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Pathology of the Pulmonary Circulation Before and After Correction of Low-Flow States

Ramiah Subramanian
Renu Virmani

Low blood flow to the pulmonary circulation occurs in congenital cardiac malformations associated with obstruction of right ventricular outflow. In such conditions, alternate routes of blood supply to the lungs are established early in development, or created surgically at a later date. Although unusual, morphologic alterations of hypertensive pulmonary vascular disease can be present in some of these patients when collateral systemic blood flow and pressure are high. Likewise, operative correction of these low-flow states may be complicated with pulmonary vascular changes of hypertension.

Information regarding pulmonary parenchymal and vascular changes associated with congenital heart defects and low blood flow to the lungs is sparse. Cardiac anatomy and pathophysiology of conditions associated with low pulmonary flow are discussed in this chapter. The pathology of the major pulmonary arteries, aortopulmonary collaterals, and intrapulmonary arteries prior to correction of low-flow states are also presented. The findings of pulmonary hypertension in low-flow states prior to and after surgical correction are reviewed, and the pathologic changes of conduits used in surgical correction of low-flow states are briefly addressed (Display 25-1).

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CONDITIONS ASSOCIATED WITH LOW-FLOW STATES

Conditions associated with low-flow states are presented in Display 25-2 and can be classified as subpulmonic, pulmonary valvular, and pulmonary artery stenosis.[1] Subpulmonic stenosis is characterized by obstruction to flow between the right ventricle and the pulmonary conus. The orifice between the right ventricle and the conus is partitioned by one or more thick muscle bundles and appears as a discrete small opening.

Two basic types of pulmonary valve stenosis are identified: valvular stenosis as an isolated lesion with intact ventricular septum, and valvular stenosis as an integral part of complex malformations (*e.g.*, tetralogy of Fallot, infundibular ventricular septal defect, various transposition complexes). In 70% of patients with pulmonic stenosis and intact ventricular septum, a poststenotic dilatation of the main pulmonary trunk and proximal left pulmonary artery is present. The preferential dilatation of the left pulmonary artery is probably related to the direction of the jet flow, because the left artery is in direct continuity with the pulmonary trunk. Histologically, the dilated pulmonary trunk shows destruction of elastic lamellae of the media. The intima may be hyperplastic, and the adventitia is thin. Rarely, the pulmonary trunk or its bifurcation may show localized stenosis, which may be significant; usually these patients have a history of intrauterine rubella. With severe pulmonary valve stenosis, the right and left pulmonary arteries may be hypoplastic.

The pulmonary trunk in tetralogy of Fallot is always smaller than the aorta; the right and left pulmonary arteries are normal or may be hypoplastic. The distal pulmonary trunk and the right and left pulmonary arteries may be moderately to severely narrowed, or there may be isolated anomalies of the right and left pulmonary arteries. Also, localized stenosis of one artery may be present, usually on the left.

Similarly, there are two basic types of pulmonary valve atresia: the isolated form with intact ventricular septum, and pulmo-

nary valve atresia associated with conotruncal malpositions (*e.g.*, tetralogy of Fallot, various transposition complexes). Pulmonary valve atresia with intact ventricular septum is a rare and highly lethal malformation: 50% of patients die within 2 weeks of birth, and approximately 85% are dead by 6 months of age.[2] Death is secondary to severe hypoxia and metabolic acidosis following spontaneous closure of the ductus arteriosus. Likewise, tetralogy of Fallot with pulmonary valve atresia, seen in 15% to 20% of cases, has a poor prognosis; if left untreated, 50% die of hypoxia by 1 year of age and many within 1 month of life.[3] However, survival is dependent on a collateral source of blood supply (see Systemic Collateral Arterial Blood Supply; Fig. 25-1). The main pulmonary trunk may be widely patent (see Fig. 25-1*A*), replaced by a fibrous cord (see Fig. 25-1*B*), or, rarely, totally absent (see Fig. 25-1*C*). The right and left pulmonary arteries are confluent and without stenosis of either branch (see Fig. 25-1*A*–*C*). The blood supply to the confluence is by way of the ductus arteriosus, or it may come from aortopulmonary collaterals. The confluence may show stenosis, which may be present in the right or left pulmonary artery but preferentially occurs at the junction of the ductus and left pulmonary artery. Rarely, the right and left pulmonary arteries are present and nonconfluent; the rarest form is the complete agenesis or absence of the pulmonary arteries (Fig. 25-1*D*).

In pulmonary artery stenosis, the obstruction to outflow of the right ventricle is distal to the pulmonary valve. The stenosis may involve the pulmonary trunk, the two main pulmonary arteries, and the lobar or segmented branches as a single lesion or any combination of lesions (Fig. 25-2). The pathologic changes consist of membranelike stenosis (type I), tubular hypoplasia (type II), and saccular dilatations (type III A–D). Membranelike stenosis is rare, is discrete, is located just above the pulmonic valve, and is best appreciated by angiography. In tubular hypoplasia or stricture, a varying segment of the pulmonary trunk is narrowed. The wall of the pulmonary trunk is thickened with no specific change in the media or adventitia, but the intima is extremely hyperplastic, leading to varying degrees of luminal narrowing. The saccular dilatations are distal to the strictures and represent poststenotic dilatations. The walls of the dilatations are thin because of loss of media.

PATHOPHYSIOLOGY OF INADEQUATE PULMONARY BLOOD FLOW

The consequences of inadequate pulmonary blood flow depend on the degree of pulmonary stenosis, the development of the pulmonary trunk and pulmonary arteries, and the presence of systemic collateral blood flow.[4] With intact ventricular and atrial septa and mild to moderate valvular or infundibular stenosis, a sufficient volume of blood reaches the lungs and the left side of the heart to maintain a physiologic cardiac output. Such patients are usually asymptomatic. However, with severe stenosis there is systemic perfusion if blood flow to the lungs drops to a critical level. An abrupt, severe drop in flow, with exercise or infection, may result in syncope and, rarely, sudden death.

