Our understanding of the complexities of congenital heart disease, a deviation from normal cardiac anatomic development that affects 8 in 1000 births, has progressed immensely since the establishment of the Board of Pediatric Cardiology (and hence the subspecialty) in 1961. Advances have paralleled improvements in diagnostic imaging, such as echocardiography and cardiac angiography, and innovations in surgical repair techniques. Basic scientific investigation has led to greater comprehension of the patterns of embryologic development and of the aberrancies that cause the common congenital anomalies. This chapter gives a broad overview of the genesis of congenital heart disease with a focus on the role of corrective surgical interventions.

Embryologic development of the heart begins with the fusion of angiogenetic cell clusters within the splanchnic mesoderm layer of the primitive embryo to form the heart tube at 18 to 21 days of gestation. The cardiac tube surrounds a core of cardiac jelly, which serves as an extracellular matrix, and plays a key role in the complex intracellular signaling and feedback mechanisms that regulate cardiac morphogenesis. The cardiac tube consists of a myocardial mantle three to five layers thick and an inner single layer of endocardial cells. The endocardial cells play a role in the formation of endocardial cushions, as well as in cellular signaling. The heart begins to rhythmically contract as early as day 17, once the functional units of the myocytes begin to form. Myocardial growth proceeds with segmentation and looping of the heart tube and cellular differentiation and migration along the embryologic axes, with the establishment of laterality and the organization of the primitive cells into a sophisticated organ.

The fetal circulation adapts to placental gas exchange and nutritional support. The right side of the heart is responsible for about two thirds of the fetal cardiac output, which is shunted through the ductus arteriosus into the descending aorta. During development, pulmonary vascular resistance is high and pulmonary blood flow is low. Closer to term, pulmonary blood flow slowly increases and, as new arterioles develop and increased pulmonary arterial cross-sectional area increases, pulmonary vascular resistance decreases. At birth, with the entrance of air into the lungs and alveolar expansion, pulmonary vascular resistance falls and pulmonary blood flow rapidly increases 8- to 10-fold. The ductus arteriosus changes from a right-to-left conduit to a left-to-right shunt after birth, until it closes within the first hours to days of life. Pulmonary arterial blood pressure is thought to reach adult levels by 2 to 6 weeks after birth. Increased pulmonary venous return to the left atrium elevates left-sided intracardiac pressures relative to the right-sided pressures, and the valve of the foramen ovale closes.

Deviations from this complex process of cardiac development lead to congenital cardiac anomalies, with presentations that vary from the immediate postnatal period to adulthood. Congenital cardiac lesions can be broadly divided into cyanotic and acyanotic lesions. The clinical manifestations of congenital heart disease in the neonatal period usually result in cyanosis, respiratory distress, and/or hypoperfusion with evidence of cardiogenic shock. Congenital heart disease is suspected when a history and physical examination, a chest radiograph, and an ECG show one or more of these clinical findings. Further evaluation by Doppler echocardiography is routine and an integral part of the noninvasive evaluation of congenital heart disease (see also chapter 44). Echocardiography can determine the basic anatomic configuration of the heart,
and Doppler studies provide information about patterns and disturbances in blood flow. Angiography can further elucidate the cardiopulmonary defects. Indications for angiography may include inconsistencies in the noninvasive findings, the need for images of the branch pulmonary arteries, or suspected complex ventricular septal defects (VSDs). Abnormalities of the aortic arch, such as coarctation or vascular rings, are best evaluated by magnetic resonance imaging.

Therapy for congenital heart disease has evolved with surgical and nonsurgical innovations. The development of transcatheter procedures has made therapeutic cardiac catheterization a viable alternative to surgery for specific congenital cardiac lesions (see chapter 45). In addition, advances in imaging and prenatal diagnosis have spurred the development of antenatal surgical intervention for congenital heart disease.

