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History, Growth, Nutrition, Physical Examination, and Routine Laboratory Tests

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The quality of patient care depends on a thorough bedside assessment of the patient's status. A complete history and physical examination enables the physician to compile an appropriate differential diagnosis, order tests in a suitable manner, and efficiently care for the patient. The physician must remember that all tests, even those viewed as non-invasive, such as echocardiography and chest radiography, are a concern to parents and patients. The ability to manage patients without overtesting is one of the features of the excellent clinician.

HISTORY

The pediatric history requires obtaining information from the care providers and, after infancy and early childhood, also from the patient. Parents who bring their children to a pediatric cardiologist even for evaluation of an innocent murmur are typically anxious[1]; therefore, it is important to establish a trusting and empathetic relationship with the family. As outlined in a previous edition of this book,[2] it is helpful to conduct the interview in a relaxed manner so that information can be recalled and shared with the physician.

Pertinent issues to be addressed in the history depend on the age of the patient and the clinical concern. The following topics need to be considered.

1. **Prenatal testing:** The results of any fetal ultrasounds performed during pregnancy can identify structural disease before birth. In a 12-month review of the in-patient cardiology consult service at Children's Hospital Boston (July 2001 to June 2002), 85% of infants with cyanosis caused by structural heart disease were identified before birth.[3]

2. **Pregnancy history:** Maternal use of medication can influence the likelihood of congenital heart disease developing in the fetus (see Chapter 5). Maternal diabetes mellitus is associated with an increased incidence of transposition of the great arteries, hypertrophic cardiomyopathy, coarctation, and ventricular septal defect. Maternal systemic lupus erythematosus is associated with fetal complete atrioventricular block.[4] Maternal exposure to infectious agents can contribute to cardiac defects in the neonate: rubella with peripheral pulmonary stenosis, patent ductus arteriosus, or ventricular septal defect; and Coxsackie virus with myocarditis (see Chapter 5).

3. **Perinatal history:** Maternal history of premature rupture of membranes, fever, or use of sedatives or anesthetics raises concern about sepsis and decreased respiratory effort. For infants with cyanosis, gestational age, Apgar scores, and history of meconium aspiration are useful to determine the likelihood of hyaline membrane disease, perinatal asphyxia, persistent hypertension of the newborn, or pneumonia. The response to oxygen helps to distinguish a cardiac from pulmonary basis for cyanosis.[5]

4. **Other birth defects:** A variety of syndromes are associated with congenital heart disease[6] (see Chapter 5). Commonly encountered syndromes and the frequency and most common type of congenital heart disease include trisomy 21 (45%; atrioventricular canal defect, ventricular septal defect, tetralogy of Fallot); VACTERL syndrome (*v*ertebral defects, *a*nal atresia, *c*ardiac defect, *t*racheo-esophageal fistula, *r*enal anomaly, *l*imb anomaly) (50%; ventricular septal defect, tetralogy of Fallot), trisomy 13 or 18 (more than 80%; ventricular septal defect), Noonan's syndrome (50%; pulmonary stenosis, hypertrophic cardiomyopathy),

Turner's syndrome (35%; aortic stenosis, cardiomyopathy, coarctation), Williams syndrome (50%; supravalvar aortic stenosis, coarctation, peripheral pulmonary stenosis), and Marfan syndrome (nearly all patients; aortic dilation, mitral valve prolapse, mitral regurgitation, aortic regurgitation).

5. **Family history:** Congenital heart disease affecting a previous child or a parent increases the risk for structural heart disease in the infant.[7] Early myocardial infarction in first-degree relatives (younger than 50 years for men, younger than 60 years for women) merits screening for hyperlipidemia (see Chapter 22). Sudden death is associated with various genetic diseases, including cardiomyopathy, prolonged QT interval, Brugada syndrome, Marfan syndrome, or arrhythmogenic right ventricular dysplasia.[8] Hypertension in the extended family should lead to close monitoring of this variable, especially in adolescence when essential hypertension may initially develop.

6. **Initial detection of murmur:** Knowledge of the time a murmur was initially detected leads a clinician to consider different categories of cardiac disease. For neonates, murmurs detected in the first 6 hours of life typically involve valve regurgitation (tricuspid valve from perinatal stress, mitral valve from cardiac dysfunction) or valve stenosis, whereas murmurs detected after 6 hours of age can also represent shunt lesions that present as pulmonary vascular resistance falls (e.g., atrial or ventricular septal defect, patent ductus arteriosus, peripheral pulmonary stenosis). It is important to note that some neonates may only be examined by a physician after 6 hours of age, and others may have both valve stenosis and septal defects (e.g., tetralogy of Fallot). Systolic murmurs detected initially at 2 to 4 years of age frequently are innocent but can represent structural heart disease if the patient was frequently uncooperative for earlier examinations, had progression in the severity of the lesion, or developed an acquired condition. During childhood, a new murmur of mitral or aortic regurgitation raises the possibility of rheumatic heart disease so that inquiry should be made about a history of streptococcal pharyngitis, unexplained fever, arthritis, chorea, and rashes.

7. **Growth and development:** The normal infant gradually eats a larger volume of food at increasing intervals. This pattern is not observed in infants with lesions associated with poor cardiac function, pulmonary edema, or significant left-to-right shunting (ratio of pulmonary to systemic flow greater than 2:1). Lesions associated with large shunts gradually become symptomatic as pulmonary vascular resistance decreases over the first 2 to 8 weeks of life. Infants with lesions associated with shunting at the ventricular or great vessel level are generally more symptomatic than those with only atrial-level shunting. Symptoms consist of tachypnea, diaphoresis, and feeding difficulties of early fatigue and decreased oral intake. Such infants can have failure to thrive and delays in developmental milestones.

8. **Cyanosis:** Cyanosis can have a cardiac, pulmonary, central nervous system, or hematologic basis. A full discussion can be found in Chapter 8. Cyanosis is often initially detected by experienced nurses in the newborn unit. The characteristics of fetal hemoglobin and the presence of darker skin pigmentation make the detection of mild cyanosis more difficult.

Infants with tetralogy of Fallot can have cyanotic spells (see Chapter 32). A single well-documented episode is an indication to proceed with surgical repair or palliation. In regions of the world where screening or infant surgery is not available, older children without prior intervention can have squatting episodes to relieve these cyanotic spells.

A common occurrence, especially in fair-skinned infants, is the transient development of peripheral cyanosis involving the distal extremities and perioral region. This appearance often occurs with cold exposure, such as after a bath, and represents vasomotor instability, a normal finding in infancy.

9. **Common issues evaluated in childhood and adolescence:** Although a variety of symptoms lead to cardiac consultation, several issues are frequently encountered.

a. *Endurance:* Parents, other adults such as teachers or coaches, or the patient may note decreased exercise tolerance compared with peers. Activity limitations may have a cardiac basis or be caused by poor general conditioning, obesity, exercise-induced reactive airway disease, other pulmonary disease, or neuromuscular disease. Determining the severity, duration, and progression of limitations and the associated symptoms helps to distinguish among these possibilities. The occurrence of limitations associated with obstructive lesions such as aortic stenosis or pulmonary stenosis is an indication for intervention.

b. *Chest pain:* Chest pain is a frequent symptom in children and has a cardiac basis in only 1% to 6% of patients.[9] Heart conditions include structural heart disease, such as left ventricular outflow obstruction, aortic dissection, ruptured sinus of Valsalva aneurysm, or coronary anomalies; acquired heart diseases, include pericarditis, myocarditis, Kawasaki disease, or arrhythmias, most commonly supraventricular tachycardia.

In children, chest pain typically has a musculoskeletal or idiopathic basis and is self-resolving. Musculoskeletal issues include costochondritis, myodynia, rib fracture, or slipping rib syndrome. Slipping rib syndrome involves the 8th, 9th, and 10th ribs, whose costal cartilages do not attach to the sternum; these ribs are attached to each other by fibrous tissue that is susceptible to trauma.[10] If these fibrous connections are weakened, the ribs can rub together, irritating the intercostal nerve and producing pain. Patients can describe "something slipping or giving away," "a popping sensation," or "hearing a clicking sound." Musculoskeletal pain typically is sharp in quality, is located at the costochondral junction or insertion site of the pectoralis major muscle group, and

frequently increases during inspiration. There often is a history of activity that can lead to muscle injury, such as sports, weight lifting, use of a knapsack to carry heavy school books, or direct trauma.

