CHAPTER 1
Introduction

A complete evaluation of the patient's medical history, physical examination, and review of pertinent laboratory and supportive tests is necessary prior to any elective cardiac surgical procedure. The intention of the preoperative evaluation is severalfold: define the status of the patient's medical condition, identify areas of uncertainty that require further evaluation, consultation or testing, devise a strategy to improve or stabilize ongoing medical conditions prior to surgery, determine a prognostic risk classification, and provide information to formulate an intraoperative and postoperative plan. The anesthesiologist must clearly understand the intended surgical procedure. This chapter will present a systems review of the common and significant features found preoperatively in the cardiac surgical patient. There will be a special emphasis on the methodology, limitations, and accuracy of the tests used most commonly in evaluation of cardiac surgical patients.

Cardiovascular evaluation

A directed history and physical examination are essential before any cardiac surgical procedure. The information obtained, in the context of the anticipated surgical procedure, will determine the requirement for subsequent evaluation, consultation or testing.

History and physical examination

There are no controlled trials evaluating the effectiveness of the history and physical; however, conditions discovered in the process help define the anesthetic plan and are often associated with strong prognostic value. For example, a history of myocardial infarction, unstable angina, congestive heart failure, dyspnea, obstructive sleep apnea, and any number of other conditions may directly affect the course of the preoperative evaluation, operative outcome, and patient satisfaction. There are many algorithms for quantifying patient risk, including the American Society of Anesthesiologists Physical Status Classification. The Revised Cardiac Risk Index is a clinically useful example of a preoperative scoring system to define perioperative cardiac risk (Table 1.1).

In most cardiac surgical procedures, the preanesthetic evaluation should take place prior to the day of surgery. This will allow time for additional testing, collection, and review of pertinent past medical records, and appropriate patient counseling. The examination can be obtained on the day of surgery for procedures with relatively low surgical invasiveness. The history provides insight into the severity of the pathologic condition. For example, a history consistent with heart failure is most alarming and requires careful deliberation before proceeding (Table 1.2). In evaluating a patient with angina, it is essential to determine if the symptoms represent unstable angina (Table 1.3). The Canadian Cardiovascular Society Classification of Angina defines anginal symptoms (Table 1.4).

At a minimum, the physical examination must include the vital signs and an evaluation of

Table 1.1 The Revised Cardiac Risk Index.

Ischemic heart disease: Includes a history of myocardial infarction, Q waves on the ECG, a positive stress test, angina, or nitroglycerine use
Congestive heart failure (CHF): Includes a history of CHF, pulmonary edema, paroxysmal nocturnal dyspnea, rales, S3 gallop, elevated β-naturetic peptide, or imaging study consistent with CHF
Cerebrovascular disease: Includes a history of transient ischemic attack or stroke
Diabetes mellitus treated with insulin:
Renal dysfunction (serum creatinine >2)
High-risk surgery: Includes any intraperitoneal, intrathoracic or suprainguinal vascular procedures

CABG, coronary artery bypass surgery; ECG, electrocardiogram.
0–2 risk factors = low risk.
3 or more risk factors = high risk.

the airway, lungs and heart. Auscultation of the chest may reveal wheezing, rales, or diminished breath sounds. Auscultation of the heart is critical in uncovering new murmurs, S4 gallops, and rhythm abnormalities. In patients older than 40 years, new heart murmurs are found in upwards of 4% of patients. Further screening with echocardiography reveals significant valvular pathology in 75% of these patients. Arterial hypertension is common in the cardiac surgical patient; however, there is little evidence for an association between admission arterial pressures less than 180 mmHg systolic or 110 mmHg diastolic and perioperative complications. In patients with blood pressures above this level, there is increased perioperative ischemia, arrhythmias, and cardiovascular lability.

Once the history and physical examination are complete, attention turns to what additional evaluation, consultation or studies are indicated prior to the operative procedure. The decision regarding which test to order should be based upon an analysis of value of the information obtained, resource utilization and timeliness in regards to the scheduled procedure. Several common tests are reviewed below.

Electrocardiogram

A preoperative electrocardiogram (ECG) should be obtained in all cardiac surgical patients. There is no consensus on the minimum patient age for obtaining an ECG, although ECG abnormalities are more frequent in older patients and those with multiple cardiac risk factors. The ECG should be examined for rate and rhythm, axis, evidence of left and right ventricular (RV) hypertrophy, atrial enlargement, conduction defects (both AV nodal and bundle branch block (BBB)), ischemia or infarction, and metabolic and drug effects.

Rate and rhythm abnormalities

There are a large number of rate and rhythm abnormalities which may be present in the cardiac surgical patient. Tachycardia may be a sign of anxiety, drug effect (i.e. sympathomimetics, β-adrenergic agonists, and cocaine intoxication), metabolic disorder (hypothyroidism), fever, sepsis or other conditions. Bradycardia is typically due to medications (β-adrenergic blocking agents), although a slow heart rate may by indicative of other pathology (hypothyroidism, drug effect, hypothermia, conduction defects). Arrhythmias are potentially more serious and require immediate evaluation. Electrolyte abnormalities are common in cardiac surgical patients and may lead to premature ventricular contractions (PVCs). The actively ischemic patient may present with ventricular irritability, frequent or multifocal PVCs, or ventricular tachycardia (VT). Atrial fibrillation is frequently observed in the elderly cardiac surgical patient. The diagnosis of new atrial fibrillation requires evaluation prior to surgery if time and the clinical condition permit.

Axis

Axis refers to the direction of depolarization in the heart. The mean QRS vector (direction of depolarization) is normally downward and to the patient's left (0–90°). This axis will be displaced with physical relocation of the heart (i.e. extrinsic cardiac compression from a mass effect), hypertrophy (axis moves toward hypertrophy), or infarction (axis moves away from infarction). In the normal condition, the QRS is positive in lead I and aV_F.

Table 1.2 American College of Cardiology/American Heart Association Classification of chronic heart failure.

Stage	Description
A. High risk for developing heart failure	Hypertension, diabetes mellitus, coronary artery disease, family history of cardiomyopathy
B. Asymptomatic heart failure	Previous myocardial infarction left ventricular dysfunction, valvular heart disease
C. Symptomatic heart failure	Structural heart disease, dyspnea and fatigue, impaired exercise tolerance
D. Refractory end-stage heart failure	Marked symptoms at rest despite maximal medical therapy

Stage A includes patients at risk of developing heart failure but have no structural heart disease at present. A high degree of awareness is important in this group

Stage B includes patients with known structural heart disease but no symptoms. Therapeutic intervention with angiotensin converting enzyme inhibitors or adrenergic beta-blocking agents may be indicated for long-term chronic treatment in this group

Stage C includes patients with structural heart disease and symptomatic heart failure. Operative risk is increased in this group. Medical therapy may include diuretics, digoxin, and aldosterone antagonists in addition to ACE inhibitors and beta-blockers depending upon the severity of symptoms. Cardiac resynchronization therapy also may be considered in selected patients

Stage D includes patients with severe refractory heart failure. These patients frequently present for heart transplantation or bridging therapy with ventricular assist devices. Acute decompensation is managed with inotropes and vasodilator therapy

ACE, angiotensin-converting enzyme.

Table 1.3 The principal presentations of unstable angina.

Rest angina	Angina occurring at rest and usually prolonged greater than 20 minutes
New onset angina	Angina of at least CCSC III severity with onset within 2 months of initial presentation
Increasing angina	Previously diagnosed angina that is distinctly more frequent, longer in duration or lower in threshold (i.e. increased by at least one CCSC class within 2 months of initial presentation to at least CCSC III severity)

CCSC, Canadian Cardiovascular Society Classification.

Left atrial enlargement

In adults, left atrial enlargement (LAE) may be found in association with mitral stenosis, aortic stenosis, systemic hypertension, and mitral regurgitation. In mitral stenosis, LAE occurs secondary to the increased impedance to atrial emptying across the stenotic mitral valve. In aortic stenosis and systemic hypertension, an elevated left ventricular (LV) end-diastolic pressure results in left atrial hypertrophy. In mitral regurgitation, LAE occurs because of the large volumes of blood regurgitated in the left atrium during systole.