INTERVENTIONAL CARDIOLOGY

Early management of congenital heart lesions was largely surgical. With the development of angiography, initially a diagnostic modality, interventional catheter-based techniques for management of congenital heart disease became possible. Definitive treatment with device closure now exists for amenable lesions such as fossa ovalis (secundum type) atrial septal defect (ASD), muscular VSD, and patent ductus arteriosus. Balloon valvuloplasty for pulmonic or aortic stenosis and balloon angioplasty with stenting for branch pulmonary artery stenosis and coarctation of the aorta are other common catheter-based interventions that have been used with some success. Studies on transcatheter perforation and pulmonic valvuloplasty in pulmonary atresia with intact ventricular septum have reported an 81% initial success rate; however, more than 50% of patients may need a systemic-to-pulmonary shunt to augment pulmonary blood flow or are better suited for definitive surgical repair.

SURGICAL TREATMENT

The development of pediatric cardiac surgery has led to the survival of many children with complex congenital heart disease. These successes have depended on improved diagnoses, advances in surgical technique, and the development of a means for extracorporeal circulation—cardiopulmonary bypass (CPB). Complex repairs for previously fatal lesions such as transposition of the great arteries and hypoplastic left-sided heart syndrome (HLHS) have become routine, with declining mortality rates and improved long-term outcomes.

Surgically Correctable Lesions: Common Congenital Anomalies

Ventricular Septal Defects

Ventricular septal defect is the most common congenital cardiac anomaly, occurring in 20% of patients with congenital heart disease (Fig. 46-1). Interventricular communication occurs with the failure of the ridges of tissue to fuse to form the septum. VSDs are traditionally classified as perimembranous, muscular, and doubly committed subarterial, with the perimembranous and muscular types further classified on the basis of anatomic location as inlet, outlet, or trabecular. Of surgically repaired defects, 80% are perimembranous. Of patients with VSDs, 50% have other associated cardiac anomalies. The flow across a VSD is related to the size of the VSD. “Restrictive” VSDs are small to medium-sized, with a pressure gradient across the defect. “Nonrestrictive” VSDs are large, with equal left ventricular and right ventricular (RV) pressures. Congestive heart failure can develop with significant left-to-right shunting and increased volume load to the pulmonary vasculature, the left atrium, and the left ventricle. Persistent elevation in pulmonary vascular resistance (PVR) can lead to equalization of PVR and systemic vascular resistance (SVR) and irreversible changes to the pulmonary vasculature. Eisenmenger’s complex (reversal of the shunt to right to left and subsequent cyanosis) can result if the VSD is left untreated. Surgical repair is performed by means of a median sternotomy and exposure via the right atrium, right ventricle, or pulmonary artery, depending on the location of the lesion.

Atrial Septal Defect

An interatrial communication accounts for 10 to 15% of congenital cardiac anomalies. The term ASD refers to a spectrum of anomalies that are broadly classified into four categories: oval fossa or “secundum” defect, ASD of the atroventricular
Figure 46-1  Transatrial Repair of Ventricular Septal Defect (VSD)

The septal leaflet of the tricuspid valve may need to be bisected to permit placement of pledgetted sutures at its junction with the VSD. Superficial sutures are placed along the inferior border of the VSD to prevent injury to the conduction system.
septal defect (AVSD) type or partial AVSD or "ostium primum" defect, superior or inferior sinus venous defects, and coronary sinus defects. ASDs often coexist with other anomalies, such as partial anomalous venous drainage. The degree of hemodynamic disturbance is related to the size of the defect and the amount of blood flow shunting. Indications for closure are a significant left-to-right shunt, leading to a ratio of pulmonary blood flow to systemic blood flow (also known as shunt fraction, $Q_p:Q_s$) of greater than 1.5:1, or known venous thrombosis (because of the risk of paradoxical embolization and cerebrovascular accident). Device closure can be performed for simple oval fossa ASDs. Surgical repair is most often performed via a median sternotomy with CPB and bicaval cannulation via a right atriotomy.

