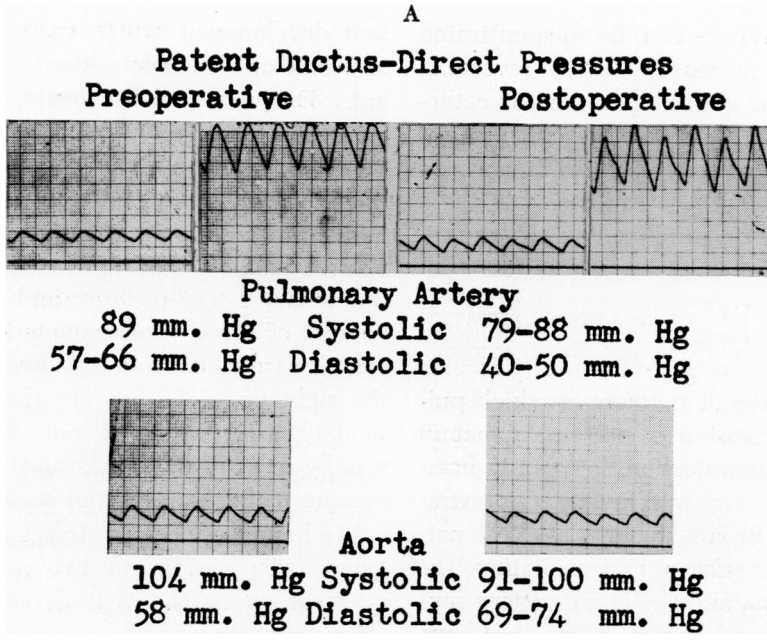
EXTRACARDIAC COMMUNICATIONS BETWEEN SYSTEMIC AND PULMONARY CIRCULATIONS

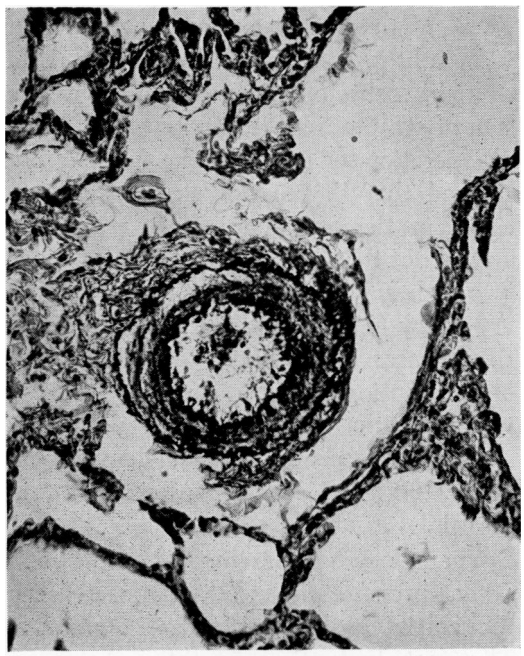
Another group of patients in which pulmonary hypertension is present is that in which the communication between the systemic and pulmonary circulation is extracardiac. This group includes atypical patent ductus arteriosus approximating the size of the aorta and aortic pulmonary septal defect. A number of authors[7, 14, 17] have recently demonstrated that in the presence of a large patent ductus arteriosus, the typical machinery-like murmur may not be present. In such cases there may be only a systolic murmur of varying intensity and duration. This difference in murmurs between the atypical and typical patent ductus is due to the fact that the diastolic pressure in the aorta and pulmonary artery is approximately the same, while the systolic pressure is higher in the aorta than in the pulmonary artery. Therefore, the flow of blood from aorta to pulmonary artery occurs only during systole, and a murmur is produced only during this phase of the cardiac cycle. As the resistance increases, the shunt through the ductus may be diminished until it is minimal or there is no shunt at all. The resistance may increase to the extent that the flow of blood through the ductus is reversed and such patients are cyanotic. This situation is rare. Whereas the typical patent ductus usually produces no symptoms in childhood, atypical ductus is nearly always symptomatic and has been often diagnosed previously as an inoperable cardiac malformation such as an interventricular septal defect. Physical growth and development are frequently retarded, and cardiac decompensation is often present. Dyspnea, hepatomegaly, and other signs of acute cardiac embarrassment may be sufficiently pronounced that special diagnostic technics and operation become mandatory in infancy. Cardiac catheterization reveals a high right ventricular and pulmonary artery pressure and the oxygen content of blood progressively increases as samples are taken from the lower portion of the right ventricle out into the main pulmonary artery. Direct aortography will usually outline the ductus or at least show opaque material in the pulmonary arteries.

We have had occasion to see four infants from seven months to two and one-half years of age with atypical patent ductus arteriosus accompanied by pulmonary hypertension and high pulmonary blood flow. Three of these infants were younger than 13 months of age, and operation was necessitated because of the severity and progression of symptoms. Pressures were obtained at operation on all but one patient and showed that the diastolic pressures were equal in the aorta and main pulmonary artery, but the systolic pressure in the aorta was slightly higher than that in the pulmonary artery (Figs. 10A and 11A). In each of these cases microscopic examination of lung biopsies showed narrowing of the lumen of the small muscular pulmonary arteries as a result of medial hypertrophy (Figs. 10B and 11B). None showed intimal fibrosis.

Upon closure of the ductus the most consistent pressure change was an increase in the aortic diastolic pressure (Fig. 11A). The fact that there is little change in the pulmonary artery pressures indicates increased pulmonary vascular resistance to blood flow. The resistance diminished over a period of several months, presumably as a result of an increase in the caliber of the small muscular pulmonary arteries. Adams[1] reported a 15-year-old patient with a large

A





B

FIG. 11.—(A) Direct pressure measurements at operation in a child two and a half years old with atypical patent ductus arteriosus. After closure there is a rise in the aortic diastolic pressure but only a slight drop in the pulmonary artery pressures.