With atrial or ventricular septal defect, the size of communication may be large and nonrestrictive, or small and restrictive. The shunt, which is left to right in early infancy, reverses in childhood or adolescence as pulmonary vascular resistance increases. Infants
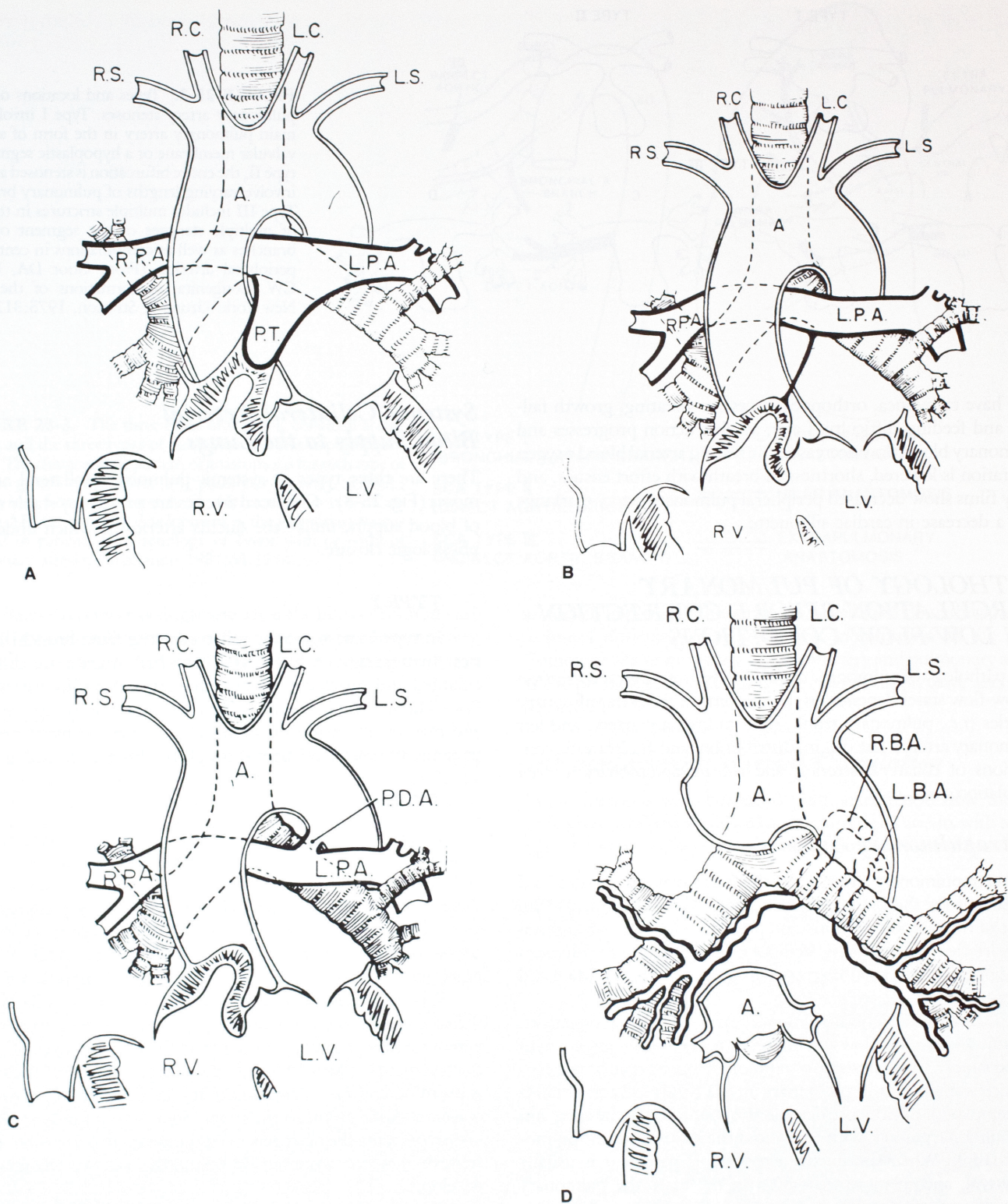
FIGURE 25-1. Pulmonary atresia. (**A**) Confluence of pulmonary arteries and proximal atresia of pulmonary trunk. (**B**) Confluence of pulmonary arteries, diffuse atresia of the pulmonary trunk, and ductus absent. (**C**) Ductus present and patent, but no identifiable pulmonary trunk. (**D**) Pulmonary arterial agenesis or atresia, arterial supply to lungs through bronchial arteries. (A, aorta; LBA, left bronchial artery; LC, left common carotid artery; LPA, left main pulmonary artery; LS, left subclavian artery, LV, left ventricle; PDA, patent ductus arteriosus; RBA, right bronchial artery; RC, right common carotid artery; RPA, right main pulmonary artery; RS, right subclavian artery; from Edwards JE, McGoon DC. Absence of anatomic origin from heart of pulmonary arterial supply. Circulation 1973;47:393.)
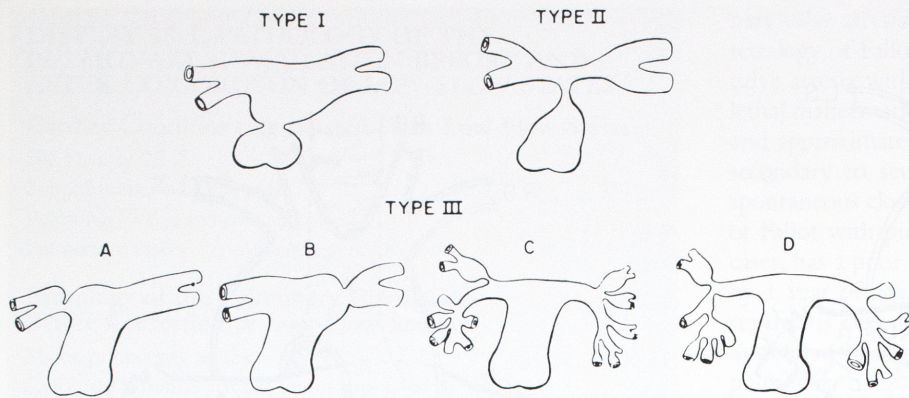
FIGURE 25-2. Types and locations of major pulmonary artery stenoses. Type I involves the main pulmonary artery in the form of a supravalvular membrane or a hypoplastic segment. In type II, the entire bifurcation is stenosed and may involve varying lengths of pulmonary branches. Type III includes multiple strictures in the form of multiple stenoses of the segment or lobar branches as well as combinations in central and peripheral arteries. (From Goor DA, Lillehei CW. Congenital malformations of the heart. New York: Grune & Stratton, 1975:312.)

may have tachypnea, orthopnea, excessive sweating, growth failure, and feeding difficulty. Later, as obstruction progresses and pulmonary blood flow decreases, the resting arterial blood oxygen saturation is lowered, shortness of breath with effort ensues, and x-ray films show decreased peripheral pulmonary artery markings and a decrease in cardiac silhouette.

PATHOLOGY OF PULMONARY CIRCULATION BEFORE CORRECTION OF LOW-FLOW CONDITIONS

The pathology of pulmonary circulation before surgical correction of low-flow states depends on the anatomy of the extrapulmonary arteries (*i.e.*, pulmonary trunk, right pulmonary artery, and left pulmonary artery): the origin, distribution, and anastomotic connections of collateral arteries; and the intrapulmonary arterial circulation.

Extrapulmonary Arteries

The extrapulmonary arterial development may be variable and dependent on the underlying condition. The extent of involvement of the pulmonary trunk and proximal right and left pulmonary arteries in pulmonary stenosis and atresia has already been mentioned; it has been discussed in greater detail by Mair and colleagues.[5]

The caliber of central pulmonary arteries is related directly to the amount of blood flow and indirectly to the anatomic sources of blood supply.[6] The presence of pulmonary confluence or nonconfluence is important in pulmonary atresia if surgical correction is contemplated. Confluence denotes the continuity of the right and left pulmonary artery, with or without the inclusion of the pulmonary trunk. When the ductus arteriosus is patent, it is usually unilateral, and in more than 80% of the cases the pulmonary arteries are confluent. When the anastomosis of a systemic collateral to a pulmonary vessel is to the proximal central pulmonary artery or its lobar branches, the central vessel may be of significant caliber. However, when the anastomosis is into distal pulmonary arteries, at the segmental level, the central pulmonary arteries are hypoplastic. With nonconfluent central pulmonary arteries, the homolateral lung has a unifocal blood supply and a normal arterial distribution, but the contralateral lung is usually supplied from several collateral arteries with a fragmented intrapulmonary arterial distribution.