**Patent Ductus Arteriosus**

*Patent ductus* arteriosus is a vascular connection postnatally between the main pulmonary trunk or proximal left pulmonary artery and the descending thoracic aorta. This anomaly occurs in about 1 in 2000 to 2500 births and accounts for 10% of congenital heart lesions. In full-term infants, the ductus arteriosus is usually functionally closed by 10 to 15 hours after birth. Persistent blood flow through this vessel is often associated with other congenital anomalies, and depending on the vascular connections, pulmonary blood flow may be dependent on patentcy of the ductus, as in lesions of RV outflow obstruction. In this case, the vessel may be kept open with prostaglandin $E_1$ therapy until an aortopulmonary connection is surgically created. When no other associated anomalies exist, and ductus closure has not occurred after medical therapy with indomethacin for 48 to 72 hours, direct surgical ligation or division via a left posterolateral thoracotomy or, alternatively, catheter-based device closure is indicated. Surgical closure before 10 days of age reduces the duration of ventilatory support, the length of hospital stay, and the overall morbidity rate.

**Atrioventricular Septal Defects**

*Atrioventricular septal defects* are defects involving deficiencies in the AV septum and abnormalities of the AV valves (mitral and tricuspid), commonly referred to as “endocardial cushion defects.” AVSDs account for 4 to 5% of congenital heart disease, and 7 to 25% of AV septal defects are associated with other cardiac defects. There is a wide spectrum of lesions, with a partial AVSD being limited to a deficiency in the atrial portion of the atrioventricular septum and a common atrioventricular valve (ostium primum ASD) and a complete AVSD referring to a deficiency of the entire atrioventricular septum with a common atrioventricular valve. Complete AVSDs are commonly seen in patients with Down’s syndrome and can occur in combination with tetralogy of Fallot (TOF) in this patient population. The mortality rate for unrepaired complete AVSDs at 2 years of age is as high as 80% because of progressive congestive heart failure and pulmonary vascular disease. Surgical repair is performed via a median sternotomy with CPB and with the use of a right atriotomy. The interatrial and/or interventricular communication is closed, and valvular competency is restored.

**Tricuspid Atresia**

*Tricuspid atresia*, a congenital lesion with an absent right-sided AV connection, occurs in up to 3.7% of patients with congenital heart disease. Left ventricular preload is dependent on interatrial blood flow via an ASD. Often, there is an associated VSD with left-to-right shunting, the degree of which depends on the size of the VSD and the right ventricle or infundibular chamber, and the right- and left-sided pressures. The physiology of the lesion varies by the amount of pulmonary blood flow. The original surgical repair, the classic Fontan procedure, involved a direct connection between the right atrium and the main pulmonary artery. Present-day conversion to the Fontan circulation usually requires a two-stage surgical approach after early palliation. A cavopulmonary anastomosis can be performed as early as 3 months of age but is usually created between 4 and 9 months, followed by the Fontan procedure, which is performed between 18 months and 3 years. The modern Fontan procedure includes a total cavopulmonary connection using a bidirectional Glenn shunt and an extracardiac conduit connection between the inferior vena cava and the pulmonary artery. The bidirectional Glenn shunt is a connection between the divided end of
the superior vena cava and the right pulmonary artery that shunts venous return from the superior vena cava directly to both lungs. This modification reduces associated morbidity and mortality rates, including a lowered incidence of early failure and a reduction in early and late arrhythmias.

Surgically Correctable Lesions: Complex Congenital Anomalies

Double-Outlet Right Ventricle

Double-outlet right ventricle is a conotruncal malformation with both great arteries arising from the right ventricle and an associated VSD. This anomaly has a wide spectrum of presentations depending on the location of the VSD, its relation to the great vessels, and the degree of arterial overriding of the interventricular septum. Classifications are based on the relationship of the VSD to the great vessels: subaortic VSD with or without pulmonary stenosis, subpulmonary VSD with or without subaortic stenosis, doubly committed VSD, and noncommitted or remote VSD. The degree of hemodynamic compromise of this lesion depends on the variable degree of subvalvar stenosis and the size and precise position of the VSD. The surgical approach also depends on the nature of the lesion.