(B) Photomicrograph of small muscular pulmonary artery from above patient with large atypical patent ductus arteriosus. Marked medial hypertrophy is present, causing narrowing of the lumen.

atypical patent ductus arteriosus who had extreme pulmonary hypertension. Catheterization one year after closure of the ductus revealed a pulmonary artery pressure only slightly above normal. This patient had not only medial thickening but also intimal fibrosis. It is our plan to carry out similar studies on our patients after a period of months or years has elapsed.

As to the method of closing the ductus, we believe that the enormous atypical ductus should be closed by division and suture of the ends. While the smaller ductus may be satisfactorily dealt with by a multiple suture technic, the larger ductus is more likely to recanalize if treated in this manner. Although it is much larger than the usual ductus, the vessel wall is much thicker and not as friable. The serrefine Potts ductus clamps are helpful in dividing the ductus. Exposure is best obtained through a posterolateral incision in the fourth or fifth intercostal space.

INTERAURICULAR SEPTAL DEFECT AND TRANSPOSITION OF THE AORTA AND PULMONARY ARTERY

Another group of patients who have pulmonary hypertension are those with inter-

auricular septal defects and transposition of the aorta and pulmonary artery. In interauricular septal defect, pulmonary hypertension may develop rather slowly depending upon the size of the defect. The mechanism of its production is not clearly understood but is possibly on the basis of the left to right shunt resulting in a high pulmonary blood flow. We have recently performed the procedure developed by Swan and his associates[22] of invaginating the auricular appendages through an interauricular septal defect in the heart of a 35-year-old man* who, before operation, was thought to have mitral stenosis and insufficiency and who was found at the time of operation to have a normal mitral valve but a very large interauricular septal defect. His symptoms had progressed rapidly so that he was in severe cardiac failure and was having hemoptysis nearly every day. He has clinically improved since operation, but more time must elapse before an accurate evaluation can be made. The pressure in his pulmonary artery was extremely high and biopsy of the lung showed marked medial hypertrophy and intimal fibrosis in most of the small muscular pulmonary arteries. Many were completely occluded by this process. Extreme cyanosis occurred immediately after invaginating the auricular appendages and was severe for about two weeks. It then gradually disappeared during the following two or three weeks. We interpreted this as an indication that an initially extremely high pulmonary resistance was present but gradually diminished. A more complete report will be made on this patient after a longer period of time has elapsed.

Transposition of the aorta and pulmonary artery must be accompanied by a communication between the two circulations if life is to continue. This communication is usually in the form of a patent ductus arteriosus, interauricular septal defect, or interventricular septal defect. Pulmonary hypertension is usually present. Probably one of the reasons present methods of surgical treatment have not been more beneficial in some of these patients is because pulmonary hypertension persists. Conceivably the creation of pulmonic stenosis as a supplement to the procedures presently used might reduce the pulmonary artery pressure and further benefit these patients.

* This patient kindly referred by Dr. William H. Leake.

SUMMARY

Pulmonary hypertension with or without increased pulmonary blood flow is present in a significant group of patients with congenital heart disease. Recently evidence has been presented to show that luminal narrowing of the small muscular pulmonary arteries which often occurs with these deformities is the result of increased pulmonary artery pressure and blood flow and is progressive. The medial thickening of the small muscular pulmonary arteries, which is present at birth, progresses and later intimal fibrosis occurs and results in a high pulmonary peripheral resistance.

Pulmonary stenosis was successfully created in two patients in order to place the point of high resistance at the stenosis and not in the smaller pulmonary arteries. Large atypical patent ductuses in four infants, three of whom were in cardiac failure, were closed. The procedure developed by Swan and his associates was performed on a 35-year-old patient who had a large interauricular septal defect.

Direct pressures in the aorta and pulmonary arteries were obtained on most of these patients and lung biopsies were taken. An attempt was made to correlate the pulmonary artery pressure and changes in the small muscular pulmonary arteries with the nature of the malformation and age of the patient. Only medial hypertrophy of the smaller pulmonary arteries was present in the infants, but in the older patients inti-

mal fibrosis also occurred and appeared to become more marked with age.

The creation of pulmonary stenosis to relieve pulmonary hypertension should be considered in patients in whom the cardiovascular deformity is such that the heart functions physiologically as a single ventricle, when there is a decreasing pulmonary resistance resulting in cardiac failure, and when there is increasing pulmonary resistance as a result of medial thickening with or without moderate intimal fibrosis. It should not be produced when extreme intimal fibrosis is present until it can be demonstrated whether or not this process is reversible.

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Addendum.—Since the submission of this report, pulmonic stenosis has been successfully created in two additional patients, one seven months and one five months of age, who were thought to have the Eisenmenger complex. Signs and symptoms of cardiac failure were no longer present after operation. The procedure was unsuccessfully performed on a two and one-half month old infant who had a true truncus arteriosus.

DISCUSSION.—DR. KEY: I would just like to ask what happened to the outside of the heart after that procedure.

DR. WILLIAM H. MULLER, JR. (closing): Los Angeles: Our patients have not gone a sufficient length of time since the creation of pulmonic stenosis to perform cardiac catheterization and other studies, but we don't see why there should be any particular change in the right ventricle. There has been no change in the pressure under which that ventricle has to operate because of the large communication between the two ventricles resulting in equal pressures in them.

In the case of the Eisenmenger complex, theoretically at least, the creation of pulmonic stenosis should produce about the same situation physiologically that one has in the tetralogy of Fallot after an artificial ductus is created.