Systemic Collateral Arterial Blood Supply to the Lungs

There are three types of systemic-pulmonary collateral anastomoses (Fig. 25-3).[7] Collateral arteries are a relatively stable source of blood supply, unlike the ductus arteriosus, which undergoes physiologic closure.

TYPE I

In type I anastomoses, collaterals arise from bronchial arteries. In tetralogy of Fallot, the bronchial arteries are diffusely enlarged and provide a nondiscrete source of pulmonary blood flow. The anastomosis with pulmonary arteries is intrapulmonary and may involve fairly medium-sized arteries. In older cyanotic patients, the collateral flow through the bronchials is large.

TYPE II

Large aortopulmonary collateral arteries constitute type II anastomoses. These occur most commonly in pulmonary atresia and rarely in tetralogy of Fallot and pulmonary stenosis. One to three aortopulmonary collaterals, which are usually large, originate from the upper or middle descending thoracic aorta. The course of these collaterals is serpiginous and terminates at the junction of the interlobar and intralobar pulmonary arteries.

The morphologic structure of aortopulmonary collaterals at the origin from the aorta varies from elastic arteries with widely patent lumina to muscular arteries with areas of stenosis. Intimal thickening in the form of intimal pads is present in 60% of cases; it is prominent at branching points and at junctions of large aortic collaterals with pulmonary arteries. Stenosis within the collateral vessels prevents the occurrence of pulmonary hypertension, but if stenosis is absent, hypertensive pulmonary vascular changes may develop.

The large, elastic aortopulmonary collaterals undergo changes as they join pulmonary arteries and approach the segmental bronchi. Intimal cushions are formed that are composed of amorphous material and fragmented elastic fibers. The vessel dilates proximal to the anastomosis, beyond which the muscular pulmonary arteries are abnormally small and sparse. In about 50% of cases of tetralogy of Fallot and large aortopulmonary collaterals, the latter enter into a complex arrangement at the hilum of the lung before connecting with interlobar and intralobar pulmonary arteries, which distribute into the lungs distally. Rarely, the aortopulmon-
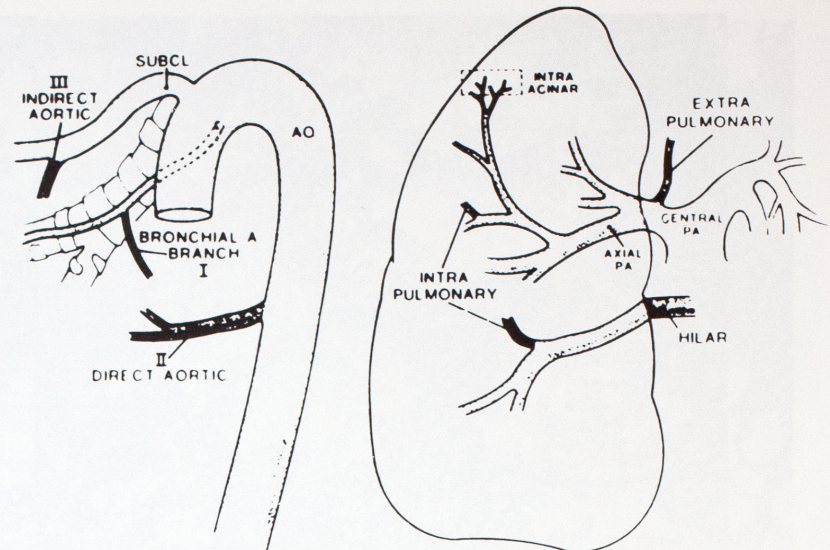
FIGURE 25-3. The three types of systemic collateral artery (SCA) and the three types of anastomosis with the pulmonary artery. The characteristic pattern of anastomosis for each type of SCA is given. (AO, aorta; PA, pulmonary artery; SUBCL, subclavian; from Rabinovitch M, Herrera-DeLeon V, Castaneda AR. Growth and development of the pulmonary vascular bed in patients with tetralogy of Fallot with or without pulmonary atresia. Circulation 1981;64:1234.)

SCA TYPE I (BRONCHIAL ARTERY BRANCH)	→	INTRAPULMONARY ANASTOMOSIS
SCA TYPE II (DIRECT AORTIC BRANCH)	⇉	HILAR ANASTOMOSIS
SCA TYPE III (INDIRECT AORTIC BRANCH)	⇄	EXTRAPULMONARY ANASTOMOSIS

ary collaterals connect as single arteries at the hilus or connect end-to-end with the hilar portion of the ipsilateral pulmonary artery. This pattern of pulmonary circulation has been called truncus type IV (see Fig. 25-1D).

TYPE III

Collaterals arise from the major branches of the aorta in type III anastomoses. The internal mammary, intercostal (Fig. 25-4), or subclavian arteries are the specific points of origin. The collaterals generally anastomose with the central pulmonary artery. Intercostal connections, however, often occur with pleural vessels

and result in pleural adhesions with large blood flow; they present technical difficulties during surgical mobilization of the lung. Communications between a coronary artery and pulmonary artery as the primary source of pulmonary blood supply have also been reported.[8]