Table 1.4 The Canadian Cardiovascular Society Classification System of angina pectoris.

Class I: Ordinary physical activity, such as walking and climbing stairs does not cause angina. Angina occurs with strenuous, rapid, or prolonged exertion
Class II: Slight limitation of ordinary activity. Angina occurs on walking or climbing stairs rapidly, walking uphill, walking or stair climbing after meals, in the cold or wind, under emotional stress or only during the few hours after awakening. Angina occurs on walking more than two blocks on the level and climbing more than one flight of ordinary stairs at a normal pace and under normal conditions
Class III: Marked limitations of ordinary physical activity. Angina occurs on walking one or two blocks on the level ground and climbing one flight of stairs in normal conditions and at a normal pace
Class IV: Inability to carry on any physical activity without anginal discomfort. Symptoms may be present at rest

Right atrial enlargement

Right atrial enlargement (AAE) may be seen with RV hypertrophy secondary to pulmonary outflow obstruction or pulmonary hypertension. RAE also may be observed in patients with tricuspid stenosis, tricuspid atresia, or Epstein's abnormality.

Left ventricular hypertrophy

In adults, left ventricular hypertrophy (LVH) commonly occurs in LV pressure overload lesions such as aortic stenosis and severe systemic hypertension. In children, LVH may be present with coarctation of the aorta and congenital aortic stenosis.

Right ventricular hypertrophy

Right ventricular hypertrophy (RVH) is a common finding in patients with congenital heart disease and may be seen in pulmonic stenosis, tetralogy of Fallot and transposition of the great arteries. In adults, RVH frequently results from pulmonary hypertension.

Conduction defects

Similar to rate and rhythm abnormalities, there are a wide variety of conduction defects which may be observed in the cardiac surgical patient. Atrioventricular (AV) block may be innocuous (1st and 2nd degree type 1) or clinically significant requiring immediate evaluation of pacemaker placement (2nd degree type 2 and 3rd degree). BBB delay depolarization in the effected ventricle and may lead to ineffective ventricular contraction.

Ischemia and infarction

New findings of active ischemia require immediate attention. In the patient with known coronary artery disease (CAD) and unstable angina, ST segment abnormalities may be observed. In patients with diabetes, there may be episodes of silent ischemia during which the heart is ischemic, but due to autonomic dysfunction and a diminished ability to perceive nociceptive signals, the patient does not experience pain. The presence of Q waves indicates an old transmural myocardial infarction. Determining the timing of the Q wave finding may be clinically relevant. For example, a Q wave not seen on an ECG 6 months prior to the evaluation suggests a myocardial infarction sometime during this recent interval. Perioperative cardiac morbidities are related to timing of surgery after a myocardial infarction, and therefore this information requires attention and clinical resolution.

Metabolic and drug effects

Elevated serum potassium will flatten the P wave, widen the QRS complex, and elevate the T wave. Low serum potassium will flatten of invert the T wave. A U wave may appear. With elevated serum calcium the QT interval shortens; whereas with hypocalcemia, the QT interval is prolonged. Digitalis toxicity will cause a gradual down sloping of the ST segment. There may also be atrial and junctional premature beats, atrial tachycardia, sinus, and AV nodal blocks.

It must be emphasized that a normal ECG does not preclude the presence of significant cardiac disease in the adult, child, or infant. The ECG is normal in 25–50% of adults with chronic stable angina. Likewise, the ECG may be normal in children with LV pressure overload (aortic stenosis) and volume overload (patent ductus arteriosus or ventricular septal defect) lesions.

Chest radiograph

Obtaining a Chest radiograph (CXR) should be based upon the necessity for the planned clinical procedure (i.e. a lateral chest film is essential in a repeat sternotomy), or in assessing the patient's clinical condition. Clinical characteristics suggesting a benefit to obtaining a CXR include a history of smoking, recent respiratory infection, chronic obstructive pulmonary disease (COPD), or cardiac disease. The posterior–anterior and lateral CXR provide a wealth of information including an assessment of pulmonary condition and maybe cardiovascular status. For example, radiographic evidence of pulmonary vascular congestion suggests poor systolic function. For patients with valvular heart disease, a normal CXR is more useful than an abnormal radiograph in assessing ventricular function. The presence of a cardio-to-thoracic ratio less than 50% is a sensitive indicator of an ejection fraction greater than 50% and of a cardiac index greater than 2.5 L/min/m^2. On the other hand, a cardio-to-thoracic ratio greater than 50% is not a specific indicator of ventricular function. For patients with CAD, an abnormal CXR is more useful than a normal radiograph in assessing ventricular function. Cardiomegaly is a sensitive indicator of a reduced ejection fraction, whereas a normal-sized heart may be associated with both normal and reduced ejection fractions.

As with the ECG, efforts should be made to correlate radiographic findings with the clinical history. LAE is expected in mitral stenosis and regurgitation. Enlargement of the pulmonary artery and right ventricle occurs with disease progression. Eccentric LV hypertrophy results from mitral and aortic regurgitation. Aortic stenosis results in concentric LV hypertrophy. In infants and children with increased pulmonary blood flow (as with a large ventricular septal or atrial septal defect), the pulmonary artery and pulmonary vasculature is prominent. In contrast, patients with reduced pulmonary blood flow (as with tetralogy of Fallot or pulmonary atresia) may manifest a small pulmonary artery and diminished vascularity. Some congenital lesions are associated with classic radiographic cardiac silhouettes: the boot-shaped heart of tetralogy of Fallot, the "figure 8" heart of total anomalous pulmonary venous return, and the "egg-on-its-side"-shaped heart seen in D-transposition of the great arteries.

Stress testing

Patients presenting for cardiac surgery frequently undergo stress testing to establish the diagnosis of CAD, assess the severity of known CAD, establish the viability of regions of myocardium, or evaluate anti-anginal therapy. Stress testing may use exercise or pharmacological agents. Pharmacological agents are useful for patients with physical disabilities that preclude effective exercise. It also is useful for patients who cannot reach an optimal exercise heart rate secondary to their medication regimen (i.e. patients on beta-blockers).

Pharmacological stress testing

Pharmacologic stress testing uses dipyridamole, adenosine, or dobutamine. Pharmacologic stress testing can be performed in conjunction with myocardial perfusion scintigraphy or echocardiography.

Adenosine and dipyridamole are potent coronary vasodilators that increase myocardial blood flow three to fivefold independent of myocardial work. Adenosine is a direct vascular smooth muscle relaxant via A_2-receptors; whereas, dipyridamole increases adenosine levels by inhibiting adenosine deaminase. Dobutamine increases myocardial work through increases in heart rate and contractility via β_1-receptors. The increased work produces proportional increases in myocardial blood flow. In this sense, dobutamine stress testing is similar to exercise stress testing.

The hyperemic response to adenosine and dipyridamole produce increased myocardial blood flow in regions supplied by normal coronary arteries. In regions of myocardium supplied by steal prone

anatomy or diseased coronary arteries, myocardial blood flow increases will be attenuated or decreased below resting levels.

Dipyridamole is infused at 0.56–0.84 mg/kg for 4 minutes, followed by injection of the radiopharmaceutical for myocardial perfusion scintigraphy 3 minutes later. If infusion produces headache, flushing, gastrointestinal (GI) distress, ectopy, angina, or ECG evidence of ischemia, the effect can be terminated with aminophylline 75–150 mg intravenously (IV). Adenosine is infused at 140 μg/kg/min for 6 minutes with injection of the radiopharmaceutical for myocardial perfusion scintigraphy 3 minutes later. Side effects are similar to dipyridamole and are terminated by stopping the infusion (the half-life of adenosine is 40 seconds). Dobutamine is infused at 5 μg/kg/min for 3 minutes and then is increased to 10 μg/kg/min for 3 minutes. The dose is increased by 5 μg/kg/min every 3 minutes until a maximum of 40 μg/kg/min is reached or until significant increases in heart rate and blood pressure occur. Injection of the radiopharmaceutical for myocardial perfusion scintigraphy takes place 1 minute after the desired dose is reached, and the infusion is continued for 1–2 minutes after injection. Side effects of dobutamine (headache, flushing, GI distress, ectopy, angina, or ECG evidence of ischemia) can be terminated by discontinuing the infusion (the half-life of dobutamine is 2 minutes).