Other causes of chest pain include hyperventilation; psychiatric disorders; breast disease; respiratory disease, including pneumonia, pneumothorax, pneumomediastinum, or reactive airway disease; pulmonary hypertension; pulmonary embolism; gastrointestinal disorders; and exposure to toxins (cocaine, cannabis, cigarettes). A full discussion can be found in Chapter 22. In the absence of associated symptoms of illness, positive physical examination findings related to the cardiac or respiratory systems, or symptoms during exertion, a serious organic cause is unlikely.[9]

c. *Syncope:* Syncope is more common during adolescence than in childhood and frequently has a vasovagal or orthostatic basis. These episodes are often preceded by symptoms of diaphoresis, nausea, or development of tunnel vision. Consciousness is usually regained quickly upon becoming supine. There often is a history of dehydration, exposure to a warm environment (crowded auditorium, hot summer day, warm shower), or standing for prolonged periods of time. Syncope can be precipitated by hair combing, cough, painful stimulation, fear, hyperventilation, micturition, or defecation. Orthostatic changes in blood pressure can be exacerbated by a variety of medications, including diuretics or vasoactive agents.

Syncope can also be caused by neurologic disorders, including seizures, breath-holding spells, or migraine headaches. Seizures can be associated with tonic-clonic movements and postepisode fatigue. Breath-holding spells often occur with sudden fright, pain, or frustration in children between 18 months and 5 years of age. Cardiac causes include right or left obstructive heart disease, pulmonary hypertension, and arrhythmia, including prolonged QT syndrome and bradyarrhythmia or tachyarrhythmia. The occurrence of symptoms during or shortly after exercise can be associated with a vasovagal mechanism but increases the risk for an underlying cardiac basis.[11,12] A review of syncope can be found in Chapter 22.

d. *Palpitations:* Awareness of palpitations may represent an abnormality in rate or rhythm. Sinus tachycardia associated with anxiety or activity usually has a gradual onset and resolution. Supraventricular tachycardia typically has a sudden onset and end as the circuit responsible for supporting the arrhythmia opens and closes. Other tachyarrhythmias (atrial flutter, atrial fibrillation, ventricular tachycardia) can have a similar pattern. Prolonged episodes of these arrhythmias can be associated with dizziness or syncope. Tachyarrhythmia occurring with exercise may represent catecholamine-sensitive ventricular tachycardia. Irregular rhythms can represent atrial, junctional, or ventricular premature beats. Some patients with rare premature beats note every single one, whereas others with thousands of daily premature beats report no symptoms and come to medical attention when an irregular rhythm is noted on physical examination.

PHYSICAL EXAMINATION

The physical examination needs to be complete because heart disease can affect multiple organ systems. The order of the examination will vary depending on the age of the patient. For infants and toddlers, it is often best to perform auscultation first when the patient is more likely to be quiet. Many portions of the physical examination can be performed with the infant or toddler in the parent's lap, which can aid in the level of patient cooperation. Infants can be fed or given a pacifier to achieve a quiet state.

General Examination

General inspection of the child will give clues to the state of health, cyanosis, or anemia. Height and weight measurements are important; plotting these values on growth curves aids in determining the presence of failure to thrive. Heart disease associated with large left-to-right shunts, pulmonary edema, or ventricular dysfunction can impair growth. In such patients, weight typically is affected before height. Infants should gain about 20 g/day; weight gain less than this amount caused by heart disease is an indication for adjustment in medication (diuretics, digoxin, correction of anemia if present) and use of caloric-supplemented food. If these methods are insufficient, surgical intervention is necessary. A normal infant can grow while receiving 100 calories/kg/day; infants whose growth is impaired by heart disease typically require 130 to 140 calories/kg/day. Expressed breast milk or formula contains 20 calories/ounce; each can be supplemented in stages with carbohydrate or fat to provide 30 calories/ounce so that caloric needs are fulfilled even if the infant has reduced volume of intake. For the mother interested in maintaining breast-feeding and depending on the degree of failure-to-thrive, some feedings can occur at the breast, whereas others can consist of supplemented expressed breast milk. An approach to caloric supplementation is outlined in Table 11-1.

General inspection also gives clues to the presence of syndromes that frequently are associated with specific heart disease. Extracardiac anomalies occur in about 20% of patients with congenital heart disease.[13] Multiple syndromes have characteristic facies (see Chapter 5). A webbed neck and short stature are seen in Turner's syndrome. Arachnodactyly, pectus deformity, scoliosis, and arm span exceeding height are features of Marfan syndrome. Radial dysplasia is a component of Holt-Oram syndrome.

TABLE 11–1. Caloric Supplementation for Infant with Failure to Thrive

	Formula	Breast Milk
Caloric concentration	13 ounces concentrated formula* 8 ounces water	3 ounces breast milk
24 cal/ounce	No additives	1 tsp infant formula powder[†]
26 cal/ounce	1 1/2 tbsp Polycose powder	1 1/2 tsp infant formula powder[†]
28 cal/ounce	3 tbsp Polycose powder	1 1/2 tsp infant formula powder[†] 1 tsp Polycose powder
30 cal/ounce	3 tbsp Polycose powder 1 tsp corn oil	1 1/2 tsp infant formula powder[†] 1 1/2 tsp Polycose powder

Days 1–3: 24 cal/ounce formula or breast milk
Days 4–6: 26 cal/ounce formula or breast milk
Days 7–9: 28 cal/ounce formula or breast milk
Days 10–12: 30 cal/ounce formula or breast milk

*Need to emphasize concentrated rather than ready-mixed formula.
[†]Any commercially available formula powder (e.g., Enfamil, Prosobee, Nutramigen, Pregestimil)
cal, calorie; tbsp, tablespoon; tsp teaspoon.

A large-for-gestational-age neonate suggests maternal diabetes mellitus.

Vital Signs

Review of the vital signs enables the clinician to form a general appraisal of the patient and consider certain diagnostic possibilities.

Pulse

The pulse is examined with respect to rate, rhythm, prominence, and variation.[14]

Rate. Sinus tachycardia occurs in a variety of conditions, including anxiety, fever, pain, anemia, large left-to-right shunts, decreased cardiac contractility, cardiac tamponade, sepsis, pulmonary disease, or hyperthyroidism. Supraventricular tachycardia in infants or children typically occurs at a rate that is too rapid to count by an observer (more than 220 beats/minute). Bradycardia occurs in high-level athletes and in children with eating disorders (anorexia nervosa, bulimia), hypothyroidism, or heart block. The average resting heart rate in the first week of life is 125 beats/minute, at 1 year is 120 beats/minute, at 5 to 8 years is 100 beats/minute, and at 12 to 16 years is 85 beats/minute.[15]

Rhythm. A phasic variation related to the respiratory cycle (faster during inspiration) is characteristic of sinus arrhythmia. This pattern is more common in young children than in adults and is a normal variant. The variation in heart rate occasionally can be profound, but review of an electrocardiogram leads to the diagnosis. Occasional premature beats can represent atrial, ventricular, or junctional premature beats. Nonconducted atrial premature beats are the most common cause of a "pause" in the well-newborn nursery[16] and typically resolve during the first month of life. Isolated ventricular premature beats are common in adolescence; resolution with exercise performed in the examination room (jumping jacks) suggests a benign etiology.

Prominence. Bounding pulses are present in febrile states, hyperthyroidism, exercise, anxiety, severe anemia, or complete heart block and with aortic runoff lesions that produce increased pulse pressure (aortic regurgitation, patent ductus arteriosus, arteriovenous malformations, aortopulmonary window, truncus arteriosus). The prominent pulse classically associated with aortic regurgitation has been termed *Corrigan's pulse* or *water hammer pulse*. Such prominent pulses also produce visible ebbing and flowing of the capillary pulse that can be observed by partially compressing the nail bed, a phenomenon termed *Quincke's pulse*.[14]

Generalized decreased pulses are associated with low cardiac output. This can be caused by acquired heart disease such as myocarditis, with congenital heart disease such as obstructive lesions or cardiomyopathy, and with pericardial tamponade or constrictive pericarditis. A rare form of vasculitis affecting the large arteries, Takayasu's arteritis, can be associated with decreased pulses and is termed *pulseless disease*.