Intrapulmonary Arterial Circulation

In all situations with decreased pulmonary blood flow there is poor growth of peripheral pulmonary arteries. Patients with tetralogy of Fallot, including those with pulmonary atresia and aor-
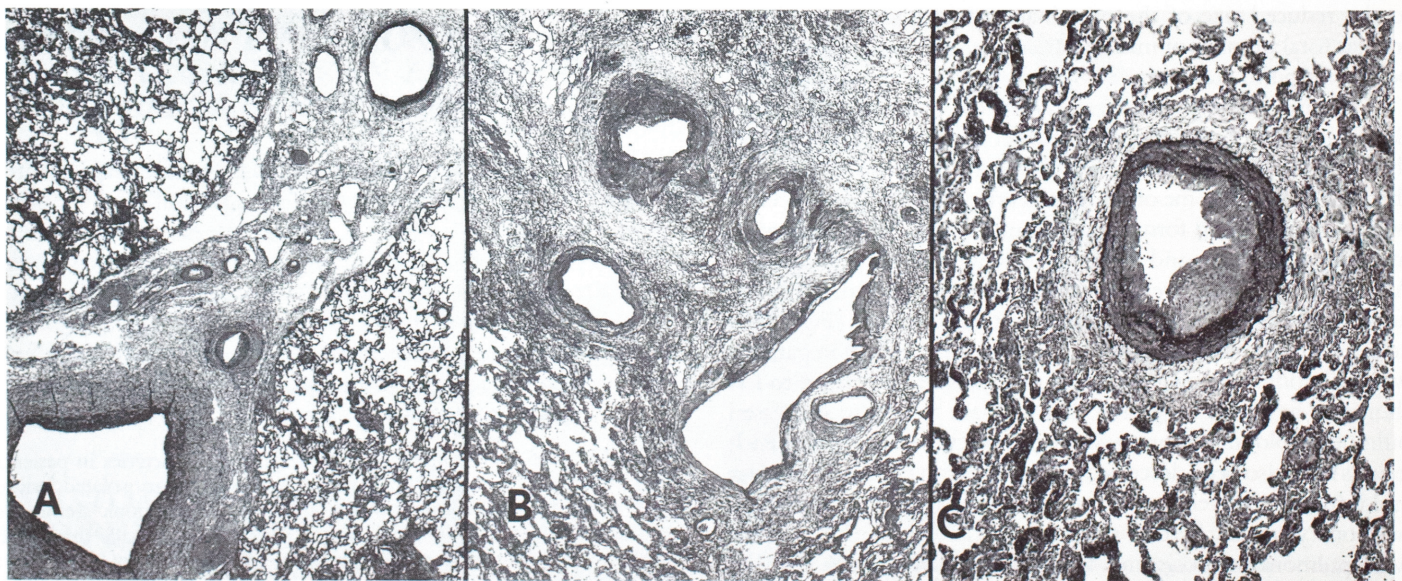
FIGURE 25-4. Collateral muscular arteries originating (**A**) from the aorta (*i.e.*, intercostal arteries) in an interlobar septum of lung and (**B**) on the pleural surface in a 40-year-old patient with tetralogy of Fallot. (**C**) Collateral muscular artery with fibrous intimal cushion, in lung parenchyma. The absence of an associated airway identifies this vessel as bronchial. (Movat elastic tissue stain; low magnification.)
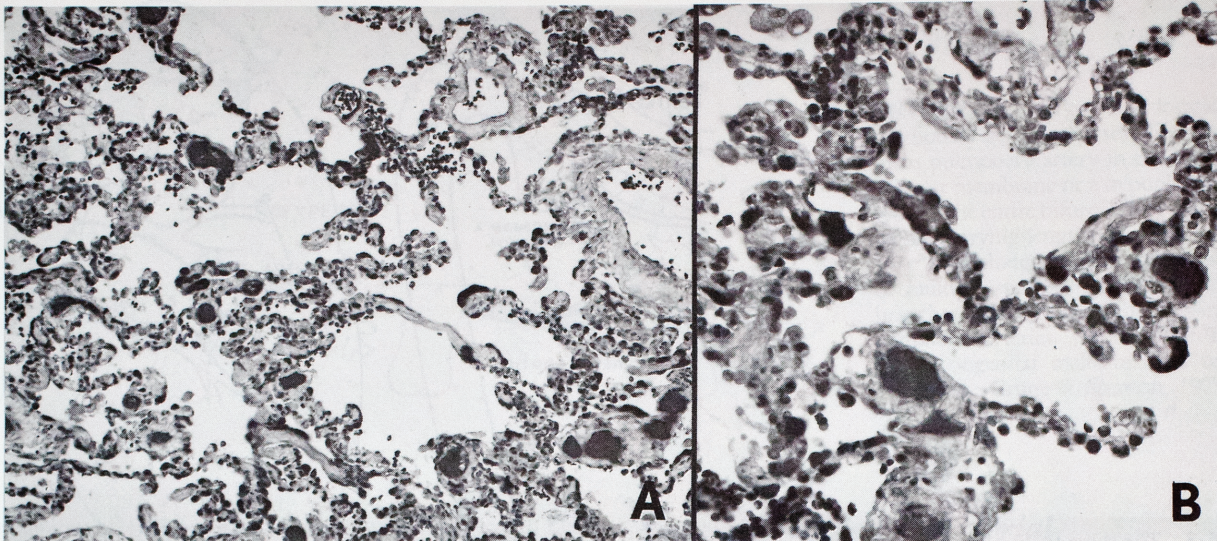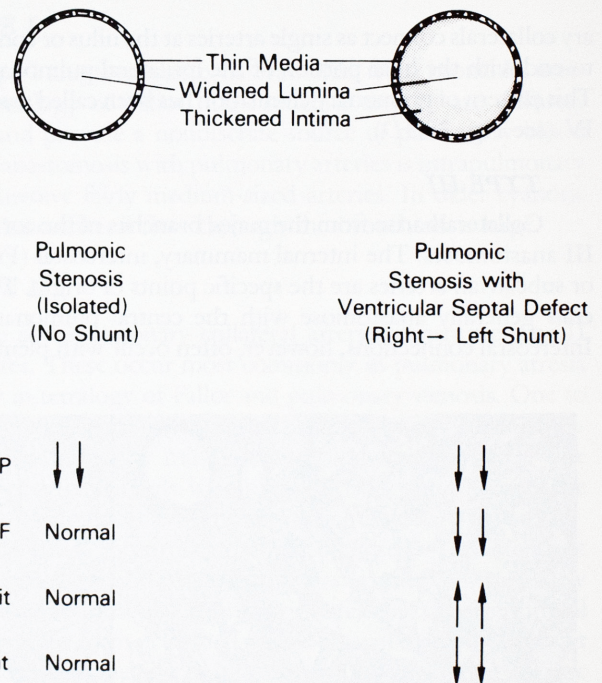
FIGURE 25-5. (**A**) Low-power and (**B**) intermediate-power views show marked dilatation of alveolar capillaries and venules in a patient with tetralogy of Fallot. (H & E stain.)

topulmonary collaterals, have intraacinar arteries of small caliber. The number of arteries is usually normal, but in certain cases of pulmonary atresia with intact ventricular septum, the intraacinar arteries are not only small but decreased in number. Therefore, the collateral blood supply is inadequate for oxygenation in most patients.[7,9,10]

Quantitative analysis indicates that medial thickness of the pulmonary arteries, expressed as a percentage of the diameter, is considerably smaller in patients with pulmonary valvular atresia than in age-matched controls. The thinning is due to deficiency in muscular arterial tissue rather than mere dilatation. These changes are observed in some cases even during the first few days of life, suggesting that they must have occurred before birth. In addition to the reduced size of the preacinar and intraacinar arteries, a smaller total number of intraacinar arteries is present in the newborn with pulmonary atresia when compared with normals.[10–12]

The morphologic changes in low-flow pulmonary states reflects chronic vasodilatation. The media is markedly thinned, and the lumen of arteries, capillaries, and veins is dilated (Figs. 25-5 through 25-8). In some of the dilated arteries, thrombosis occurs, which organizes and forms multiluminal channels with intervening intimal fibrous and fibrinous change. The septa of these Arnold Rich lesions[13] are often very delicate and thin, dividing the lumen into multiple channels that are endothelialized (Figs. 25-9 and 25-10). Because Arnold Rich lesions are common in patients with pulmonic stenosis, ventricular septal defects, and right-to-left shunts, it has been suggested that they are related to decreased pulmonary blood flow and associated polycythemia. Arnold Rich lesions have also been described in patients with pulmonic valvular and infundibular stenosis and an intact ventricular septum.[14] The pulmonary vascular bed, however, appears normal in most patients with pulmonic stenosis and intact ventricular septum without cyanosis. The major capillary and postcapillary changes in pulmonary low-flow states consist of capillary and venous dilation and engorgement in spite of the diminished flow.[15]