Hypoplastic Left Heart Syndrome

Hypoplastic left heart syndrome (HLHS), a congenital lesion with univentricular physiology, involves an atretic left ventricle, an underdeveloped mitral or aortic valvular apparatus, or both, and hypoplasia of the ascending aorta. Systemic blood flow is usually ductal-dependent, and the appearance of symptoms in the neonatal period usually correlates with spontaneous ductal closure. Thus, early management with prostaglandin E1 to maintain ductal patency is life-sustaining. The appropriate balance between pulmonary and systemic blood flow (Qp:Qs) is critical. HLHS accounts for 25% of cardiac mortality during the first week of life. The major neonatal palliative approach is the Norwood procedure, in which an aortopulmonary connection is created (Figs. 46-2 and 46-3). This procedure involves the enlargement of the aortic arch with a homograft patch, and a shunt to provide pulmonary blood flow. The surgery is usually performed during the neonatal period and carries a 20 to 40% risk of mortality. The Norwood procedure is followed by a bidirectional Glenn shunt at 3 to 6 months of age and a Fontan procedure at 2 to 3 years of age. Alternatively, cardiac transplantation is favored for HLHS at some centers. The operative risk of cardiac transplantation in the neonatal period is 10%, but there is a high mortality rate (25%) for patients on the waiting list.

Tetralogy of Fallot

Classically, TOF refers to four major congenital defects: VSD, infundibular pulmonary stenosis, dextroposition of the aorta, and RV hypertrophy (Fig. 46-4). The common anatomic abnormality responsible for all features is posterior malalignment of the outlet septum. TOF can present with a range of clinical findings: from cyanosis at birth to oxygen desaturation without cyanosis (“the pink tetralogy”). The degree of compromise is determined by the severity of the RV outflow obstruction and the size and location of the VSD. The reported mortality rate for unrepaired TOF is 30% by 6 months of age, 50% by 2 years, and up to 84% by 5 years. Infants with severe forms of TOF are often maintained on prostaglandin E1 to support pulmonary blood flow until repair. Studies reviewing early palliative procedures versus complete repair show lower overall mortality rates for early complete repair of uncomplicated TOF relative to a two-stage approach to TOF repair. Total correction is accomplished on CPB. Closure of the VSD and provision of unobstructed flow from the right ventricle are the main goals of surgery.

Total Anomalous Pulmonary Venous Return

There are three types of total anomalous pulmonary venous return: supracardiac (most common, 50%), with pulmonary venous drainage into the innominate vein through a vertical vein; intracardiac, with drainage into the coronary sinus or the right atrium (least common); and infracardiac, with drainage into the inferior vena cava. Total anomalous pulmonary venous return may present with total pulmonary venous obstruction and pulmonary edema, requiring urgent surgical intervention. Without surgery, the mortality rate is 100% in the first year of life. Surgical repair with direct anastomosis of the
Stage II
At about 6 months of age, after pulmonary vascular resistance falls, a bidirectional Glenn shunt is necessary to reduce volume load on the right ventricle. The previous Blalock-Taussig shunt is divided.

Stage I
Hypothermic cardiopulmonary bypass and right atriotomy are utilized to excise the interatrial septum. The main pulmonary artery is transected and a "neoaorta" is created.

The main pulmonary artery and a cryopreserved aortic homograft create a neoaorta. Pulmonary blood flow is established through a systemic-to-pulmonary artery shunt.
common pulmonary venous channel to the right atrium is accomplished under circulatory arrest or low-flow continuous CPB and carries a mortality rate of approximately 16%.

**Transposition of the Great Arteries**

The neonate with discordant ventriculoarterial connections is dependent on intracardiac mixing for survival and typically presents with cyanosis at birth. Initial management of transposition of the great arteries with prostaglandin E1 and balloon septostomy to increase atrial mixing is life-sustaining, but the mortality rate without surgical repair is very high. Initial complete repair is optimal if it can be done within the first 30 days of life. Correction involves the redirection of systemic venous blood to the pulmonary circulation and pulmonary venous blood to the systemic arterial circulation. Over the years, numerous surgical approaches have been proposed for correction of transposition of the great arteries. Based on the outcomes obtained at numerous centers, the surgical approach of choice today is the arterial switch procedure (Fig. 46-5). Mortality rates have steadily declined since the arterial switch procedure has become widely accepted.