Differential prominence of pulses is present in several conditions. The most common is coarctation of the aorta, which usually is associated with easily palpable upper extremity pulses (if left ventricular function is normal) and reduced or absent femoral pulses. If there is a large coexisting patent ductus arteriosus and right-to-left ductal shunting, the lower extremity pulses may be normal, although in such circumstances, there may be differential oxygen saturation levels between the upper and lower body. In infants with large thighs, the femoral pulse occasionally can be difficult to locate. The leg should be abducted; the femoral artery is located in the groin region along the line that joins the knee with the umbilicus. Coarctation usually occurs in the aortic isthmus just distal to the origin of the left subclavian artery. In some infants, the origin of the left subclavian artery can be involved, so that the pulse in the left arm is weaker than the pulse in the right arm. In rare cases, there can be anomalous origin of the right subclavian artery from the descending aorta in an infant with coarctation, so that the pulses in all four extremities are reduced; in such patients, the carotid pulse will be more prominent. A second condition associated with differential pulses is supravalvar

aortic stenosis, a lesion often present in patients with Williams syndrome. In these patients, the pulse in the right arm can be more prominent than the pulse in the left arm; this discrepancy is produced by the Coanda effect, which increases flow to the innominate artery. Finally, Takayasu's aortitis can preferentially affect the individual brachio-cephalic arteries or portions of the aorta with resultant differences in extremity pulses.[17]

Variation. Variable pulse impulse in the same location occurs in several conditions. Pulsus paradoxus involves an exaggerated decrease in inspiratory systolic pressure of more than 10 mm Hg and is associated with pericardial tamponade or severe respiratory distress (see discussion of blood pressure below). Pulsus alternans consists of a decrease in systolic pressure on alternate beats and indicates severe left ventricular dysfunction. This variation is more easily appreciated when observing intravascular blood pressure recordings than by palpating the pulse.[2] Pulsus bisferiens consists of a pulse with two peaks separated by a plateau and can occur in patients with either obstructive left ventricular cardiomyopathy or large left ventricular stroke volumes.[14]

Blood Pressure

While four extremity blood pressures are often obtained, with the rare exceptions of aortitis or aberrant origin of the subclavian artery in a patient with coarctation, obtaining the blood pressure in the right arm and one leg provides sufficient screening. The right arm is preferred because the origin of the left subclavian artery can be stenosed in some patients with coarctation. Unless a femoral artery was injured in a previous catheterization, the pressure should be similar in each leg.

Accuracy of blood pressure measurement depends on selection of a properly sized cuff, in infants and toddlers on a quiet and cooperative state, and in older children and adolescents on assessment of the presence of anxiety (white-coat hypertension). The inflatable bladder should have a length sufficient to fully encircle the circumference of the extremity and a width to cover about 75% of the distance between the joints on either end of the portion of the extremity around which the cuff is placed.[18] If the cuff is too small, artificially high values are obtained. The cuff needs to be applied snugly around the extremity because a loose-fitting cuff needs higher pressure to occlude the artery.[14] Agitation leads to elevation in blood pressure. A coarctation can be missed if the infant is quiet while the arm pressure is obtained and crying during measurement of the leg pressure. In many clinics, the blood pressure is measured by assistants, and note is not made of patient behavior. If the femoral pulses are diminished and the blood pressure values demonstrate no arm–leg discrepancy, the physician should repeat the measurements when the infant is observed to be cooperative to confirm the values. If hypertension is noted in children or adolescents who are anxious, it is helpful to repeat the measurements at the end of the examination when the patient may be more relaxed.

There are several techniques available to measure blood pressure, including palpation and the Doppler method, each of which estimates systolic pressure; auscultation, which is technically difficult in an infant or toddler; and the oscillo-metric method, which is the most commonly used technique in clinics and medical wards. Another method, the flush technique, is rarely used and yields values closer to the mean pressure. The techniques are reviewed in Chapter 23. The lower extremity systolic pressure can be 5 to 10 mm Hg greater than the upper extremity value because of the standing wave effect, with successive heart beats adding to the pressure downstream. Systolic pressure in the upper extremity that is more than 10 mm Hg higher than that in the lower extremity is a sign of coarctation of the aorta.

The pulse pressure is the difference between systolic and diastolic values. The pulse pressure is increased in conditions associated with bounding pulses and decreased in states associated with diminished pulses (see pulse description given earlier).

When checking for pulsus paradoxus, the auscultation method must be used. Finding a manometric blood pressure cuff occasionally is difficult on wards accustomed to the use of oscillometric equipment. Initially, the systolic pressure is estimated by quickly deflating the inflated cuff. The cuff is then reinflated about 20 mm Hg above this value and slowly deflated (1 to 2 mm Hg per beat). The systolic pressures at which the Korotkoff sound is initially auscultated intermittently and then consistently are noted; the difference in these values is the pulsus paradoxus. A pulsus paradoxus of more than 10 mm Hg is abnormal and is a feature of pericardial tamponade or severe respiratory disease.

Respirations

Tachypnea is present with pulmonary parenchymal disease, pulmonary edema, large left-to-right shunts that elevate pulmonary venous pressure, and conditions causing metabolic acidosis. In infants at rest, persistent respiratory rates of more than 60 breaths/minute are abnormal; transient increases can occur after eating or agitation.[14] Quiet tachypnea is often present in left-to-right shunt lesions, whereas labored tachypnea is observed in patients with pulmonary disease.[2] Both can be accompanied by intercostal or subcostal retractions, flaring of the alae nasi, or audible wheezing. Orthopnea is a sign of left ventricular dysfunction or severe elevation in pulmonary venous pressure.

Venous Pressure

In the cooperative child or adolescent, venous pressure can be estimated by examination of the jugular vein. When the

patient is sitting or reclining at a 45-degree angle, the jugular vein should not be visible above the level of the clavicle. Measuring the difference in the height of the jugular vein with a parallel line drawn through the level of the manubrium yields central venous pressure (Fig. 11-1).

The venous pulsation is undulating and nonpalpable, decreases with inspiration, and changes in height with patient position. Distinguishing the various components (a, c, and v waves; x and y descents) is difficult in children, both because of neck size and the presence of tachycardia. Prominent jugular venous waves are present in a variety of conditions, including atrial contraction into a stiff right ventricle or against a closed tricuspid valve (tricuspid atresia; complete heart block, in which case prominent pulsation is intermittent), tricuspid regurgitation, pericardial disease (pericardial tamponade, constrictive pericarditis), vein of Galen malformation, or superior vena cava obstruction.[14]

Cardiac Examination

The cardiac examination includes inspection, palpation, and auscultation. The classic description by Osler also included percussion of the cardiac border, which is currently rarely done and is not as reliable in detecting cardiomegaly as the readily available imaging techniques of radiography or echocardiography.

Inspection

A visible apical impulse can be seen in left ventricular volume overload lesions, including significant mitral or aortic regurgitation, or lesions associated with large left-to-right shunts. A visible parasternal impulse is associated with right ventricular volume overload lesions, including tetralogy of Fallot, absent pulmonary valve associated with severe pulmonary regurgitation or severe tricuspid regurgitation
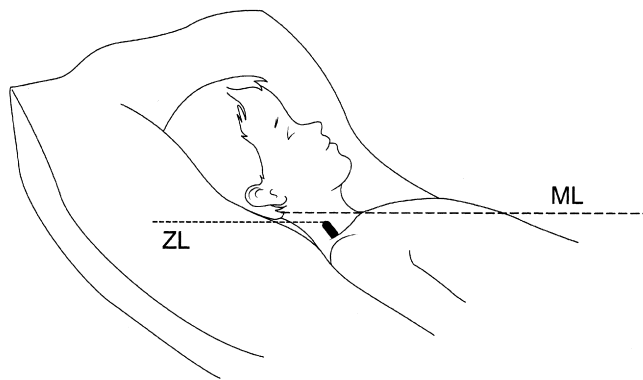
FIGURE 11–1 *Clinical estimation of venous pressure. With the patient lying at approximately 45 degrees, the pressure (ZL) in the right atrium does not rise above the manubrium (ML).*
From Lewis T. Diseases of the Heart Described for Practitioners and Students, 2nd ed. New York: Macmillan, 1937.

associated with Ebstein's anomaly, and large arteriovenous malformations.

Palpation

Palpation involves evaluation of ventricular impulses, thrills, and heart sounds. The apical impulse is best appreciated using the tips of the index and middle fingers and is normally located in the left midclavicular line in the fourth or fifth intercostal space. The apical impulse is displaced laterally and is more prominent in left ventricular overload lesions such as severe aortic or mitral regurgitation or lesions associated with large left-to-right shunts at the ventricular or great vessel level. The apical impulse is right-sided in dextrocardia or displaced in a rightward direction in dextroposition in conditions including left-sided congenital diaphragmatic hernia, left lobar emphysema, or scimitar syndrome. The right ventricular impulse is best detected by placing the hand on the chest with the heads of the metacarpals along the left costochondral junctions. A prominent lift indicates right ventricular hypertension or right ventricular volume overload. The right ventricular impulse can also be assessed in the epigastric area. The palm of the right hand is placed on the abdomen so that the index and middle fingers can slide under the xiphoid process; the tips of the fingers can palpate the right ventricular impulse.