	Pulmonic Stenosis (Isolated) (No Shunt)	Pulmonic Stenosis with Ventricular Septal Defect (Right → Left Shunt)
PASP	↓↓	↓↓
PBF	Normal	↓↓
Hematocrit	Normal	↑↑
SAO₂ Sat	Normal	↓↓

Abbreviations: PASP= Pulmonary Arterial Systolic Pressure; PBF = Pulmonary Blood Flow; SA = Systemic Artery; Sat = Saturation

FIGURE 25-6. The appearance of the pulmonary arteries in patients with pulmonary hypotension. If pulmonic stenosis is an isolated lesion, there is usually no thickening of the intima, but if pulmonic stenosis is combined with ventricular septal defect, the intima is usually thickened. PASP, pulmonary arterial systolic pressure; PBF, pulmonary blood flow; SA, systemic artery; Sat, saturation. (From Virmani R, Roberts WC. Pulmonary arteries in congenital heart disease: a structure function analysis. In: Roberts WC, ed. Adult congenital heart disease. Philadelphia: FA Davis, 1987:77.)
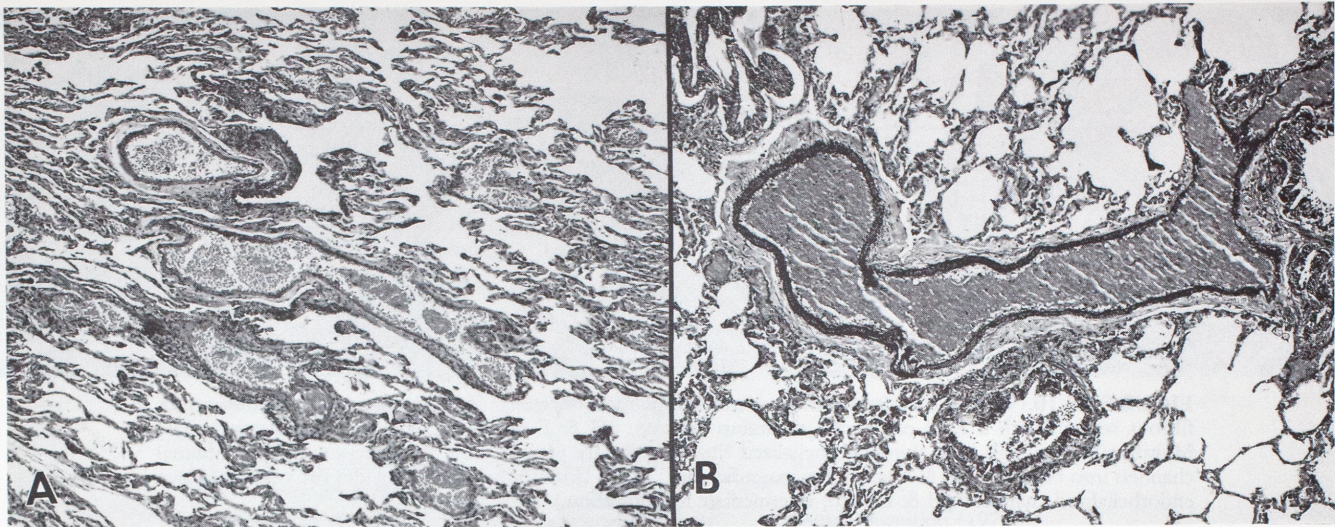
FIGURE 25-7. (**A, B**) Dilated muscular pulmonary artery branches with thin media are present in a patient with pulmonary atresia. (Elastic van Gieson stain; low magnification.)
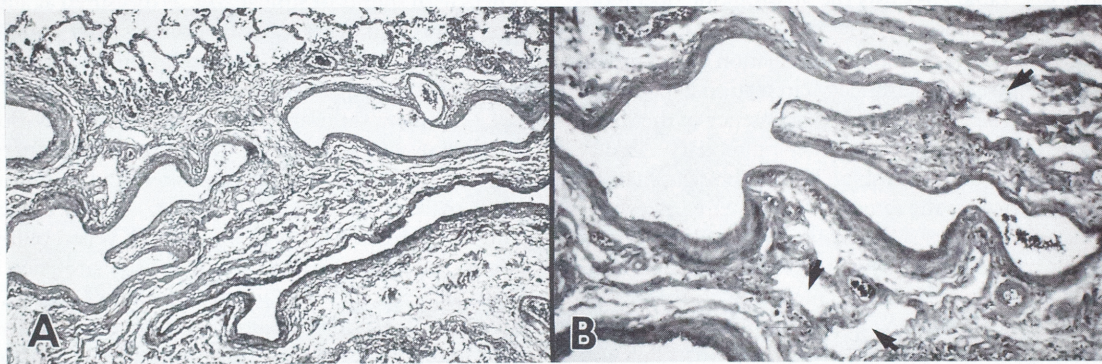

FIGURE 25-8. (**A, B**) Pleural venous and lymphatic vessel (*arrows*) dilatation in a patient with tetralogy of Fallot. (Movat elastic tissue stain; low magnification.)

HYPERTENSIVE PULMONARY VASCULAR DISEASE IN LOW-FLOW STATES BEFORE OPERATION

Although uncommon, changes of hypertensive pulmonary vascular disease have been reported in low-flow states.[16] When systemic artery collaterals directly supply a portion of the lung, severe pulmonary hypertensive changes may occur when there is absence of stenosis of these collaterals (Fig. 25-11*A, B*). Medial hypertrophy suggestive of pulmonary hypertension may be present microscopically.[10] Necrotizing arteritis with plexiform lesions (*i.e.*, grade VI of Heath and Edwards classification; Fig. 25-12) has also been reported in a patient with uncorrected tetralogy of Fallot.[17]

ANASTOMOTIC OPERATIONS AND PULMONARY HYPERTENSION

Surgical intervention in pulmonary low-flow states may involve creation of a shunt between systemic and pulmonary circulations with or without placement of a conduit, or complete surgical

Fresh
Thrombus
(Fibrin)

Organizing
Thrombus
(Fibrin + Fibrous)

"Organized
Thrombus"
(Fibrous)
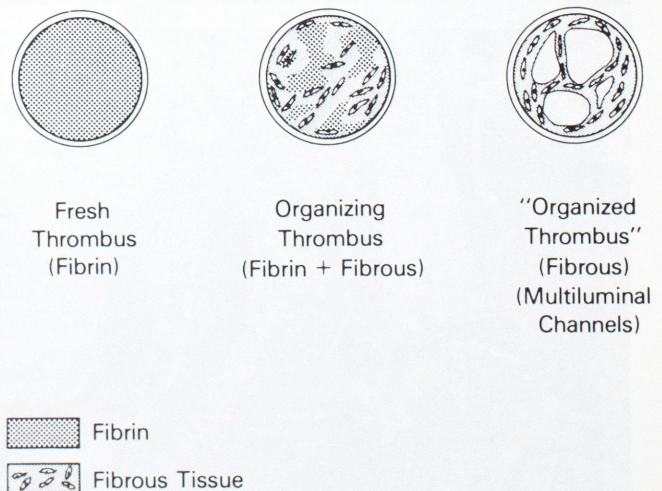(Multiluminal
Channels)