Exercise stress testing

Exercise stress testing increases in myocardial oxygen consumption to detect limitations in coronary blood flow. Exercise increases cardiac output through increases in heart rate and inotropy. Despite vasodilatation in skeletal muscle, exercise typically increases arterial blood pressure as well. As a result, exercise is accompanied by increases in the three major determinants of myocardial oxygen consumption: heart rate, wall tension, and contractility. To meet the demands of exercise, the coronary vascular bed dilates. The ability of the coronary circulation to increase blood flow to match exercise-induced increases in demand is compromised in the distribution of stenosed coronary arteries because vasodilatory reserve is exhausted in these beds.

All exercise tests increase metabolic rate and oxygen consumption ($V\text{O}_2$). Isometric exercise may be used to increase the workload, but more commonly, dynamic exercise using either a treadmill or a bicycle is used. $V\text{O}_{2\text{max}}$ is the maximal amount of oxygen a person can use while performing dynamic exercise. $V\text{O}_{2\text{max}}$ is influenced by age, gender, exercise habits, and cardiovascular status. Exercise protocols are compared by using metabolic equivalents (METs). One MET is equal to a $V\text{O}_2$ of 3.5 mL oxygen(O_2)/kg/min and represents resting oxygen uptake. Different exercise protocols are compared by comparing the number of METs consumed at various stages.

The Bruce treadmill protocol is the most commonly used protocol for exercise stress testing. This protocol uses seven 3-minute stages. Each progressive stage involves an increase in both the grade and the speed of the treadmill. During stage 1 the treadmill speed is 1.7 miles/h on a 10% grade (5 METs); during stage 5 the treadmill speed is 5 miles/h on an 18% grade (16 METs). The patient progressively moves through the stages until either exhausted, a target heart rate achieved without ischemia, or the detection of ischemic changes on the ECG. Exercise stress testing can be performed in conjunction with traditional ECG analysis, myocardial perfusion scintigraphy, or echocardiography. The details of stress myocardial perfusion scintigraphy, stress radionucleotide angiography, and stress echocardiography are discussed below.

The following factors must be considered in interpretation of an ECG exercise stress test:

- *Angina*. Ischemia may present as the patient's typical angina pattern; however, angina is not a universal manifestation of ischemia in all patients. Ischemic pain induced by exercise is strongly predictive of CAD.
- $V\text{O}_{2\text{max}}$. If patients with CAD reach 13 METs, their prognosis is good regardless of other factors; patients with an exercise capacity of less than 5 METs have a poor prognosis.
- *Dysrhythmias*. For patients with CAD, ventricular dysrhythmias may be precipitated or aggravated by exercise testing. The appearance of reproducible sustained (>30 seconds) or symptomatic ventricular

tachycardia (VT) is predictive of multivessel disease and poor prognosis.

- *ST segment changes*. ST segment depression is the most common manifestation of exercise-induced myocardial ischemia. The standard criterion for an abnormal response is horizontal or down sloping (>1 mm) depression 80 ms after the J point. Down sloping segments carry a worse prognosis than horizontal segments. The degree of ST segment depression (>2 mm), the time of appearance (starting with <6 METs), the duration of depression (persisting >5 minutes into recovery), and the number of ECG leads involved (>5 leads) are all predictive of multivessel CAD and adverse prognosis.
- *Blood pressure changes*. Failure to increase systolic arterial blood pressure to greater than 120 mmHg, or a sustained decrease in systolic blood pressure with progressive exercise, is indicative of cardiac failure in the face of increasing demand. This finding suggests severe multivessel or left main CAD.

Comparison of stress test methods

The sensitivity of detection of CAD with exercise myocardial perfusion scintigraphy or exercise echocardiography is superior to that of exercise ECG testing. The superiority of these two modalities over ECG testing in detecting CAD is greatest for patients with single vessel CAD. When comparing myocardial perfusion scintigraphy to stress echocardiography, the data suggest a trend toward greater sensitivity with myocardial perfusion scintigraphy, particularly for patients with single-vessel disease. Moderate to large perfusion defects by either stress echocardiography or thallium imaging predicts postoperative myocardial infarction or death in patients scheduled for elective noncardiac surgery. Negative tests assure the clinician of a small likelihood of subsequent adverse outcome (negative predictive value = 99%). Unfortunately, however, the positive predictive value (i.e. the chance that a patient with a positive test will have an adverse cardiovascular event) is poor ranging from 4% to 20%. In a meta-analysis comparing the two techniques, stress echocardiography is slightly superior to thallium imaging in predicting postoperative cardiac events. The choice of which technique should be made based upon institutional expertise and patient-specific attribute. In either case, angiography should be considered in patients with moderately large defects.

Limitations of exercise ECG testing are the inability to accurately localize and assess the extent of ischemia. Furthermore, no direct information regarding left ventricle function is available. Stress myocardial perfusion scintigraphy, radionuclide angiography, and echocardiography provide this information. On the other hand, these methods are more expensive and technically more demanding than exercise ECG testing.

Myocardial perfusion scintigraphy

Myocardial perfusion scintigraphy assesses myocardial blood flow, myocardial viability, the number and extent of myocardial perfusion defects, transient stress-induced LV dilatation, and allows for risk stratification. Myocardial perfusion scintigraphy is performed most commonly in conjunction with stress testing. Stress testing can be accomplished with exercise or pharmacologically with dipyridamole, adenosine, or dobutamine. With this technology, it is possible to determine which regions of myocardium are perfused normally, which are ischemic, which are stunned or hibernating, and which are infarcted. The technique is based on the use of radiopharmaceuticals that accumulate in the myocardium proportional to regional blood flow. Single-positron emission computed tomography (SPECT) or planar imaging is used to image regional myocardial perfusion in multiple views and at various measurement intervals. Patients with small fixed perfusion defects have reduced perioperative risk profiles, whereas patients with multiple larger defects are at higher risk.

The radiopharmaceuticals currently in use are thallium-201 and technetium-99m methoxyisobutyl isonitrile (Sestamibi). Thallium has biologic properties similar to potassium and thus is transported across the myocardial cell membrane by the sodium–potassium adenosine triphosphatase (ATPase) pump proportional to regional myocardial blood flow. Sestamibi is not dependent on ATP to enter myocardial cells because it is highly lipophilic but its distribution in myocardial tissue is proportional to blood flow.

Thallium

Thallium-201 is injected at the peak level of a multistage exercise or pharmacological stress test. Scintillation imaging begins 6–8 minutes after injection (early views) and is repeated again 2–4 hours after injection (delayed or redistribution views). Identical views must be used so the early and delayed images can be compared. During stress, myocardial blood flow and thallium-201 uptake will increase in areas of the myocardium supplied by normal coronary arteries. Subsequently, thallium redistributes to other tissues, thus clearing from the myocardium slowly. Areas of myocardium supplied by diseased arteries are prone to ischemia during stress and have a reduced ability to increase myocardial blood flow and thallium-201 uptake. These areas will demonstrate a perfusion defect when compared with normal regions in the early views. In the delayed views, late accumulation or flat washout of thallium-201 from the ischemic areas compared with the nonischemic areas results in equalization of thallium-201 activity in the two areas. These *reversible perfusion* defects are typical of areas of myocardium that suffer transient, stress-induced ischemia. *Nonreversible perfusion defects* are present in both the early stress and delayed redistribution images. These defects are believed to represent areas of nonviable myocardium resulting from old infarctions. *Reverse redistribution* is the phenomenon in which early images are normal or show a defect and the delayed images show a defect or a more severe defect. This is seen frequently in patients who have recently undergone thrombolytic therapy or angioplasty and may result from higher-than-normal blood flow to the residual viable myocardium in the partially infarcted zone.