Precordial thrills indicate the presence of a murmur of at least grade 4. The timing and location of thrills should be noted. Systolic thrills at the left lower sternal border usually are caused by ventricular septal defects that may be small and associated with a high interventricular pressure gradient or large and associated with a large left-to-right shunt. Occasionally, a thrill in this region is caused by tricuspid regurgitation if there is right ventricular hypertension. Mitral, aortic, and pulmonary thrills are located at the apex, right upper sternal border, and left upper sternal border, respectively. Aortic valve thrills can sometimes also be detected over the carotid artery or in the suprasternal notch. A suprasternal notch thrill is rarely associated with pulmonary stenosis and helps to distinguish aortic stenosis from pulmonary stenosis. Thrills associated with aortic or pulmonary stenosis indicate significant degrees of obstruction. Although most thrills occur in systole, diastolic thrills can occur at the apex with mitral stenosis, or along the left sternal border with aortic or pulmonary regurgitation.

A palpable second heart sound usually indicates severe pulmonary hypertension but can also be present in conditions in which the aorta has an anterior location, such as transposition of the great arteries. A palpable first heart sound can be present in hyperdynamic states.[14]

Auscultation

Thorough auscultation requires the examiner to follow a simple rule: listen to one sound at a time. Components to

be evaluated or assessed to be present include S_1, S_2, S_3, S_4, ejection click, opening snap, pericardial rub, and murmurs (systolic, diastolic, continuous). Some congenital cardiac lesions can produce multiple abnormal sounds and murmurs, and a system of auscultation is required so that all available data are collected and a reliable diagnosis is made. For example, a soft systolic murmur at the left upper sternal border may represent an innocent flow murmur. If there is also a widely fixed split S_2, the murmur may represent an atrial septal defect, or if there is a variable systolic ejection click in the same region, the murmur may represent valvar pulmonary stenosis.

For auscultation to be completed, the proper environment and tools must be used. The examination room should be quiet without extraneous noises from the patient, relatives, or heating or air-conditioning system. The stethoscope should have a bell to detect low-frequency sounds and a diaphragm for high-frequency sounds. In infants, an adult-sized diaphragm covers most of the precordium so that a pediatric-sized version aids in localizing sounds. The tubing should be no longer than 16 to 18 inches with a bore of $1/8$ inch. There should be no leak from the chest piece to ear piece so that sound transmission is optimized.[19] The patient should be evaluated in more than one position, including supine, sitting, and standing, depending on the diagnosis, because some heart sounds change or are more easily appreciated with different patient posture.

First Heart Sound (S_1). S_1 is produced by mitral and tricuspid valve closure and is coincident with the QRS complex on the electrocardiogram (Fig 11-2). S_1 is usually perceived as a single sound because the mitral and tricuspid valve components are nearly simultaneous.[20] In the pediatric age range, however, some patients can have a perceptibly split S_1 that typically is most easily detected over the tricuspid area at the left lower sternal border. If the split is detected at the apex, consideration must be given to an early systolic ejection click associated with a bicuspid aortic valve, and echocardiography may be needed for differentiation. S_1 also can be split in right bundle branch block owing to delay in tricuspid valve closure.[21]

The intensity of S_1 is increased in high cardiac output states because of greater velocity of leaflet closure and in conditions associated with greater mitral valve excursion during closure, including short PR interval and mild mitral stenosis (because the elevated left atrial pressure maintains the valve in a more open position). The intensity of S_1 is decreased in conditions associated with low cardiac output, elevated ventricular end-diastolic pressure, mitral regurgitation due to failure of valve coaptation, or decreased valve excursion present in patients with prolonged PR interval or severe mitral stenosis.[20] Patients with complete heart block have variable intensity of S_1.[2]
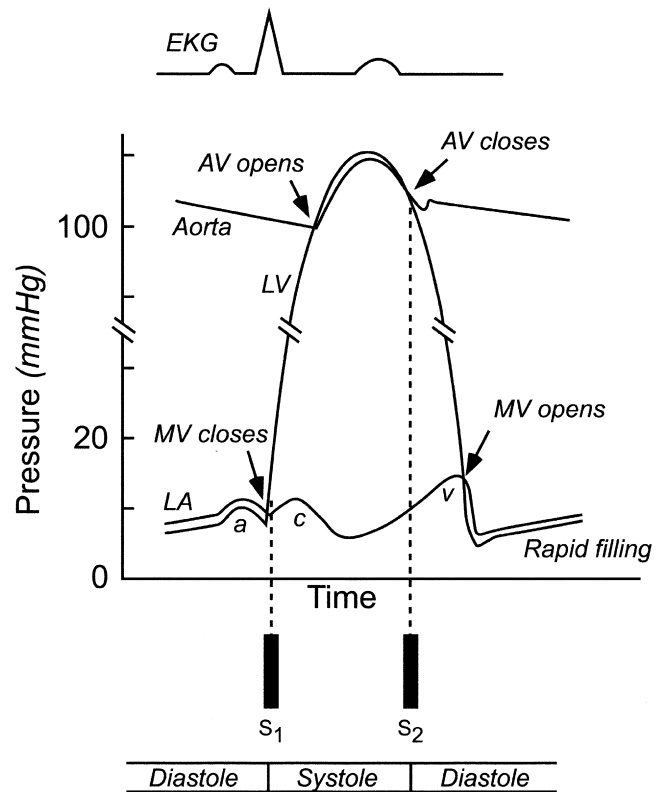
FIGURE 11–2 *The normal cardiac cycle depicted for left-sided chambers. Similar relationships exist for the right-sided chambers. Substitute right atrium for left atrium (LA), right ventricle for left ventricle (LV), and pulmonary artery for aorta. The a wave of the atrial pulse coincides with the P wave on the electrocardiogram (ECG). The mitral valve (MV) closes as left ventricle pressure exceeds atrial pressure and produces the first heart sound (S1). This coincides with the QRS complex on the ECG. Mitral valve closure increases atrial pressure and produces the c wave on the atrial pressure curve. The aortic valve (AV) subsequently opens as ventricular pressure exceeds aortic pressure. The aortic valve closes during ventricular relaxation and produces the second heart sound (S2). This roughly coincides with the end of the T wave on the ECG. Atrial pressure rises (v wave) owing to filling of the atria while the mitral valve is closed. The mitral valve opens as left ventricular pressure falls below left atrial pressure.*
From Marino BS, Goldblatt A. Heart sounds and murmurs. In Lilly LS [ed]. Pathophysiology of heart disease. Philadelphia: Lea & Febiger, 1992:18.

Second Heart Sound (S_2). S_2 is produced by closure of the semilunar valves and is typically best appreciated at the left upper sternal border. The quality of S_2 yields important information on cardiac physiology and provides a framework for the remainder of the auscultatory examination. The pulmonary valve normally closes after the aortic valve because of relative delayed electrical activation of the right ventricle and lower pulmonary impedance.

The respiratory cycle has different effects on the pulmonary and systemic circulations. Inspiration increases venous return to the right heart and lowers pulmonary impedance, which prolongs right ventricular systole, and reduces pulmonary venous return to the left heart, which shortens left ventricular systole. During inspiration, the aortic and pulmonary valve components of S_2 split by about 0.05 seconds. These effects are reversed in expiration, so that S_2 typically becomes single. Detecting splitting of S_2 is always challenging. If the split is easily detected, the split is often wide. In infants with tachycardia and tachypnea, correlating S_2 with the respiratory cycle is impossible. The best the examiner can do is to detect variability with a split present in some beats and not in others.

A widely fixed split S_2 occurs with right ventricular volume overload lesions, the most common of which is atrial septal defect. The less common conditions of total or partial anomalous pulmonary venous connection or large arteriovenous malformation can produce a similar feature. In these conditions, the persistent right ventricular volume overload delays pulmonary valve closure so that the split is greater than 0.05 seconds, often as long as 0.10 seconds. Wide inspiratory splitting with respiratory variation occurs with right bundle branch block, pulmonary stenosis, or idiopathic dilation of the main pulmonary artery due to delayed activation or prolonged contraction of the right ventricle.[14] As pulmonary stenosis progresses, splitting becomes difficult to detect owing to a softer pulmonary closure sound and prolongation of the murmur beyond the aortic component. Wide splitting can also occur with significant mitral regurgitation due to shortened left ventricular ejection time and earlier closure of the aortic valve.[21] Paradoxical splitting is uncommon in children and involves detecting two components to S_2 in expiration and a single sound in inspiration; this can occur with delayed or prolonged left ventricular contraction in patients with left bundle branch block, aortic stenosis, or some forms of Wolff-Parkinson-White syndrome.[14]

The intensity of S_2 depends on the pressure closing the semilunar valves and the anterior-posterior position of the great arteries. The most common cause of a loud S_2 is pulmonary hypertension, which can arise from a variety of causes.[22] Pulmonary hypertension can be caused by increased pulmonary flow or elevated pulmonary vascular resistance; evaluation of murmurs often helps to distinguish between these two mechanisms, with the former being associated with diastolic rumbles across the atrioventricular valve that receives increased flow. Increased intensity of S_2 is also present in patients with transposition of the great arteries because of the anterior location of the aorta, and often in tetralogy of Fallot.