Fibrin

Fibrous Tissue

FIGURE 25-9. Arnold Rich lesions occurring in patients with pulmonary hypotension and inadequate pulmonary blood flow. (From Virmani R, Roberts WC. Pulmonary arteries in congenital heart disease: a structure function analysis. In: Roberts WC, ed. Adult congenital heart disease. Philadelphia: FA Davis, 1987:77.)
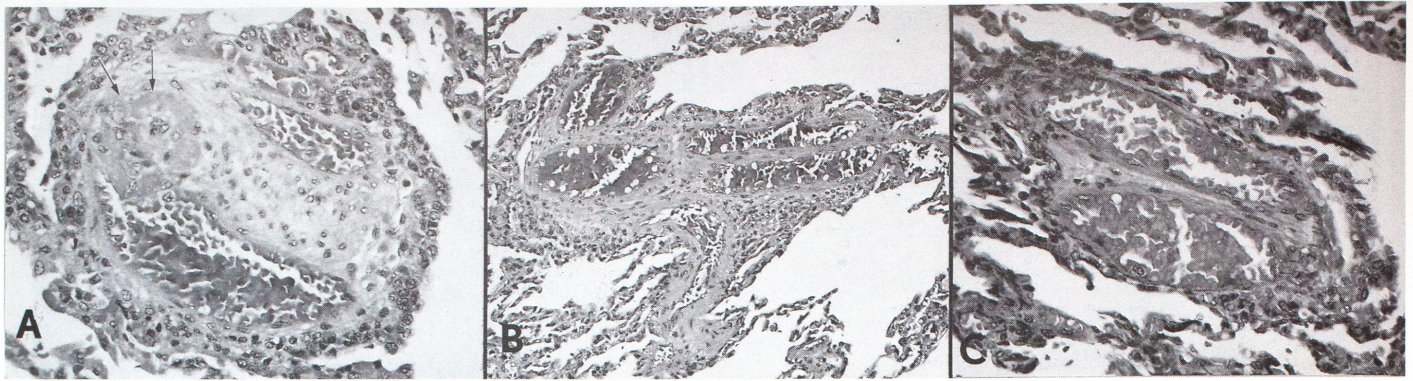
FIGURE 25-10. Arnold Rich lesions in a patient with pulmonary atresia. (**A**) The lumen is divided by a thick fibrous septum with a focal organizing thrombus (*arrows*). (H & E stain; intermediate magnification.) (**B**) Multiluminal channels with thin endothelialized fibrous septa are present; note the extension of multiluminal channels into branches. (H & E stain; low magnification.) (**C**) A thin fibrous septum divides the vessel into two endothelialized channels. (H & E stain; intermediate magnification.)

repair by patch closure of the ventricular septal defect and excision of pulmonic stenosis. Table 25-1 lists the anastomotic operations performed to improve pulmonary flow.

The consequences to the pulmonary circulation of creation of a shunt between systemic and pulmonary circulation depends on factors such as location, size, and duration of patency of the shunt (Fig. 25-13). When changes of hypertensive pulmonary vascular disease occur after the creation of a shunt, the pathologic changes in the pulmonary arteries are the same as in other cases of a shunt between systemic and pulmonary circulation. Concentric intimal fibrosis, plexogenic pulmonary arteriopathy, and necrotizing arteritis have all been noted to occur.[13] The incidence of progressive pulmonary vascular disease is much greater in patients with aortopulmonary arterial shunts, such as those used in the Potts and Waterston operations (Fig. 25-14). However, a large number of patients with large aortopulmonary shunts do not experience significant pulmonary vascular disease.[18] It is not clear why some patients undergo advanced pulmonary vascular changes, whereas others with shunts of similar size, as measured at autopsy, have no significant pulmonary vascular changes after equal or longer periods of shunt duration.[18] Advanced pulmonary vascular disease rarely occurs with a shunt duration of less than 4 to 5 years.[18]

Complete surgical repair of pulmonary low-flow states such as tetralogy of Fallot results in increased pulmonary blood flow. Subsequent pulmonary hypertension is uncommon; only 61 of 1400 patients developed pulmonary arterial hypertension after complete repair of tetralogy of Fallot.[19] When pulmonary hypertension does occur, it results from the presence of a residual ventricular septal defect, absence of a left or rarely a right pulmonary artery, or acquired occlusion of a pulmonary artery; the latter two conditions result in contralateral increased pulmonary vascular resistance. Histologically, pulmonary vascular disease may be noted in the early postoperative period, usually 2 to 3 months after surgical repair if the septal defect reopens.[14]
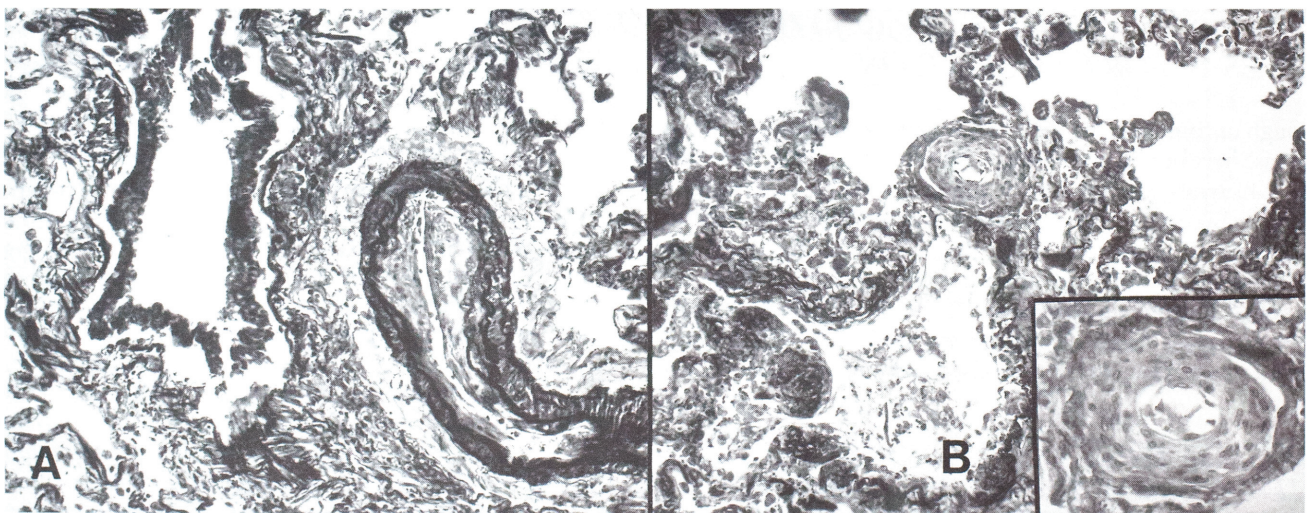
FIGURE 25-11. (**A**) Concentric intimal proliferation, Heath and Edwards grade III, is seen in sections of the left lung from a patient with tetralogy of Fallot and absent left pulmonary artery. The blood supply to the left lung was through aortopulmonary collaterals. (**B**) Focal intimal proliferation is present in a pulmonary artery from the same lung. A higher magnification of the lesion is shown (*inset*). (Movat elastic issue stain; low magnifications; inset at intermediate magnification.)