Modified thallium scintigraphy protocols are useful in detecting areas hibernating myocardium. Hibernating myocardium exhibits persistent ischemic dysfunction secondary to a chronic reduction in coronary blood flow, but the tissue remains viable. Hibernating myocardium has been shown to exhibit functional improvement after surgical revascularization or angioplasty and restoration of coronary blood flow. Stunned myocardium, in contrast, has undergone a period of transient hypoperfusion with subsequent reperfusion. As a result, these regions exhibit transient postischemic dysfunction in the setting of normal coronary blood flow. Stunned myocardium is detected by identifying regions of dysfunctional myocardium in which no perfusion defect exists.

Some regions of myocardium that do not exhibit redistribution at 2.5–4.0 hours exhibit redistribution in late images at 18–24 hours. This late redistribution represents areas of hibernating myocardium. Another approach to detecting hibernating myocardium is reinjection of thallium at rest after acquisition of the 2.5–4.0-hour stress images. Persistent defects that show enhanced uptake after reinjection represent areas of viable myocardium. Finally, serial rest thallium imaging has proved useful in detecting hibernating myocardium. Images are obtained at rest after injection of thallium and then are repeated 3 hours later. Regions of myocardium that exhibit rest redistribution represent areas of viable myocardium.

Increased lung uptake of thallium is related to exercise-induced LV dysfunction and suggests multivessel CAD. Because increased lung uptake of thallium is due to an elevated left atrial pressure (LAP), other factors besides extensive CAD and exercise-induced LV dysfunction (such as mitral stenosis, mitral regurgitation, and nonischemic cardiomyopathy) must be considered when few or no myocardial perfusion defects are detected. Transient LV dilation after exercise or pharmacologic stress also suggests severe myocardial ischemia.

Sestamibi

Sestamibi, unlike thallium, does not redistribute. As a result, the distribution of myocardial blood flow at the time of injection remains fixed over the course of several hours. This necessitates two separate injections: one at rest and one at peak stress. The two studies must be performed so that the myocardial activity from the first study decays enough not to interfere with the activity from the second study. A small dose is administered at rest with imaging approximately 45–60 minutes later. Several hours later, a larger dose is administered at peak stress, with imaging 15–30 minutes later. Reversible and fixed defects are detected by comparing the rest and stress images. As with thallium,

late imaging after Sestamibi stress imaging may be helpful in detecting hibernating myocardium.

Sestamibi allows high-count-density images to be recorded, providing better resolution than thallium. In addition, use of Sestamibi allows performance of first pass radionuclide angiography (see below) to be performed in conjunction with myocardial perfusion scintigraphy. Use of simultaneous radionuclide angiography and perfusion scintigraphy has proved useful in enhanced detection of viable myocardium. Viable myocardium will exhibit preserved regional perfusion in conjunction with preserved regional wall motion.

Radionuclide angiography

Radionuclide angiography allows assessment of RV and LV performance. Two types of cardiac radionuclide imaging exist: first-pass radionuclide angiography (FPRNA) and equilibrium radionuclide angiography (ERNA), also known as radionuclide ventriculography or gated blood pool imaging. ERNA is also known as multiple-gated acquisition (MUGA) or multiple-gated equilibrium scintigraphy (MGES).

FPRNA involves injection of a radionuclide bolus (normally technetium-99m) into the central circulation via the external jugular or antecubital vein. Subsequent imaging with a scintillation camera in a fixed position provides a temporal pictorial presentation of the cardiac chambers as the radiolabeled bolus makes its way through the heart. First-pass studies may be gated or ungated. Gated studies involve synchronization of the presented images with the patient's ECG such that systole and diastole are identified. Ungated studies simply present a series of images over time.

ERNA involves use of technetium-99m-labeled red cells, which are allowed to distribute uniformly in the blood volume. Radiolabeling of red cells is accomplished by initially injecting the patient with stannous pyrophosphate, which creates a stannous-hemoglobin complex over the course of 30 minutes. Subsequent injection of a technetium-99m bolus results in binding of technetium-99m to the stannous-hemoglobin complex, thus labeling the red cells.

After equilibrium of the labeled red cells in the cardiac blood pool, gated imaging with a scintillation camera is performed. A computer divides the cardiac cycle into a predetermined number of frames (16–64). Each frame represents a specific time interval relative to the ECG R wave. Data collected from each time interval over the course of several hundred cardiac cycles are then added together with the other images from the same time interval. The result is a sequence of 16–64 images, each representing a specific phase of the cardiac cycle. The images can be displayed in an endless loop format or individually. The procedure can then be repeated with the camera in a different position.

Below is a summary of the relative advantages and disadvantages of first-pass and equilibration studies. Both types of studies currently are used for adults, infants, and children.

- With both FPRNA and ERNA studies, the number of radioactive counts during end systole and end diastole can be used to determine stroke volume, ejection fraction, and cardiac output.
- Both types of studies allow reliable quantification of LV volume using count-proportional methods that do not require assumptions to be made about LV geometry.
- Although both studies allow determination of RV and LV ejection fractions, determination of RV ejection fraction is more accurate with a first-pass study because the right atrium overlaps the right ventricle in equilibrium studies.
- First-pass studies allow detection and quantification of both right-to-left and left-to-right intracardiac shunts, whereas shunt detection is not possible with equilibration studies.
- First-pass studies allow sequential analysis of right atrial (RA), RV, left atrial (LA), and LV size, whereas equilibration studies do not. Abnormalities in the progression of the radioactive tracer through the heart and great vessels assist in the diagnosis of congenital abnormalities.
- Equilibration studies provide better analysis of regional wall motion abnormalities than first-pass studies due to higher resolution.
- Both types of studies can be used with exercise. First-pass studies can be performed rapidly

but do not allow assessment of ventricular wall motion at different exercise levels, nor do they allow assessment of wall motion from different angles.

• Mitral or aortic regurgitation is detectable with both first-pass and equilibration studies by analysis of the stroke volume ratio. This method tends to overestimate regurgitant fraction and is not reliable for detection of minor degrees of regurgitation.

Echocardiography

Transthoracic and transesophageal echocardiography has revolutionized the noninvasive structural and functional assessment of acquired and congenital heart disease. Transthoracic echocardiography (TTE) and transesophageal echocardiography (TEE) often play a major role in the evaluation of cardiac surgical patients. Routine use of two-dimensional imaging, color flow Doppler, continuous wave Doppler, pulsed wave Doppler, and M-mode imaging allows the following:

• *Assessment of cardiac anatomy.* Delineation of the most complex congenital heart lesions is feasible. In many instances, information acquired from a comprehensive echocardiographic examination is all that is necessary to undertake a surgical repair.

• *Assessment of ventricular function.* A comprehensive assessment of RV and LV diastolic and systolic function is feasible.

• *Assessment of valvular abnormalities.* Assessment of the functional status of all four cardiac valves is possible. In addition, quantification of valvular stenosis and insufficiency is accurate and reliable. Assessment of prosthetic valves also is feasible.

• *Characterization of cardiomyopathies.* Hypertrophic, dilated, and restrictive cardiomyopathies can be identified.

• *Assessment of the pericardium.* Pericardial effusions, cardiac tamponade, and constrictive pericarditis are reliably identified.

• *Assessment of cardiac and extracardiac masses.* Vegetations, foreign bodies, thrombi, and metastatic and primary cardiac tumors can be identified.

• *Contrast echocardiography.* Contrast solutions containing microbubbles enhance the image allowing assessment of myocardial perfusion, intracardiac shunts, enhancement of Doppler signals, and improved assessment of regional and global LV function.

• *Stress echocardiography.* Stress echocardiography is based on the concept that exercise or pharmacologically induced wall motion abnormalities develop early in the course of ischemia. Stress-induced wall motion abnormalities occur soon after perfusion defects are detected by radionuclide imaging because, in the ischemic cascade, hypoperfusion precedes wall motion abnormalities. Comparison of resting and stress images allows resting abnormalities to be distinguished from stress-induced abnormalities. Resting abnormalities indicate prior infarction, hibernating or stunned myocardium; whereas, stress-induced abnormalities are specific for ischemia. Furthermore, dobutamine stress echocardiography may be useful in determining myocardial viability. Regions that are hypokinetic, akinetic, or dyskinetic at rest and improve with dobutamine administration probably contain areas of stunned or hibernating myocardium. Such areas demonstrate functional improvement after myocardial revascularization.