S_2 is single in patients with severe pulmonary hypertension because the elevated diastolic pressure in the pulmonary circulation closes the pulmonary valve sooner. Mild or moderate pulmonary hypertension is associated with a narrowly split S_2. S_2 is also single when there is atresia of one the semilunar valves.

Third Heart Sound (S_3). The third heart sound is produced during the rapid filling phase of the ventricle in early diastole and is best heard with the bell of the stethoscope. This sound produces a gallop rhythm that has the cadence of the syllables of "Ken-tuc-ky." The last component of this sequence represents the third heart sound.[20] This sound can be detected in some normal children, although this is not very common. Cardiac diseases associated with a third heart sound include myocardial dysfunction or volume overload conditions, especially those created by large left-to-right shunts. In the latter, the sound is followed by a diastolic murmur created by increased flow across the affected atrioventricular valve. A third heart sound produced by the left ventricle is detected in the apical region, whereas that from the right ventricle is noted at the left lower sternal border. Right ventricular sounds often increase during inspiration because of increased flow.[21]

Fourth Heart Sound (S_4). The fourth heart sound is produced by atrial contraction in late diastole and is also best heard with the bell of the stethoscope. This sound produces a gallop rhythm that has the cadence of the syllables of "Ten-nes-see." The first component of this sequence represents the S_4.[20] This sound is abnormal and is seen in conditions associated with decreased ventricular compliance so that increased atrial contractile force is required to fill the ventricle. These conditions include those produced by myocardial ischemia or ventricular hypertrophy such as hypertrophic cardiomyopathy, systemic hypertension, and valvar aortic or pulmonary stenosis. An S_4 is not produced if there is coexisting atrial fibrillation or junctional tachycardia because of absent atrial contraction.[2,21]

When both an S_3 and S_4 are present, there is a quadruple rhythm. In such a situation, if there is tachycardia and resulting shortening of diastole, the two extra sounds may become superimposed and create a summation gallop.[20,23,24]

Opening Snap. An opening snap is a high-frequency sound associated with mitral stenosis. As the degree of mitral stenosis progresses, the opening snap occurs earlier in diastole because of elevated atrial pressures and becomes softer because of decreased leaflet mobility.

Clicks. Ejection clicks are brief, high-frequency, sharp sounds that have a quality distinct from S_1 and S_2. They usually are associated with abnormal valve structure. Evaluation of location, timing (early versus mid-systolic), and nature (constant versus variable) enables the examiner to determine the affected valve (Table 11-2). In patients with mitral valve prolapse, the click may be associated with a murmur of mitral regurgitation that is only present or louder

TABLE 11–2. Qualities of Clicks Associated with Valve Disorders

Valve	Location	Timing in Systole	Nature
Mitral	Apex	Mid to late	Constant
Aortic	Apex	Early	Constant
Pulmonary	LUSB	Early	Variable
Tricuspid	LLSB	Mid to late	Constant

LLSB, left lower sternal border; LUSB, left upper sternal border.

in the standing than supine position because of reduced left ventricular volume that produces a greater degree of prolapse. An analogy is observing the mainsail on a sailboat. When fully hoisted, the sail "prolapses" through the plane of the boom and mast. If one climbed the mast and cut off the top 15 feet (correlating with the reduced left ventricular volume in the standing than supine position) and hoisted the sail again, it would "prolapse" to a greater degree.

The click associated with aortic stenosis or bicuspid aortic valve is best detected at the apex rather than the aortic valve region at the right upper sternal border. At times, it is difficult to distinguish a split S_1 (normal variant) from an aortic valve ejection click, and echocardiography is needed for differentiation. The click associated with pulmonary stenosis is located at the left upper sternal border and is variable and louder in expiration because of greater systolic valve excursion in this phase of the respiratory cycle.[21] Clicks associated with semilunar valve stenosis become softer as the degree of obstruction progresses because of reduced valve mobility. Ebstein's anomaly of the tricuspid valve can be associated with a systolic click at the left lower sternal border.

Clicks occasionally occur in conditions associated with dilation of the aorta or pulmonary artery. The latter can occur with pulmonary hypertension, patent ductus arteriosus, or idiopathic dilation of the main pulmonary artery. In neonates with left-to-right shunting across a patent ductus arteriosus, there may be multiple systolic clicks at the left upper sternal border that sound like rolling a pair of dice in one's hand. This sound may be produced by wavelike expansion of the pulmonary artery. Clicks can also be produced by membranous ventricular septal defects associated with aneurysm of the ventricular septum and are located at the left lower sternal border.

Pericardial Friction Rub. A pericardial friction rub is created when inflamed visceral and parietal pericardial surfaces contact each other. The sound is similar to rubbing two pieces of sandpaper together and has a grating quality. The rub may be auscultated in systole, diastole, or continuously and is best heard with the diaphragm. The rub is typically loudest along the left sternal border with the patient sitting and leaning forward and often has inspiratory accentuation. It commonly is present after surgery involving entry into the pericardial space and in pericarditis. The sound is not present if there is a moderate to large pericardial effusion because the two surfaces of the pericardium cannot rub together.

Murmurs. Various features of a murmur need to be evaluated to fully assess this finding.[14,21]

Intensity. The intensity of a murmur is graded on a scale of 1 through 6[25] (Table 11-3). Murmurs grade 4 or greater are associated with a palpable thrill. The loudness depends on both the pressure gradient and the volume of blood flowing across the site creating the murmur. For example, the murmur associated with moderate neonatal pulmonary stenosis or large ventricular septal defect increases in the first few weeks of life as pulmonary vascular resistance decreases, producing a larger pressure gradient in the former and an increased left-to-right shunt in the latter.

Timing. Systolic murmurs are created by flow through stenotic semilunar valves or regurgitant atrioventricular valves, other stenotic regions (coarctation, double chamber right ventricle, subvalvar or supravalvar semilunar valve obstruction, peripheral pulmonary stenosis), or increased cardiac output across normal semilunar valves associated with tachycardia or anemia. The innocent Still's murmur is discussed separately in Chapter 22.

Diastolic murmurs are caused by regurgitant flow across semilunar valves or turbulent flow across atrioventricular valves. The latter can represent true stenosis, as in mitral stenosis, or relative stenosis that is seen in patients with large left-to-right shunt lesions or significant atrioventricular valve regurgitation. The normal atrioventricular valve can accommodate twice the normal stroke volume nonturbulently.

TABLE 11–3. Grading of Intensity of Heart Murmurs

Grade 1: faintest sound that can be detected; often detected by cardiologists but not by general physicians
Grade 2: soft murmur that is readily detectable
Grade 3: louder than grade 2 but not associated with a palpable thrill
Grade 4: easily detected murmur associated with a palpable thrill
Grade 5: very loud murmur audible with the stethoscope placed lightly on the chest
Grade 6: extremely loud murmur audible with the stethoscope off the chest

From Marino BS, Goldblatt A. Heart sounds and murmurs. In Lilly LS (ed): Pathophysiology of Heart Disease. Philadelphia: Lea & Febiger, 1992: 18–29; and Freeman AR, Levine SA. The clinical significance of the systolic murmur: A study of 1,000 consecutive "non-cardiac" cases. Ann Intern Med 6:1371, 1933.

Larger blood flows create a murmur. Left-to-right shunt lesions associated with pulmonary-to-systemic flow ratio (Qp/Qs) greater than 2:1 in patients with an atrial septal defect will produce a diastolic murmur across the tricuspid valve at the left lower sternal border and in patients with a ventricular septal defect will create a diastolic murmur across the mitral valve at the apex; similar murmurs are present with moderate to severe tricuspid and mitral regurgitation, respectively. Such murmurs are low velocity, best heard with the bell of the stethoscope, and usually of low intensity (grade 1 or 2).