TABLE 25-1
Systemic–Pulmonary Shunt Operations

| Operation	Eponym (Year)
Anastomosis of proximal end of divided subclavian artery to the side of the right or left main pulmonary artery	Blalock-Taussig shunt (1944)
Shunt between the side of the descending thoracic aorta and the side of the left pulmonary artery	Potts anastomosis (1946)
Anastomosis of the superior vena cava to the pulmonary artery	Glenn operation (1954)
Placement of Gore-Tex conduit between the subclavian artery and ipsilateral pulmonary artery branch	Kirklin modification of Blalock-Taussig shunt (1960)
Anastomosis of the ascending aorta to the right pulmonary artery	Waterston-Cooley (1962)
Placement of a conduit connecting the right ventricle and the pulmonary trunk	Rastelli operation (1969)
Connection of the right atrium to the pulmonary artery	Fontan operation (1971)
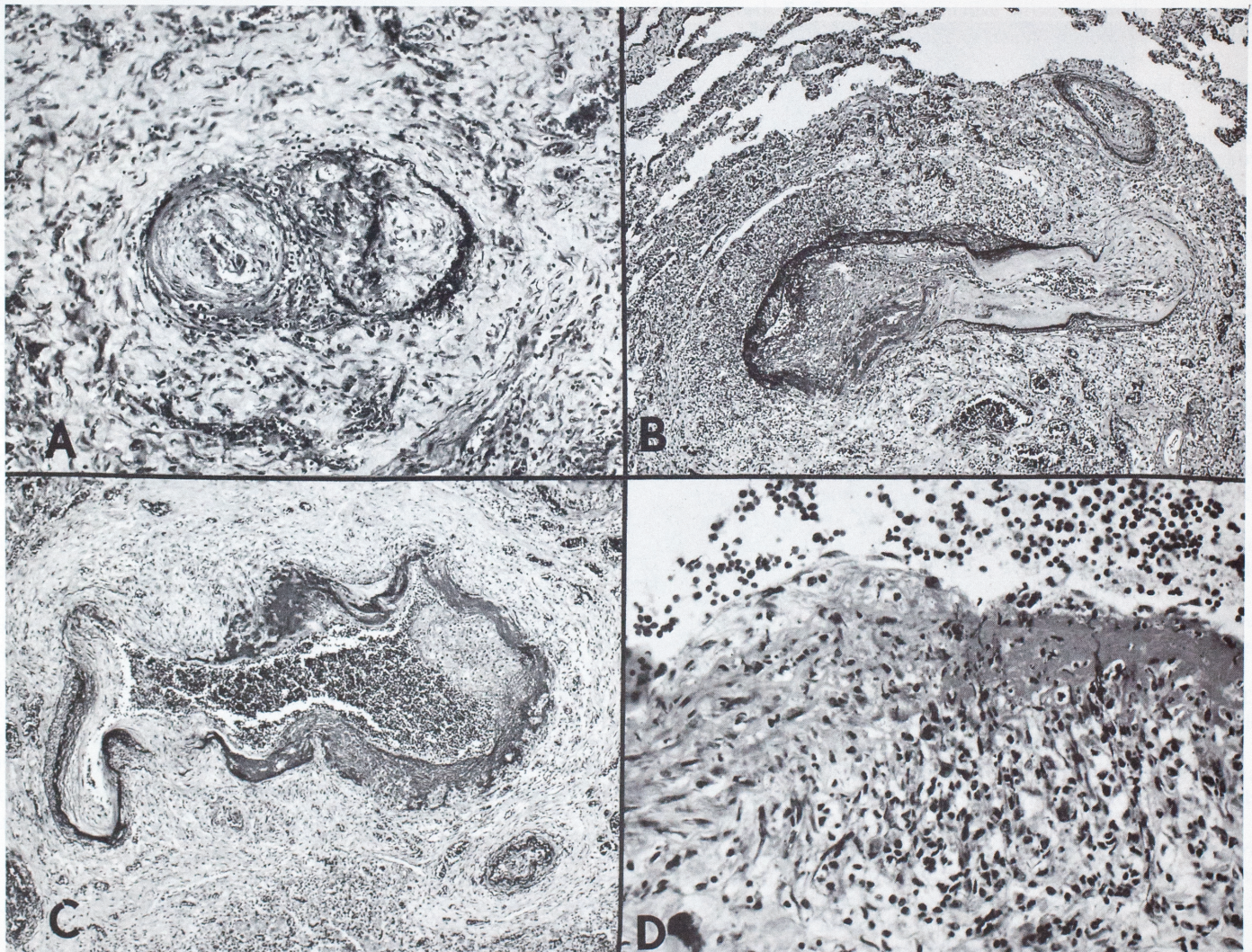
FIGURE 25-12. Sections from the left lung of a patient with unoperated tetralogy of Fallot with pulmonary atresia and a large aortopulmonary collateral blood supply. The muscular pulmonary arteries are involved by fibrinoid necrosis and vasculitis. (**A**) Early plexiform lesion. (**B**) A vessel wall shows inflammatory cell infiltration and fibrin deposition and organization. (**C**) The wall is disrupted with aneurysmal dilatation and intimal fibromuscular proliferation. (Movat elastic tissue stain; low magnifications.) (**D**) A vessel wall shows fibrinoid necrosis and acute and chronic inflammation. (H & E stain; intermediate magnification.)
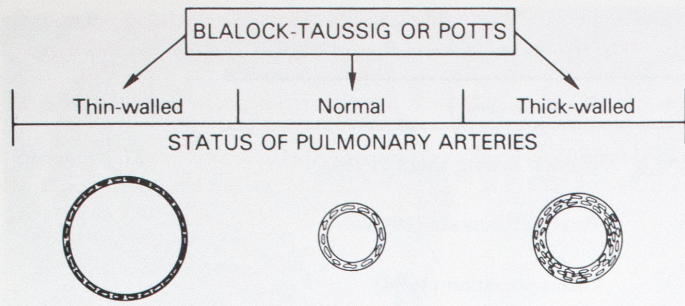
FIGURE 25-13. The effect of operative creation of systemic-to-pulmonary arterial communications on pulmonary arteries of patients with pulmonary hypotension. The media of the pulmonary arteries may remain thin-walled and dilated (*left*), increase to normal thickness (*center*), or develop abnormally thickened media (*right*). (From Virmani R, Roberts WC. Pulmonary arteries in congenital heart disease: a structure function analysis. In: Roberts WC, ed. Adult congenital heart disease. Philadelphia: FA Davis, 1987:77.)