**Truncus Arteriosus**

*Truncus arteriosus*, a relatively uncommon defect (0.21–0.34% of those with congenital heart disease), consists of a single semilunar valve (the truncal valve) that regulates outflow from the single arterial trunk (rather than normally separate LV and RV outflow tracts) to the aorta, pulmonary arteries, and coronary circulation. The single arterial trunk overrides the interventricular septum. Left-to-right shunting occurs via a VSD and the aortopulmonary connection.
Figure 46-4  Tetralogy of Fallot

Deoxygenated blood
Patent ductus arteriosus
Stenotic pulmonary artery

Oxygenated blood
VSD with right to left shunt

Right ventricular hypertrophy

GORE-TEX® graft with pledges
Retracted tricuspid valve

Hypertrophied right ventricle

Ligated ductus arteriosus
Stenotic pulmonary trunk
Stenotic pulmonary valve
Aortic and mitral valve seen through VSD

Pulmonary valvotomy followed by pericardial patch to reduce stenosis
Pericardial patch to reduce subpulmonic stenosis

Tetralogy of Fallot
Patients are occasionally cyanotic at birth but most often develop symptoms of CHF within the first weeks of life. Surgical repair can be accomplished safely in the neonatal period (Fig. 46-6). The mortality rate for untreated truncus arteriosus is as high as 65% at 6 months of age and 75% at 1 year.

Pediatric Heart Transplantation

The success of pediatric cardiac transplantation is highest in the neonatal period. For HLHS or primary cardiomyopathies, the 5-year survival rate after transplantation is greater than 80%. Pediatric heart transplantation has been performed in more than 3500 children since the late 1960s. Congenital heart disease indications for transplantation are HLHS, severe Ebstein’s anomaly, pulmonary atresia with intact ventricular septum, unbalanced AV canal, single ventricle with subaortic stenosis, complex truncus arteriosus, and double-inlet left ventricle. Of the transplantation rates for the two broad categories of indications for heart transplantation in children, the rates of transplantation for congenital heart disease have recently reached and surpassed the rates for cardiomyopathy, the previously more common indication for transplantation.

The major drawback to cardiac transplantation as an answer to end-stage disease is the availability of donors, with a potential recipient to donor ratio of approximately 15:1. Two risk factors have been identified for death while waiting on the cardiac transplantation list: status 1 at listing (ICU patients on inotropic agents) and ventilator dependence. An obstacle to long-term survival after cardiac transplantation, besides rejection, is the development of graft coronary disease, which occurs in 2 to 30% of patients at 1 year after transplantation and in up to 50% of patients at 5 years. Rejection accounts for approximately 30% of deaths in children who have undergone heart transplantation. Developments in the field of immunosuppression and improvements in graft preservation and operative techniques have resulted in much improved outcomes, and further advances in these areas are on the horizon.
CONGENITAL HEART DISEASE

SURGICAL INTERVENTIONS FOR CONGENITAL HEART DISEASE

Ligated ductus arteriosus

Bisected pulmonary trunk

Right ventriculotomy exposes aortopulmonary valve through VSD

Common aortopulmonary trunk with single large valve

Deoxygenated blood

Oxygenated blood

VSD

Running closure of aortic wall

Pericardial patch over closure of right ventriculotomy

Homograft with semilunar valve connects right ventricle with pulmonary artery bifurcation

Care is taken not to damage the cardiac conduction system when sewing Gore-TEX® graft over the inferior rim of the VSD

Figure 46-6

Truncus Arteriosus

FUTURE DIRECTIONS

Research in the field of perinatology and the development of prenatal diagnostic modalities have led to advances in fetal heart surgery. Improvements in fetal Doppler ultrasound now permit diagnosis of fetal heart disease as early as 10 to 14 weeks of life. Antenatal intervention in fetal heart disease is an emerging, but yet unproven field. To date, published information about antenatal interventions has been limited to isolated case reports of balloon valvuloplasty for severe semilunar valvular obstruction, per-
formed with minimal success. There are reports of attempted pulmonic valvular dilatation antenatally in pulmonary atresia with intact ventricular septum and of attempted transuterine percutaneous pacemaker lead placement for congenital complete heart block. Future directions involve further development of transuterine as well as transumbilical approaches to fetal heart disease.

REFERENCES