Continuous murmurs begin in systole and persist through S_2 into early, mid, or all of diastole. Such murmurs often are audible throughout the cardiac cycle but can have phasic variation in intensity depending on the pressure gradient in systole and diastole. They are produced when there are connections between the following:

1. Systemic and pulmonary arterial circulations: surgically created Blalock-Taussig, Waterston, Potts, or central shunts, patent ductus arteriosus, aortopulmonary collateral artery, aortopulmonary window, anomalous left coronary artery arising from the main pulmonary artery
2. Systemic arteries and veins: arteriovenous malformation
3. Systemic arteries and cardiac chambers: coronary arteriovenous fistula, ruptured sinus of Valsalva aneurysm
4. Disturbed flow in arteries: collateral circulation associated with severe coarctation
5. Disturbed flow in veins: venous hum

A continuous murmur is distinguished from a to-and-fro murmur, which consists of two murmurs, one that occurs in systole and the other that occurs in diastole. A to-and-fro murmur does not continue through S_2 but instead has peak intensity earlier in systole. Examples include patients with combined aortic stenosis and aortic regurgitation (as can occur after balloon dilation of a stenotic bicuspid valve), combined pulmonary stenosis and pulmonary regurgitation (as can occur after repair of tetralogy of Fallot), or ventricular septal defect, prolapsed aortic cusp, and aortic regurgitation.

Timing also includes whether the murmur occurs in early, mid, or late systole or diastole. An early systolic murmur at the left lower sternal border is characteristic of a small muscular ventricular septal defect; in this condition, as the ventricle contracts, the septal defect closes so that the murmur is not holosystolic. A mid to late systolic murmur at the apex is characteristic of mild mitral regurgitation associated with mitral valve prolapse; as the ventricle decreases in size during systole, a mitral valve with either redundant valve tissue or lengthened chordae tendineae can become incompetent.

Location and Radiation. The region where a murmur is loudest and direction of radiation provide additional clues to the diagnosis. Aortic valve stenosis has maximal intensity at the right upper sternal border and may radiate to the suprasternal notch and carotid arteries. Aortic valve regurgitation is most easily detected at the left upper sternal border with the patient sitting, leaning forward, in expiration. Pulmonary stenosis and regurgitation are maximal at the left upper sternal border. The severity of aortic or pulmonary regurgitation correlates with the amount of radiation: mild limited to the left upper sternal border, moderate being audible also at the left midsternal border, and severe radiating to the left lower sternal border. The systolic murmur of peripheral pulmonary stenosis common in infancy is maximal at the left upper sternal border and radiates to the infraclavicular and axillary regions and to the back. Systolic murmurs at the left lower sternal border usually represent a ventricular septal defect but can be associated with tricuspid regurgitation. The murmur of tricuspid regurgitation usually increases during inspiration. Mitral valve disease is best heard at the apex with the patient in the lateral decubitus position. Mitral regurgitation typically radiates to the axilla.

Sites other than the precordium need to be auscultated as well. Coarctation is best heard in the intrascapular region on the back. Long-standing severe coarctation can produce collateral circulation audible as continuous murmur over the ribs where the intercostals arteries course. Arteriovenous malformations may be audible over the affected body region, for example, the cranium for vein of Galen malformations or right upper quadrant for hepatic source.

Shape. Diamond-shaped murmurs occur with ventricular obstructive lesions (semilunar valvar, subvalvar, or supravalvar stenosis, coarctation) or hyperdynamic states (anemia, hyperthyroidism, fever). These murmurs begin after S_1 and end before the component of S_2 (aortic or pulmonary) associated with the side of the heart from which the murmur originates.[21] Holosystolic murmurs have a plateau shape and are characteristic of ventricular septal defects other than small muscular defects or with atrioventricular valve regurgitation. These murmurs begin with S_1 and end with the aortic or pulmonary component of S_2, depending on whether they are left- or right-sided in origin. Decrescendo murmurs decrease in intensity during the cardiac cycle and include the diastolic murmurs of aortic regurgitation and pulmonary regurgitation.

Quality. Harsh murmurs are characteristic of murmurs caused by ventricular outflow tract obstruction or hyperdynamic states. Blowing murmurs are typical of valve regurgitation. A rumbling quality is a feature of diastolic turbulence across atrioventricular valves. A vibratory, musical, or humming property is associated with the innocent Still's murmur.

Chest Examination

Chest Deformity

Congenital heart disease associated with cardiomegaly can produce prominence of the left chest due to the effects of cardiac contraction against an elastic rib cage.[2] Pectus carinatum is a feature of Marfan syndrome. Pectus excavatum is associated with mitral valve prolapse; the mitral valve prolapse often improves after surgical correction of the chest wall deformity.[26] An asymmetric precordial bulge can also be seen in pulmonary conditions, including atelectasis, pneumothorax, emphysema, and diaphragmatic hernia.[27]

Chest Wall Examination

Chest pain in children frequently has a musculoskeletal basis, including costochondritis, slipping rib syndrome, or myodynia. The diagnosis of musculoskeletal pain can be confirmed by an ability to reproduce a similar quality of discomfort by palpation of the chest. The examination should include palpation of the costochondral junctions, the insertion site of the pectoralis major muscle group by grasping the head of the muscle between the examiner's fingers and thumb, the inframammary area, and other regions of the chest where pain is reported. Although one would expect the right and left costochondral junctions to be equally affected, the left-sided junctions are more typically involved.[28] In patients with slipping rib syndrome, the examiner can perform the "hooking" maneuver by placing fingers around the lower costal margin and lifting anteriorly to elicit a click and reproduce pain.[10] The demonstration of pain reproduction and an explanation of the anatomic basis are reassuring to the family and patient and help allay concerns about the heart.

Pulmonary Auscultation

Lesions associated with excessive pulmonary flow or left-sided dysfunction or obstruction can be associated with inspiratory rales or expiratory wheezing. These features are also present in patients with reactive airway disease or pneumonia.

Abdomen Examination

Palpation of the liver yields information about visceral situs and central venous pressure. A right-sided liver indicates normal situs of the abdominal viscera, a left-sided liver indicates situs inversus, and a midline liver indicates the presence of situs ambiguous and heterotaxy. Hepatomegaly is present in conditions associated with elevated central venous pressure. Percussion of the liver size helps to distinguish patients with "false" hepatomegaly caused by inferior displacement by a flattened diaphragm caused by hyperinflation. Palpation of the liver is easier when the abdomen is soft. Flexing the knees can relax the abdominal musculature. In infants, the liver can normally be palpated about 2 cm below the costal margin in the mid-clavicular line. In children, the liver can be palpated 1 cm below the right costal margin. An engorged liver is usually tender to palpation. A pulsatile liver is palpated in patients with elevated right atrial pressure, most commonly associated with significant tricuspid regurgitation.

In infants, a spleen tip can normally be palpated under the costal margin. Location of the spleen also aids in determination of visceral situs. Elevated central venous pressure usually does not produce splenomegaly. An enlarged spleen is a feature of bacterial endocarditis, and in a known cardiac patient with fever or new regurgitant murmur, this physical finding should prompt thorough evaluation of that complication.

Ascites is an uncommon feature of congenital heart disease. Placing one hand in each flank and detecting a fluid wave with one hand created by pressure applied by the other can determine its presence.

Extremities Examination

Edema

Pitting edema in infants generally has a renal rather than cardiac basis. In children and adolescents, edema can be caused by cardiac dysfunction, and in patients with a modified Fontan procedure, it can be caused by protein-losing enteropathy, a complication that occurs with high venous pressure. Swelling of the face, neck, and arms can occur with superior vena cava obstruction that occasionally is seen after Senning or Mustard repair for transposition of the great arteries, bidirectional Glenn shunt for palliation of functional single ventricle, intravascular thrombosis associated with an indwelling central venous catheter, or obstructing mediastinal mass. Obstruction of the inferior vena cava or iliac or femoral veins occasionally occurs secondary to *in utero* thrombosis or as a complication of catheterization and can produce edema of the abdomen and lower extremities. Doughy, nonpitting swelling of the hands and feet represents lymphedema that is seen in some infants with Turner's syndrome.

Clubbing

Clubbing is a feature of chronic cyanosis and is uncommon in early infancy. The change in appearance of the distal portion of the digit consists of rounding or convexity of the nail bed and thickening and shining of the skin at the base of the nail (Fig. 11-3). With marked clubbing, the terminal phalange becomes bulbous. Mild cases can be detected by dividing the diameter of the finger at the base of the nail bed by the diameter at the distal interphalangeal joint; clubbing is present when the value is greater than 1.[14,29]

FIGURE 11–3 *Clubbed fingers.*
From Fyler DC (ed). Nadas' Pediatric Cardiology. Philadelphia: Harley & Belfus, 1992.