Computerized tomography and magnetic resonance imaging

Advances in imaging techniques have played a major role in defining anatomy in cardiac surgical patients. Computerized tomography (CT) and magnetic resonance imaging (MRI) now allow the clinician detailed anatomy, three-dimensional rendering, and functional assessment of myocardial performance and blood flow (Fig. 1.1). It is likely that new advances in imaging techniques will continue to improve the quality and the anatomic detail afforded by these techniques. Molecular imaging, i.e. imaging of cellular function, is a developing area in cardiac imaging. The applications of these new technologies remain to be seen.

Cardiac catheterization

Cardiac catheterization remains the gold standard for evaluation of acquired and congenital heart disease. Cardiac catheterization is covered in detail in Chapter 2.

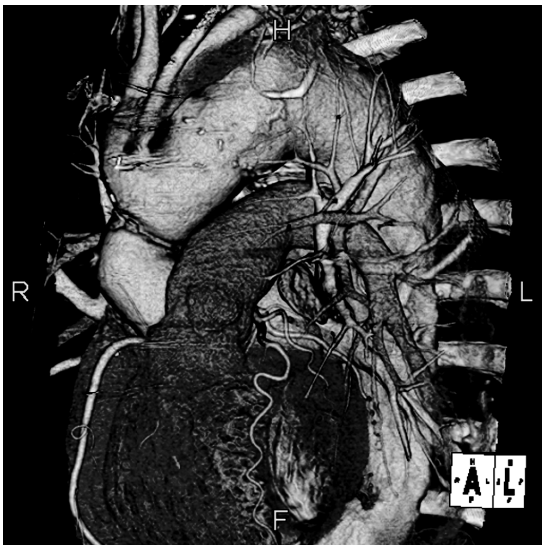

Fig. 1.1 Three dimension reconstruction of the heart and aorta

Respiratory evaluation

A preoperative assessment of pulmonary function (other than CXR) is required in all cardiac surgical patients. The evaluation must include a history of known pulmonary disease, current respiratory symptoms, and a physical examination. Evaluation may include consultation with specialists and specific pulmonary testing (pulmonary function testing, spirometry, pulse oximetry, arterial blood gas analysis). The history should determine the extent and length of tobacco use, the presence of COPD, asthma, recurrent or acute pulmonary infections, and the presence of dyspnea. Physical examination should focus on the detection of wheezes, flattened diaphragms, air trapping, consolidations, and clubbing of the nails. A CXR is indicated in nearly all cardiac surgical patients. Pulmonary function tests (PFTs) play a limited role in preoperative assessment. If there is confusion about whether intrinsic pulmonary disease exists, its cause, and its appropriate treatment, then pulmonary function testing may help guide the clinician. Spirometry measures lung volumes, capacities, and flow. Spirometry of expiratory flow rates allows measurement of the forced expiratory volume in 1 second (FEV_1), the forced vital capacity (*FVC*), and the forced mid-expiratory flow (*FEF* 25–75%). Arterial blood gases should be obtained for patients in whom carbon dioxide (CO_2) retention is suspected and for those with severe pulmonary dysfunction as determined by history, physical examination, PFTs, or cardiac catheterization.

Pulmonary assessment and congenital heart disease

Lesions that produce excessive pulmonary blood flow (large ventricular septal defect, truncus arteriosus, dextrotransposition of the great arteries, and patent ductus arteriosus) are associated with pulmonary dysfunction. Occasionally, large airway compression occurs in response to enlargement of the pulmonary arteries. More commonly, however, these lesions produce pulmonary vascular changes that affect pulmonary function. The pulmonary vascular smooth muscle hypertrophy that accompanies increased pulmonary blood flow produces peripheral airway obstruction and reduced expiratory flow rates characteristic of obstructive lung disease. In addition, smooth muscle hypertrophy in respiratory bronchioles and alveolar ducts in patients with increased pulmonary blood flow contributes to this obstructive pathology. These changes predispose the patient to atelectasis and pneumonia. Children with Down syndrome have a more extensive degree of pulmonary vascular and parenchymal lung disease than other children with similar heart lesions. This predisposes patients with Down syndrome to greater postoperative respiratory morbidity and mortality.

Patients with lesions that reduce pulmonary blood flow (pulmonary atresia or stenosis, tetralogy of Fallot) also have characteristic pulmonary function changes. These patients have normal lung compliance as compared with the decreased compliance seen in patients with increased pulmonary blood flow. However, the large dead space to tidal volume ratio in these patients greatly reduces ventilation efficiency, and large tidal volumes are required to maintain normal alveolar ventilation. Finally, 3–6% of patients with tetralogy of Fallot will have an absent pulmonary valve and aneurysmal dilatation of the pulmonary arteries. This aneurysmal

dilatation produces bronchial compression and respiratory distress at birth.

Pulmonary assessment and acquired heart disease

Pulmonary dysfunction ranks among the highest predictors of postoperative pulmonary complications. Pulmonary dysfunction is defined as a productive cough, wheeze, or dyspnea. Pulmonary function testing consistent with pulmonary dysfunction shows a $FEV_1 < 70\%$ of predicted or $FEV_1/FVC < 65\%$ of predicted, plus either vital capacity (VC) < 3.0 L or maximum voluntary ventilation (MVV) < 80 L/min. For patients undergoing valvular surgery, the presence of pulmonary dysfunction is associated with up to a 2.5-fold increase in perioperative mortality and a 2.5-fold increase in postoperative respiratory complications. For patients undergoing only coronary revascularization, pulmonary dysfunction is less predictive of postoperative morbidity and mortality.

Pulmonary assessment and tobacco use

Chronic tobacco use has several physiologic effects that may complicate anesthetic management. Smoking accelerates the development of atherosclerosis. Further, smoking reduces coronary blood flow by increasing blood viscosity, platelet aggregation, and coronary vascular resistance. Nicotine, through activation of the sympathetic nervous system and elevated catecholamine levels, increases myocardial oxygen consumption by increasing heart rate, blood pressure and myocardial contractility. Furthermore, the increased carboxyhemoglobin level, which may exceed 10% in smokers, reduces systemic and myocardial oxygen delivery. This is particularly detrimental to the patient with CAD due to the high extraction of oxygen that normally occurs in the myocardium. The threshold for exercise-induced angina is reduced by carboxyhemoglobin levels as low as 4.5%. Short-term abstinence (12–48 hours) is sufficient to reduce carboxyhemoglobin and nicotine levels and improve the work capacity of the myocardium.

There is an increased incidence of postoperative respiratory morbidity in patients who smoke. These complications include respiratory failure, unanticipated intensive unit admission, pneumonia, airway events during induction of anesthesia (cough, laryngospasm), and increased need for postoperative respiratory therapy. Smoking increases mucus secretion, impairs tracheobronchial clearance, and causes small airway narrowing. For patients undergoing coronary revascularization, abstinence from smoking for 2 months may reduce the incidence of postoperative respiratory complications. Abstinence for less than 2 months is ineffective in reducing the incidence of postoperative respiratory complications. Similar studies of patients undergoing other surgical procedures have confirmed the necessity of a 4–6-week abstinence period. Typically, tobacco-using patients presenting for cardiac surgery will not have had the recommended abstinence period required to reduce complications. Acute cessation of smoking during the perioperative period is not associated with elevated risk. There is no added cardiovascular risk for patients using nicotine replacement therapy (NRT).

Pulmonary assessment and asthma

Asthma is characterized by paroxysmal or persistent symptoms of wheezing, chest tightness, dyspnea, sputum production, and cough with airflow limitation. There is hyper-responsiveness to endogenous or exogenous stimuli. Preoperative evaluation of asthma confirms the diagnosis and evaluates the adequacy of treatment. Adequate control is demonstrated when the patient reports normal physical activity, mild and infrequent exacerbations, no missed school or work days, and less than four doses of β_2-agonist therapy per week. Long-term treatment is largely preventive in nature. First-line pharmacologic treatment often incorporates inhaled corticosteroids (ICSs). Beclomethasone significantly improves FEV_1, peak expiratory flow, and reduces β-agonist use and exacerbations. Leukotriene receptor antagonists (LTRAs) are sometimes used as first-line therapy; however, their role is less clearly established when compared to the ICS agents. Long-acting β_2-agonists are safe and effective medications for improving asthma control in older children and adults when ICSs therapy does not adequately control the disease. Theophylline is

less effective than ICSs and LTRAs in improving asthma control.