PATHOLOGY OF CONDUITS USED IN THE SURGICAL CORRECTION OF LOW-FLOW STATES

Aortic homografts and porcine-valved extracardiac conduits are used to reconstruct the right ventricular outflow tract in the total correction of complex congenital anomalies (Display 25-3). The conduit may be valved or nonvalved, and heterograft or aortic homografts may be used. Pathologic changes noted in the valved conduits may involve the bioprosthetic valves present in the conduit or the conduit itself.[20]

Pathologic changes seen in the bioprosthetic valves can be classified as early or late.[21] Early changes occur within 2 months of placement and consist of plasma protein insudation, fibrin deposition, collection of platelets or erythrocytes, and deposition of macrophages and giant cells. Collagen disruption, erosion of valve
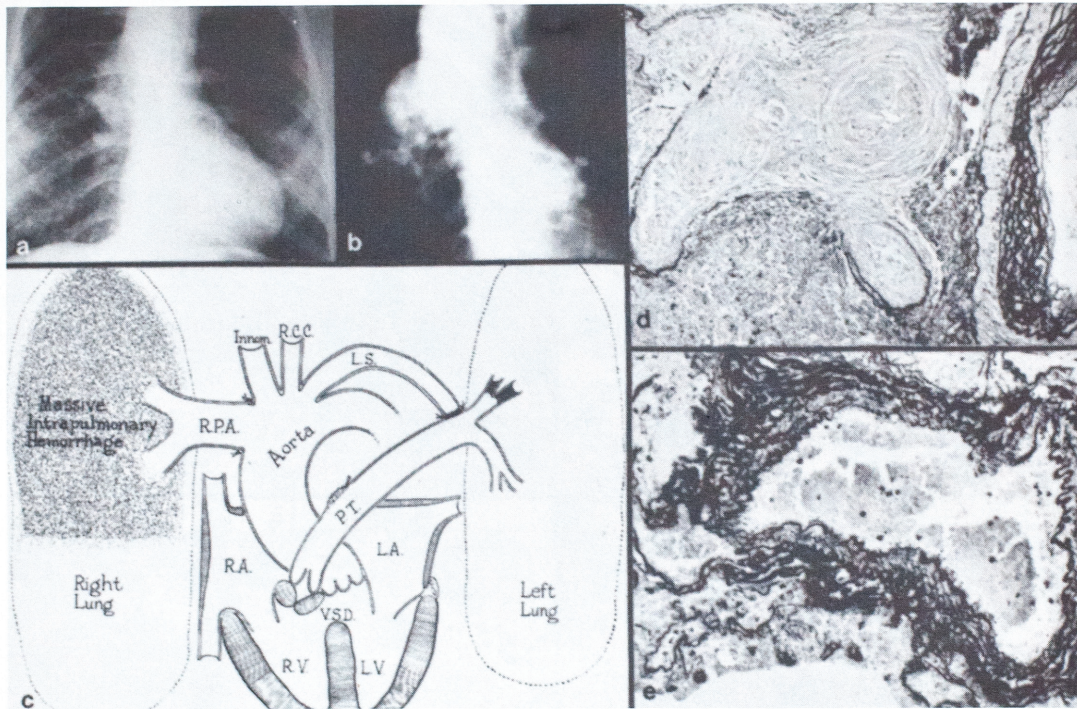

FIGURE 25-14. A 19-year-old woman with tetralogy of Fallot. A left subclavian–to–left pulmonary arterial anastomosis was performed at 3 years of age. There was little improvement, however, and an end-to-side anastomosis between the aorta and the right main pulmonary artery was performed 2 years later. She was nearly asymptomatic until age 11, when exercise tolerance diminished and cyanosis returned. At age 18, hematocrit was 80%. (**A**) Chest radiograph shows the right aortic arch, decreased vascularity in the left lung, and increased vascular markings in the central portion of the right lung. The pulmonary trunk could not be entered by catheter from the right ventricle. Simultaneous right ventricular, femoral arterial, and right main pulmonary artery systolic pressures were equal (108 mm Hg). Oxygen saturation in the femoral artery was 70%. (**B**) Right ventricular angiography shows all contrast material being ejected into the aorta, and the lumens of the intrapulmonary branches of the right main pulmonary artery were severely narrowed. No contrast entered the pulmonary trunk, left main pulmonary artery, or left lung. Because of systemic pressure in the right pulmonary arteries and absent blood flow to the left lung, the patient was considered inoperable. At age 19, she died suddenly of massive intrapulmonary hemorrhage. (**C**) Findings in heart and lungs at autopsy. (**D**) A portion of the wall of the right pulmonary artery, arising from the pulmonary artery but not connected in this section, is a plexiform lesion. (**E**) The left pulmonary artery is normal. (Innom, innominate artery; LA, left atrium; LS, left subclavian artery; LV, left ventricle; PT, pulmonary trunk; RA, right atrium; RCC, right common carotid artery; RPA, right main pulmonary artery; RV, right ventricle; VSD, ventricular septal defect; from Virmani R, Roberts WC. Pulmonary arteries in congenital heart disease: a structure function analysis. In: Roberts WC, ed. Adult congenital heart disease. Philadelphia: FA Davis, 1987:77.)

DISPLAY 25-3. PATHOLOGIC ALTERATIONS IN EXTRACARDIAC CONDUITS

Aortic Homografts

Calcification
Neointima (*i.e.*, peel)
Endocarditis
Thrombosis

Valved Synthetic Conduits

Bioprosthetic valve
  Stenosis as a result of:
    Calcification
    Thrombosis
    Fusion of cusps
  Insufficiency as a result of:
    Cusp tears caused by degeneration
    Thrombotic adhesions
    Endocarditis
    Fusion of cusps

Conduit
  Neointima (*i.e*, peel)
  Thrombosis
  Pannus formation at anastomoses

Nonvalved Synthetic Conduits

Neointima (*i.e.*, peel)
  Thrombosis

From Virmani R, Atkinson JB, Forman MB. Aortocoronary bypass grafts and extracardiac conduits. In: Silvered MD, ed. Cardiovascular pathology. London: Churchill-Livingstone, 1991:1607.

surfaces, platelet aggregation, lipid accumulation, and calcification occur later.[22] Calcification may lead to valvular stenosis.[21] Edwards and colleagues noted that valvular stenosis results from thrombosis and calcification, whereas valvular insufficiency results from cusp tears, thrombotic adhesions, and destruction of the valve by endocarditis.[23]

A luminal fibrous peel or neointima develops within all conduits. The peel may be thick and result in obstruction.[21–23] Conduit peels appear similar histologically regardless of thickness or apparent age and consist of a luminal, densely collagenous portion and a conduit portion composed of active granulation tissue with focal collections of acute and chronic inflammatory cells. Varying amounts of fibrous tissue may be found along the outer surface of the conduit.

Obstruction of a conduit may result from a diffuse or localized thick fibrous neointima, thrombotic expansion of the interface between the conduit and neointima, or creation of a flap-valve by dislodgment of a portion of the neointima. Edwards and colleagues found that calcific stenosis of the porcine valve accounted for obstruction in 46%, thick fibrous neointima alone in 30%, and valvular stenosis with a thick neointima in 16% of conduits.[23] Nonobstructed conduits are occasionally replaced because the patient has outgrown the prosthesis.

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