Differential Cyanosis

Certain congenital heart defects create an effect of differential cyanosis in which the upper half of the body is pink and the lower half blue, or vice versa. Systemic-level pulmonary vascular resistance and a patent ductus arteriosus need to be present for this phenomenon to occur. The oxygen saturation can be higher in the upper extremity in patients with normally related great arteries if there is right-to-left shunting at the level of the ductus arteriosus. This can occur in infants with either persistent pulmonary hypertension of the newborn, severe coarctation of the aorta, or interrupted aortic arch. The differential effect is reduced if there is also right-to-left shunting at the level of the foramen ovale, or if there is left-to-right shunting across a coexisting ventricular septal defect.[30] The lower portion of the body can be more cyanotic than the upper segment in older patients with Eisenmenger syndrome caused by a persistent large patent ductus arteriosus. In patients with transposition of the great arteries associated with either coarctation or pulmonary hypertension, differential cyanosis can be reversed with lower levels of oxygen saturation in the upper extremity.

ROUTINE LABORATORY TESTS

A variety of laboratory tests may be required for appropriate management of children with congenital heart disease. Selective aspects of these tests are mentioned below.

Hematology Tests

Leukocytosis

The white blood cell count may be elevated in infectious diseases (acute rheumatic fever, bacterial endocarditis, pericarditis), airway disease associated with excessive pulmonary flow or pulmonary venous congestion, or inflammatory conditions (aortitis, collagen vascular disease). Leukocytosis can also occur in patients with urinary tract infections, common in those with renal anomalies, or in patients with sinusitis, which can be a complication of chronic use of a nasogastric tube for nutritional support.

Hematocrit

The hematocrit is elevated in patients with cyanotic heart disease. In such patients, it is important to also check the mean corpuscular volume (MCV) to rule out relative anemia. Patients with microcytic anemia (MCV less than 80) are at increased risk for thrombotic complications, including cerebrovascular accidents.[31] The normal red blood cell has a biconcave surface membrane structure; the microcytic red blood cell has a less redundant membrane and is more likely to lodge in rather than pass through the capillary bed. In such patients, low-dose iron therapy should be instituted and the hematocrit response carefully monitored to avoid excessive polycythemia. Hematocrit levels greater than 70% are associated with exponential increases in blood viscosity and decreased cardiac output that can produce symptoms of decreased exercise tolerance, headache, cerebrovascular accident, and chest pain.[32] If such symptoms are present in patients with this degree of polycythemia, partial erythropheresis should be performed. The amount of whole blood to remove can be calculated from the following formula:

Blood volume to remove (mL)
$$= \text{Estimated blood volume (mL)} \times (\text{Hct}_i - \text{Hct}_d)/\text{Hct}_i,$$

where Hct_i is the initial central venous hematocrit and Hct_d is the desired central venous hematocrit.

The blood volume in a neonate is 85 mL/kg, in a child is 70 mL/kg, and in an adult is 65 mL/kg. The hematocrit should not be reduced by more than 10% because such patients require increased oxygen carrying capacity for adequate oxygen delivery to the tissues. It is safest to do an isovolumetric exchange, replacing blood withdrawn with an equal volume of normal saline, fresh frozen plasma, or 5% salt-poor albumin.

Platelets

Polycythemia is frequently associated with thrombocytopenia (platelet levels, 50,000 to 80,000/mm^3) because megakaryocytes are "crowded out" by red blood cell

precursors in the bone marrow. Thrombocytosis is a feature of Kawasaki disease, with platelet counts occasionally exceeding 1 million/mm.[3]

Howell-Jolly Bodies

Patients with heterotaxy syndrome can have asplenia. Microscopic evaluation of the peripheral blood smear will demonstrate Howell-Jolly bodies. Howell-Jolly bodies can normally be present in the first few weeks of life. A liver-spleen scan with technetium-99m or abdominal ultrasound can confirm the absence of a spleen.

The erythrocyte sedimentation rate (ESR) is elevated in inflammatory conditions and in bacterial endocarditis. The ESR correlates with the severity of congestive heart failure and is lower in patients with lower cardiac output or elevated right atrial pressure.[33]

Urinalysis

Hematuria can be a feature of bacterial endocarditis. The specific gravity yields information on fluid status. Pyuria can be associated with urinary tract infections or inflammatory conditions such as Kawasaki disease.

Blood Chemistries

Serum levels of sodium, potassium, chloride, calcium, magnesium, and phosphorous are monitored for patients receiving diuretics or those presenting with arrhythmias, especially if ventricular in origin. Serum levels of various antiarrhythmic or antiseizure medication can be determined. Digoxin levels should be drawn 8 to 12 hours after an oral dose to determine peak serum levels. Anticoagulation can be monitored by determining plasma heparin levels if this medication is used. The normal value is 0.3 to 0.5 U/mL. The infusion rate is adjusted to achieve this level. For those receiving warfarin sodium (Coumadin), the international normalized ratio (INR) is monitored. The goal for the INR value for patients with a prosthetic mechanical valve is 2.5 to 3.5, and for cerebrovascular accident prophylaxis for those with atrial fibrillation, cardiomyopathy, or right-to-left atrial level shunting, 2.0 to 2.5. Special precautions are required for obtaining an INR in patients with polycythemia and hematocrit greater than 55% to 60%. The typical tubes used for the assay contain a set amount of diluent that assumes a normal plasma volume. Patients with significant polycythemia need some of the diluent removed or else an artificially elevated INR value will be obtained. The laboratory should be contacted to determine the amount of diluent to remove for a given hematocrit level.

Blood Cultures

Blood cultures for bacterial and fungal pathogens are required for the evaluation of endocarditis. Ideally, a minimum of three cultures from separate venipunctures are obtained on the first day to definitively evaluate this condition; if there is no growth by the second day, an additional two cultures may be obtained[34] (see Chapter 28).

Level of Oxygenation

Transcutaneous oxygen saturation from preductal and postductal sites identifies patients with cyanosis, including those with differential cyanosis as described in an earlier section. Transcutaneous oxygen saturation is also useful in establishing the response to prostaglandin E_1 infusion. The oxygen dissociation curve is steep for values less than 70 mm Hg; thus, for lower levels, small decreases in oxygen tension are associated with large decreases in oxygen saturation.[35]

Additional information is obtained from arterial blood gas measurement. An elevated arterial P_{CO_2} value indicates the presence of pulmonary disease. A reduced pH level raises concern about poor cardiac output. The combination of severe hypoxemia, metabolic acidosis, and marked hypercarbia can also occur in patients with D-transposition of the great arteries when there is inadequate mixing at the atrial, ventricular, and great vessel level. A combination of low oxygen saturation and normal oxygen tension is present in methemoglobinemia. In this uncommon condition, blood has a chocolate-brown color and does not become red when exposed to air.[36]

The hyperoxia test is useful in distinguishing cardiac from pulmonary causes of cyanosis. In cyanotic heart disease associated with intracardiac right-to-left shunting, blood in the pulmonary veins is fully saturated with oxygen in ambient air. Administering higher concentrations of inspired oxygen increases the amount of dissolved oxygen but has minimal effect on systemic oxygen saturation or oxygen tension levels. Conversely, patients with pulmonary disease have pulmonary venous desaturation. Administering supplemental oxygen typically increases pulmonary venous oxygen levels and improves systemic oxygenation. The hyperoxia test is performed by placing the patient in 100% oxygen for 10 minutes either using an Oxyhood or endotracheal tube if already intubated. An arterial blood gas should be obtained from a preductal source (right arm); alternatively, transcutaneous P_{O_2} monitors can be used. Patients with cyanotic heart disease rarely have the preductal oxygen tension exceed 150 mm Hg, whereas patients with pulmonary disease usually exceed this value.[37] The level of arterial P_{O_2} in 100% oxygen helps to distinguish the various types of cyanotic heart disease (Table 11-4).

The interpretation of the hyperoxia test requires determination of both the arterial P_{O_2} and oxygen saturation. Because of the characteristics of the oxygen dissociation curve, a patient receiving a fractional inspired oxygen concentration of 1.0 could have 100% oxygen saturation

TABLE 11–4. Typical Results of Hyperoxia Test

| | FiO$_2$ = 0.21 | | FiO$_2$ = 1 |
	PaO$_2$	PaO$_2$	PaCO$_2$
Normal	>70 (>95)	>300 (100)	35
Pulmonary disease	50 (85)	>150 (100)	50
Neurologic disease	50 (85)	>150 (100)	50
Methemoglobinemia	>70 (<85)	>200 (<85)	35
Cardiac disease			
Parallel circulation*	<40 (<75)	<50 (<85)	35
Mixing with reduced PBF†	<40 (<75)	<50 (<85)	35
Mixing without restricted PBF‡	40-60 (75-93)	<150 (<100)	35
Preductal Postductal			
Differential cyanosis§	70 (95)	<40 (<75)	variable, 35–50
Reverse differential cyanosis¶	<40 (<75)	>50 (>90)	variable, 35–50

*Transposition of the great arteries with or without ventricular septal defect.