For patients in whom bronchospasm is well controlled preoperatively, it is essential to continue therapy during the perioperative period. Beta-2-agonist metered-dose inhaler or nebulizer therapy can be continued until arrival in the operating room and can be restarted soon after emergence from anesthesia. Metered-dose inhalation therapy can be delivered via the endotracheal tube. For patients not on bronchodilator therapy who present for surgery with bronchospasm, a trial of bronchodilators with measurement of PFTs before and after therapy is often helpful. An increase in the FEV_1 of 15% or more after inhalation of a nebulized bronchodilator suggests a reversible component of bronchospasm. Surgery should be delayed until the asthma is controlled. If this is not possible, acute therapy with steroids and β_2-agonists is indicated. Therapy for the cardiac surgical patient should be initiated with a β_2-selective metered-dose inhaler or nebulized solution.

Renal function

Patients presenting for cardiac surgery may possess varying degrees of renal dysfunction ranging from mild elevations in creatinine to dialysis dependence. Assessing renal function preoperatively is vitally important in the cardiac surgical patient. Renal dysfunction after cardiac surgery is associated with increased mortality, morbidity, resource utilization and intensive care unit stay. Depending on the definition of acute renal failure (ARF), anywhere from 5% to 30% of patients demonstrate renal dysfunction after cardiac procedures. Renal dysfunction requiring dialysis is associated with a 50–80% increased risk of death. ARF is among the strongest predictors for death with an odds ratio of 7.9 (95% confidence interval 6–10) in cardiac surgical patients. Identification of high-risk candidates remains important for appropriate patient consent, risk-benefit analysis, and hospital resource utilization planning (Table 1.5).

The dialysis-dependent patient will require dialysis preoperatively. If dialysis is unobtainable preoperatively, it can be managed intraoperatively.

Table 1.5 Risk factors for acute renal failure after cardiac surgery.

Female gender
Congestive heart failure
LV ejection fraction <35%
Preoperative use of an intraaortic balloon pump
Chronic obstructive pulmonary disease
Previous cardiac surgery
Emergency surgery
Valve or valve + CABG surgery
Elevated preoperative creatinine

CABG, coronary artery bypass graft.

Dialysis will correct or improve the abnormalities in potassium, phosphate, sodium, chloride, and magnesium. In addition, the platelet dysfunction that accompanies uremia will be improved. L-deamino-8-D-arginine vasopressin (DDAVP) administration may improve uremia-induced platelet dysfunction and should be considered if clinically significant post-dialysis platelet dysfunction exists. Dialysis will not favorably affect the anemia, renovascular hypertension, or immune-system compromise associated with chronic renal failure.

For nondialysis-dependent patients, preoperative hydration is necessary to prevent prerenal azotemia from complicating the underlying renal dysfunction. This is particularly important after procedures such as cardiac catheterization with arteriography. Creatinine clearance falls after contrast arteriography; in patients with preexisting azotemia, this reduction is much more likely to result in ARF. Hydration ameliorates contrast-induced renal dysfunction. Treatment with acetylcysteine and sodium bicarbonate reduce post-contrast ARF.

Patients with renal transplants occasionally present for cardiac surgical procedures. The extrarenal component of renal blood flow autoregulation is absent in the denervated kidney. Therefore, preoperative hydration and maintenance of systemic perfusion pressure are particularly important to maintain renal perfusion. Sterile technique is mandatory in these immunocompromised patients.

Renal dysfunction often results in electrolyte imbalance. Potassium regulation is often difficult in the cardiac surgical patient. Hyperkalemia

(>5.5 mEq/L) is uncommon in patients with normal renal function; however, it may occur with injudicious potassium administration. The major causes of hyperkalemia result from diminished renal excretion of potassium secondary to reduced glomerular filtration rate (acute oliguric renal failure, chronic renal failure). Reduced tubular secretion may lead to hyperkalemia as seen in Addison's disease, potassium-sparing diuretics and angiotensin converting enzyme inhibitors. Other causes include transcellular shifts of potassium as seen in acidosis, trauma, burns, beta-blockade, rhabdomyolysis, hemolysis, diabetic hyperglycemia, and depolarizing muscle paralysis with succinylcholine. The clinical manifestations relate to alterations in cardiac excitability. Peaked T waves will appear with a potassium level of 6.5 mEq/L. At levels of 7–8 mEq/L the PR interval will prolong and the QRS complex will widen. At 8–10 mEq/L sine waves appear and cardiac standstill is imminent. Treatment is multimodal and includes glucose, insulin, bicarbonate and β-agonists (shifting potassium to the intracellular compartment), diuretics, exchange resins and dialysis (enhancing potassium elimination), and calcium (no change in serum potassium concentration, but calcium counteracts the cardiac conduction effects of hyperkalemia).

Hypokalemia (<3.5 mEq/L) is not uncommon in the cardiac surgical patient. The most common etiology is chronic diuretic therapy, but other causes such as GI loss (nasogastric suction, diarrhea, vomiting), mineralocorticoid excess, acute leukemia, alkalosis, barium ingestion, insulin therapy, vitamin B_{12} therapy, thyrotoxicosis and inadequate intake must be considered. The clinical manifestations of hypokalemia are observed in skeletal muscle, heart, kidneys, and the GI tract. Neuromuscular weakness is observed with levels of 2.0–2.5 mEq/L. Hypokalemia leads to a sagging of the ST segment, depression of the T wave, and the appearance of a U wave on the ECG. In patients treated with digitalis, hypokalemia may precipitate serious arrhythmias. Treatment of hypokalemia involves either oral or parenteral replacement. A deficit in serum potassium reflects a substantial total body deficit. A decrease in plasma potassium concentration of 1 mEq/L with a normal acid-base balance represents approximately 300 mEq of total body potassium deficiency. In preparing the cardiac surgical patient for surgery, it is reasonable to maintain serum potassium higher than 3.5 mEq/L for patients on digitalis, those at high risk for myocardial ischemia and those who have suffered acute reductions in serum potassium. Potassium replacement is not without risk (iatrogenic hyperkalemia). In general, potassium replacement should not exceed 10–20 mEq/h or 200 mEq/day. Serum potassium must be closely monitored during the replacement therapy.

Endocrine evaluation

A careful evaluation for endocrine abnormalities should be sought in the history and physical examination. Diabetes mellitus (DM) and hypothyroidism deserve special consideration.

Diabetes mellitus

Diabetes mellitus is a risk factor for development of CAD; therefore, perioperative management of DM is a common problem facing those who anesthetize patients for cardiac surgery. Patients with insulin-dependent diabetes have reduced or absent insulin production due to destruction of pancreatic beta cells. Patients with noninsulin-dependent diabetes have normal or excessive production of insulin but suffer from insulin resistance. This resistance may be due to a reduction in insulin receptors, a defect in the second messenger once insulin binds to receptors, or both. Patients with noninsulin-dependent diabetes may be managed with diet, oral hypoglycemic agents (agents that increase pancreatic insulin production), or exogenous insulin. Patients with insulin-dependent diabetes must receive exogenous insulin.

Cardiopulmonary bypass (CPB) is associated with changes in glucose and insulin homeostasis in both diabetic and nondiabetic patients. During normothermic CPB, elevations in glucagon, cortisol, growth hormone, and catecholamine levels produce hyperglycemia through increased hepatic glucose production, reduced peripheral use of glucose, and reduced

insulin production. During hypothermic CPB, hepatic glucose production is reduced and insulin production remains low such that blood glucose levels remain relatively constant. Rewarming on CPB is associated with increases in glucagon, cortisol, growth hormone, and catecholamine levels and is accompanied by enhanced hepatic production of glucose, enhanced insulin production, and insulin resistance. The transfusion of blood preserved with acid-citrate-dextrose, the use of glucose solutions in the CPB prime, and the use of β-adrenergic agents for inotropic support, further increase exogenous insulin requirements. For nondiabetic patients, these hormonally mediated changes usually result in mild hyperglycemia. For diabetic patients, these changes may produce significant hyperglycemia and ketoacidosis.

Management of perioperative glucose is directly related to perioperative outcome. Uncontrolled, or poorly controlled, perioperative glucose is associated with increased mortality, wound infection, and intensive care unit length of stay. This relationship is true in cardiac and noncardiac surgical patients admitted to an intensive care unit setting. The ideal level of glucose is unknown; however, if a target of 130 mg/dL can be achieved, this is associated with improved clinical outcome. Administration of exogenous insulin should be administered early in the perioperative period to achieve this goal. The clinician must remember that achieving this goal may be impossible in some patients. Insulin resistance and the physiologic conditions encouraging hyperglycemia may be too great in some patients. Similarly, the clinician must exercise caution when administering insulin. Serum glucose levels should be checked as frequently as every 15–30 minutes perioperatively while insulin therapy is utilized. Unrecognized hypoglycemia can adversely affect patient outcome.

Because of the varying insulin requirements during cardiac surgery and the unreliable absorption of subcutaneously administered insulin in patients undergoing large changes in body temperature and peripheral perfusion, insulin is best delivered IV for patients undergoing cardiac surgery. The goal of therapy should be maintenance of normoglycemia during the pre-CPB, CPB, and post-CPB periods. On the morning of surgery, the usual insulin dose is withheld. On arrival in the operating room, the patient's blood glucose is measured. For tight control, a continuous regular insulin infusion can be started and adjusted to maintain blood glucose between 100 and 150 mg/dL during the operative procedure. Determinations of blood glucose are made every 15–30 minutes. Table 1.6 provides guidelines for insulin administration. It must be emphasized that the alterations in glucose homeostasis and the insulin resistance that accompany hypothermic CPB may necessitate alteration in infusion rates, and therefore insulin must be titrated against demonstrated patient response by measuring serial serum glucose levels.

Table 1.6 Recommendations for insulin administration.

Blood glucose (mg/dL)	Insulin infusion rate (U/kg/h)	Rate in 100 kg patient (U/h)*
150–200	0.02	2
200–250	0.03	3
250–300	0.04	4
300–350	0.05	5
350–400	0.06	6

* The actual rate of administration will vary from patient to patient and should be titrated against measured serum glucose levels and patient response.

Patients taking oral hypoglycemic agents should discontinue them at least 12 hours before surgery. For patients managed with these agents and patients managed with diet, blood glucose determinations should be made every 30–60 minutes during the operative procedure. These patients frequently require insulin infusions to maintain glucose homeostasis during surgery.

Hypothyroidism

Hypothyroidism is characterized by a reduction in the basal metabolic rate. In patients with hypothyroidism cardiac output may be reduced by up to 40% due to reductions in both heart rate and stroke volume. In addition, both hypoxic and hypercapnic ventilatory drives are blunted by hypothyroidism.

Furthermore, hypothyroidism may be associated with blunting of baroreceptor reflexes, reduced drug metabolism, renal excretion, reduced bowel motility, hypothermia, hyponatremia from syndrome of inappropriate antidiuretic hormone (SIADH), and adrenal insufficiency. The hypothyroid patient may not tolerate usual doses of antianginal drugs such as nitrates and β-adrenergic blocking agents. Hypothyroid patients on beta-blockers typically require very low anesthetic drug requirements.

Despite these problems, thyroid replacement for cardiac surgical patients, particularly those with ischemic heart disease, is not always desirable. For hypothyroid patients requiring coronary revascularization, thyroid hormone replacement may precipitate myocardial ischemia, myocardial infarction, or adrenal insufficiency. Coronary revascularization may be managed successfully in hypothyroid patients with thyroid replacement withheld until the postoperative period. Mild to moderate hypothyroid patients undergoing cardiac surgery have perioperative morbidity and mortality similar to euthyriod patients. Hypothyroid patients may experience delayed emergence from anesthesia, persistent hypotension, tissue friability, bleeding and adrenal insufficiency requiring exogenous steroids. Hypothyroidism is preferentially treated with levothyroxine (T4). In healthy adults without CAD, a starting dose of 75–100 μg/day is appropriate. In elderly patients, and those with CAD, the initial dose is 12.5–25.0 μg/day and is increased by 25–50 μg every 4–6 weeks allowing for a slow increase in metabolic rate thereby avoiding a mismatch in coronary blood supply and metabolic demand.

Hematologic evaluation

By the nature of the surgery, and the associated cardiovascular medications (heparin, clopidogrel), cardiac surgical patients are at higher perioperative risk of bleeding. A hemoglobin and hematocrit is indicated based on the invasiveness of the procedure (i.e. relative risk of blood loss and transfusion), the history of liver disease, anemia, bleeding, other hematologic disorders or an extreme in age. Serum chemistry (i.e. potassium, sodium, glucose, renal and liver function studies) are indicated in patients anticipating invasive surgery with possible metabolic alterations, diabetic patients and other patients at specific risk of renal or liver dysfunction. Plasma N-terminal pro-brain naturetic peptide (NTproBNP) is secreted by the left ventricle in response to wall stress. It is elevated in patients with LV dysfunction and heart failure. Preoperative NTproBNP levels greater than 450 ng/L are predictive of cardiac complications with a sensitivity of 100% and a specificity of 89%. Hence, an NTproBNP level may assist in preoperative risk assessment and resource management in selected patients. A urinalysis is usually not indicated unless there are specific urinary findings. A pregnancy test should be considered in all female patients of childbearing age. Coagulation studies are indicated depending on the invasiveness of the procedure, a history of renal or liver dysfunction, and in patients on anticoagulant medications.

Medical management of acute coronary syndromes, myocardial infarction, peripheral vascular disease, atrial fibrillation, and stroke often includes antithrombotic medications such as aspirin, clopidogrel bisulfate, heparin, coumadin, and others. These medications are common in patients presenting for cardiac surgery and may have a major impact on the management and preoperative evaluation of the patient. Patients may present with a long history of aspirin or clopidogrel use. In the acute setting, heparin or shorter acting IIb/IIIa inhibiting agents such as integrelin may be in use. These agents are beneficial in reducing the incidence of stent occlusion, myocardial infarction, or other thrombotic sequaela of peripheral vascular disease or hyper-coagulation. A thoughtful plan regarding the continued administration of these medications is required prior to the operative procedure. In the case of clopidogrel, stable patients presenting for elective surgery may be advised to stop the medication for 5 days to reduce the risk of excessive bleeding during the operation. All of the agents, including aspirin, are associated with increased blood loss during surgery. The relative risk of stopping the agent versus the increased risk of excessive bleeding must

be weighed in each patient. Consultation with surgeon and cardiologist are recommended before discontinuing antithrombotic therapy.

In addition to the medication history, all patients scheduled for cardiac surgical procedures require a careful bleeding history with emphasis on abnormal bleeding occurring after surgical procedures, dental extractions and trauma. Signs of easy bruising should be sought on physical examination. All patients should undergo laboratory screening for the presence of abnormalities in hemostasis. A platelet count, partial thromboplastin time (PTT), and prothrombin time (PT) should be obtained. Time permitting, all abnormalities should be evaluated prior to surgery so that post-CPB hemostasis is not complicated by unknown or unsuspected medical conditions.

PT and PTT elevations

Elevations in PT and PTT should be investigated for factor deficiencies, factor inhibitors, and the presence of anticoagulants such as warfarin and heparin. It is important that documentation of a normal PTT and PT existing before warfarin or heparin administration is initiated so that other causes of an elevated PTT and PT are not overlooked. Deficiencies of factors VIII, IX, and XI are most commonly encountered. These deficiencies and their management are summarized in the following sections.