†Tricuspid atresia with pulmonary stenosis, pulmonary atresia, critical pulmonary stenosis with intact ventricular septum, or tetralogy of Fallot.

‡Truncus arteriosus, total anomalous pulmonary venous connection without obstruction, hypoplastic left heart syndrome, single ventricle without pulmonary stenosis of pulmonary atresia.

§Persistent pulmonary hypertension of the newborn, interrupted aortic arch, severe coarctation.

¶Transposition of the great arteries associated with either coarctation or suprasystemic pulmonary vascular resistance.

Adapted from Marino BS, Bird GL, Wernovsky G. Diagnosis and management of the newborn with suspected congenital heart disease. Clin Perinatol 28:91, 2001.

associated with an arterial PO$_2$ of 75, a value that is abnormal. It is important to note that systemic oxygen tension can increase in some patients with cyanotic heart disease if there is coexisting airway disease (e.g., pulmonary edema or pneumonia) or mixing lesions involving both right-to-left and left-to-right shunting. In the latter situation (e.g., truncus arteriosus or single ventricle with patent ductus arteriosus), supplemental oxygen may decrease pulmonary vascular resistance, thereby increasing pulmonary flow, which when mixing with a fixed amount of systemic venous return, produces a higher level of aortic oxygenation. For such patients, the chest radiograph typically demonstrates cardiomegaly and prominent pulmonary vascularity. Nevertheless, even though the preductal oxygen tension may increase over ambient air levels in these conditions, the value rarely exceeds 150 mm Hg.[37] Also, some patients with severe lung disease may have minimal improvement with supplemental oxygen. In these patients, however, the chest radiograph and arterial PCO$_2$ level aid in establishing the underlying disorder.

Chest Radiograph

The chest radiograph provides information on heart size, pulmonary blood flow, situs of the aortic arch, and pulmonary disease (pulmonary hypoplasia, pneumonia, emphysema, atelectasis, pneumothorax or pneumomediastinum, and pleural effusion). The normal heart size is less than 50% of the cardiothoracic diameter. In infants, a large overlying anterior thymus can give the impression of cardiomegaly. The thymus has a nonsmooth, frequently undulating border that distinguishes it from a cardiac chamber.

Left-to-right shunt lesions have increased pulmonary arterial markings, whereas cyanotic lesions associated with obstructive right-sided lesions typically have dark, underperfused lung fields. Some patients with D-transposition of the great arteries can have asymmetric blood flow with more prominent markings in the right lung because the long axis of the left ventricle is more in line with the right than left pulmonary artery. Because of the relationship of the bronchi with the pulmonary arteries and left atrium, the left main, left upper, and right middle bronchi are more susceptible to compression by enlarged vessels or chambers (Fig. 11-4). Depending on the degree of obstruction, emphysema or atelectasis is produced.[38]

The tracheal air shadow has an indentation on the side of the aortic arch (Fig. 11-5). A right aortic arch is present in about 25% of patients with tetralogy of Fallot and in 30% of patients with truncus arteriosus.

Radioisotope Scans

Nuclear perfusion scans are helpful in determining the percentage of perfusion to the right and left lungs and aid in determining the effect of intervention
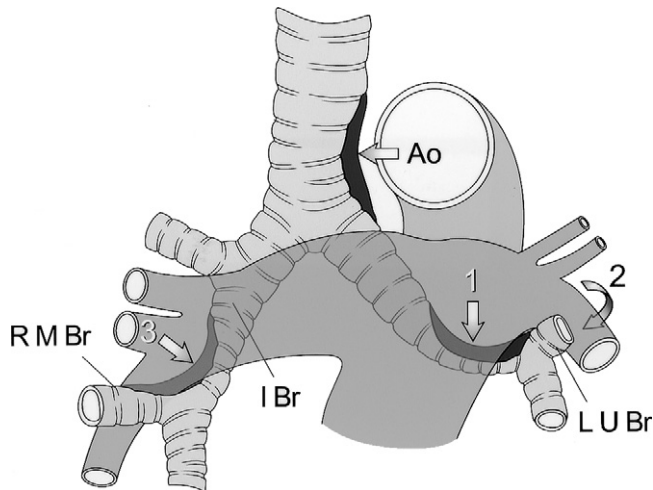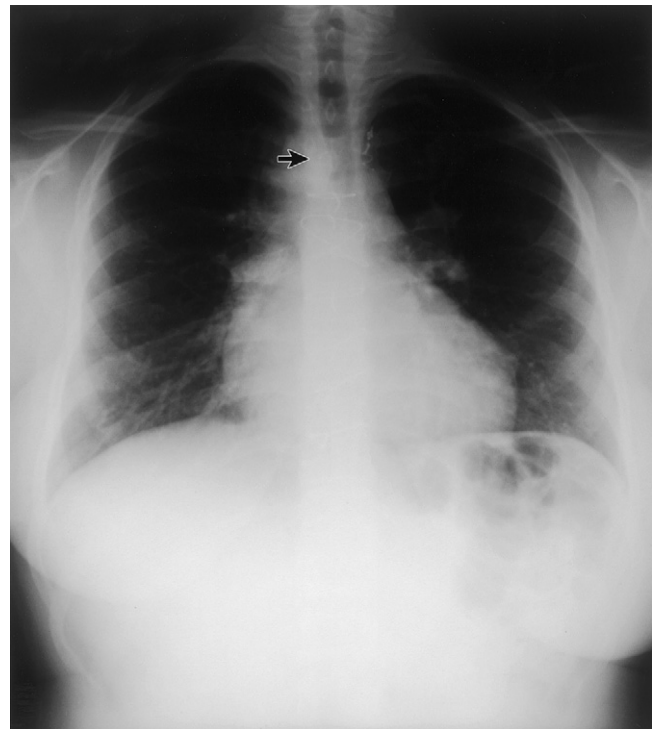
FIGURE 11–4 *Portions of the tracheobronchial tree at increased risk for compression from enlarged pulmonary arteries or left atrium. The left pulmonary artery courses superior to the left main bronchus (L. Br.)[1] and hooks around the left upper bronchus (L.U. Br.).[2] The distended left pulmonary artery pushes the aorta (Ao) medially and accentuates the indentation of the trachea made by a left aortic arch. The left recurrent laryngeal nerve lies in this area and can be compressed. The branch of the right pulmonary artery that supplies the right lower lobe crosses the junction of the intermediate bronchus (I. Br.) and right middle bronchus (R.M. Br.). The left atrium lies below the tracheal bifurcation. Enlargement of the left atrium increases the angle of the tracheal bifurcation mainly by upward deflection of the left main bronchus.*
From Stranger P, Lucas RV Jr, Edward JE. Anatomic factors causing respiratory distress in acyanotic congenital heart disease. Pediatrics, 43:760, 1969.

FIGURE 11–5 *Right aortic arch in a patient with tetralogy of Fallot. Note the indentation on the right side of the trachea made by the aortic arch (black arrow).*
From Fyler DC (ed). Nadas' Pediatric Cardiology. Philadelphia: Harley & Belfus, 1992.

(surgical or catheterization) for peripheral pulmonary stenosis. Quantitative nuclear angiography can also estimate the degree of left-to-right shunting; this noninvasive measurement assists the clinician in determining whether a significant sized shunt is present.[39] Myocardial perfusion scans evaluate ventricular function and are discussed in Chapter 15.

Arrhythmia Evaluation

Various recording devices are available to record the heart rhythm on an outpatient basis. A 24-hour Holter monitor is able to record every beat but is somewhat cumbersome to wear. This test is helpful to quantitate the amount and degree of ventricular ectopy or extent of bradycardia; intermittent symptoms frequently do not occur on the day this type of monitor is used. Intermittent symptoms can be recorded with the use of an event monitor or loop recorder. The former consists of a small unit about twice the size of a typical pager unit; at the time of symptoms, the unit is placed directly on the left precordium, and the rhythm is recorded. The latter consists of a small unit with wire attachments to three chest electrodes. The heart rhythm is recorded for several minutes, and then a new interval is recorded over the former tracing; at the time of symptoms, the unit is activated to save the current tracing. Both the event and loop monitor tracings can be sent over the telephone and permit correlation of symptoms with cardiac rhythm. These units are helpful in the diagnosis of intermittent tachyarrhythmias, the former for episodes that last for more than 1 minute and the latter for shorter episodes. In patients with recurrent syncope, palpitations, or dizziness for whom an arrhythmia cannot be ruled out by these devices, an insertable loop recorder can be used. This device is inserted under local anesthesia in the upper chest and can continuously record the heart rate and rhythm for up to 14 months.[40]

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