Factor VIII deficiency (hemophilia A)

The half-life of factor VIII in plasma is 8–12 hours; normal persons have approximately 1 unit of factor VIII activity per 1 mL of plasma (100% activity). Patients with severe hemophilia A will have as little as 1% factor VIII activity, whereas mildly affected patients will have up to 50% activity. Patients present with an elevated PTT and varying degrees of clinical bleeding. The diagnosis is made by a factor assay. Safe conduct of cardiac surgery requires 80–100% factor VIII activity during the operative procedure, with maintenance of activity levels in the 30–50% range for 7 days postoperatively. An infusion of 1.0 unit of factor VIII per kilogram of body weight will increase the patient's factor VIII activity level by 2%. The 12-hour half-life of factor VIII requires that factor VIII be re-infused every 12 hours during the perioperative period. Factor VIII may be provided with cryoprecipitate, which contains 100 units of factor VIII per bag (10–20 mL). Factor VIII concentrates that contain 1000 units of factor VIII in 30–100 mL also may provide factor VIII.

Factor IX deficiency (hemophilia B)

The half-life of factor IX in plasma is 24 hours; normal persons have approximately 1 unit of factor IX activity per 1 mL of plasma (100% activity). Factor IX deficiency is clinically indistinguishable from factor VIII deficiency. Diagnosis is made by factor assay. Safe conduct of cardiac surgery requires 60% factor IX activity during the operative procedure, with maintenance of activity levels in the 30–50% range for 7 days postoperatively. An infusion of 1.0 unit of factor IX per kilogram of body weight will increase the patient's factor IX activity level by 1%. The 24-hour half-life of factor IX requires that factor IX be re-infused only every 24 hours during the perioperative period. Fresh frozen plasma (FFP) contains 0.8 units of all of the procoagulants per milliliter and generally is used to replace factor IX. A 250-mL bag of FFP will provide 200 units of factor IX. For patients in who factor IX replacement with FFP will require infusion of prohibitively large volumes, factor IX concentrates are used.

Factor XI deficiency (Rosenthal syndrome)

The half-life of factor XI in plasma is 60–80 hours; normal persons have approximately 1 unit of factor XI activity per 1 mL of plasma (100% activity). Factor XI deficiency is most common among patients of Jewish descent and is associated with a prolonged PTT. Many of these patients have no symptoms or have a history of bleeding only with surgery or major trauma. The diagnosis is made by factor assay. FFP administration replenishes factor XI. It is recommended that 10–20 mL of FFP/kg/day be used during the preoperative and postoperative periods to manage this deficiency.

Platelet dysfunction

Thrombocytopenia should be evaluated and treated as necessary to avoid excessive operative bleeding. A platelet count and platelet function monitoring are important laboratory evaluations. The bleeding time is not a reliable predictor of perioperative or postoperative bleeding. Other measurements of platelet dysfunction include thromboelastography and assays of activated platelet aggregation (aggregometry). These evaluations provide information on the functional integrity of platelet action. In the case of thromboelastography, clot formation and fibrinolysis are observed. The information gained provides insight into both factor content and platelet function. The activated platelet aggregation assays provide both a total platelet count and a percentage of active platelets. Platelet dysfunction can result from a variety of causes.

Thrombocytopenia

Thrombocytopenia may due to dilution (i.e. with massive fluid replacement), increased peripheral destruction (sepsis, disseminated intravascular coagulation, thrombotic thrombocytopenic prupura, prosthetic valve hemolysis or platelet antibodies) or sequestration (splenomegaly, lymphoma). In the cardiac surgical patient, dilutional thrombocytopenia is common. Thrombocytopenia is also frequently the result of platelet destruction from the CPB circuit and from activation of heparin induced platelet antibodies.

Heparin-induced thrombocytopenia and thrombosis (HITT) occurs due to the presence of an anti-heparin-platelet factor 4 antibodies. The condition can be terminated by withdrawal of heparin therapy. Ideally, heparin therapy should not be restarted until *in-vitro* platelet aggregation in response to heparin no longer occurs. Heparin induced thrombocytopenia may re-occur up to 12 months after the initial episode. Patients with HITT requiring CPB before the antibody can be cleared present a management problem. These patients may be treated by a variety of alternate anticoagulation agents. Direct thrombin inhibitors such as danaparoid, lepirudin, bivalirudin, and argatroban have all been used with success. Other agents such as tirofiban and epoprostenol have been used in combination with unfractionated heparin with good result. In the preoperative setting, identification of patients who have experienced HITT is paramount. If HITT is diagnosed, then the surgery should either be delayed long enough to clear the heparin antibodies (usually 90–100 days), or an alternate anticoagulation strategy devised. If heparin re-exposure is considered, testing for the presence of HITT antibodies, generally by enzyme-linked immunosobent assay (ELISA), is required.

Qualitative platelet defects

Abnormalities in platelet function are observed with some medications, renal failure, hepatic failure, paraproteinemias (i.e. multiple myeloma), myeloproliferative disorders, and hereditary disorders of platelet function. In the cardiac surgical patient, medication related dysfunction, uremic dysfunction are most common.

There is an ever growing list of medications that inhibit platelet function. Some medications altering function and commonly observed in the cardiac surgical patient include aspirin, nonsteroidal anti-inflammatory drugs (NSAIDs), thienopyridine adenosine diphosphate (ADP) receptor antagonists (clopidogrel, ticlopidine) and GP IIb/IIIa antagonists (abciximab, integrelin, and tirofiban), dextran, dipyridamole, heparin, plasminogen activators, and beta-lactam antibiotics. NSAIDs inhibit platelet function by blocking platelet synthesis of prostaglandins and platelet function is normalized when these drugs are cleared from the blood. Aspirin irreversibly acetylates prostaglandin synthase (cyclooxygenase) impairing platelet function for the life of the platelet (7–10 days). Like aspirin, the effects of clopidogrel are present for the life of the platelet. It is recommended that for elective surgery, clopidogrel should be held for 5 days allowing adequate time to reestablish a normal platelet response to bleeding. Integrelin inhibits fibrinogen from binding to the platelet surface GP IIb/IIIa receptor. Integrelin should be discontinued 12 hours before surgery to ensure adequate return of platelet function.

Renal dysfunction with uremia inhibits platelet function. The cause of this effect is unknown. In addition to the qualitative defect there is often

thrombocytopenia in these patients. The bleeding time is usually prolonged and there is associated anemia. Bleeding may be treated with platelet transfusion or administration of DDAVP, or cryoprecipitate. DDAVP and cryoprecipitate raise the levels of factor VIII (antihemophilic factor/von Willebrand factor). When DDAVP is used, 0.3 μg/kg is infused IV over 15 minutes and the half-life of its activity is 8 hours.

Coagulopathy and congenital heart disease

Coagulopathies in children with congenital heart disease are common. The etiology of these coagulopathies is multifactorial. Cyanosis has been implicated in the genesis of coagulation and fibrinolytic defects particularly in patients where secondary erythrocytosis produces a hematocrit greater than 60%. Thrombocytopenia and qualitative platelet defects are common. Defects in bleeding time, clot retraction, and platelet aggregation to a variety of mediators have all been described. Platelet count and platelet aggregation response to ADP are inversely correlated with hematocrit and positively correlated with arterial oxygen saturation. In cyanotic patients, generation of platelet microparticles, hypofibrinogenemia, low-grade disseminated intravascular coagulation (DIC), deficiencies in factors V and VIII, and deficiencies in the vitamin-K-dependent factors (II, VII, IX, X) have all been implicated in the genesis of coagulapathy. In patients who are cyanotic and erythrocytotic, the plasma volume and quantity of coagulation factors are reduced, and this may contribute to the development of a coagulopathy. In some instances, erythrophoresis with whole blood removed and replaced with fresh frozen plasma or isotonic saline may be justified.

In addition to the defects induced by cyanosis, defects inherent to normal infants and to children with congenital heart disease are present. Neonatal platelets are hypo-reactive to thrombin (the most potent platelet agonist), epinephrine/ADP, collagen, and thromboxane A_2. In addition, neonatal fibrinogen is dysfunction as compared to older children and adults. An acquired deficiency of the large von Willebrand multimers has been demonstrated in patients with congenital heart disease. Finally, factors synthesized in the liver may be reduced in both cyanotic and acyanotic patients in whom severe right heart failure results in passive hepatic congestion and secondary parenchymal disease.

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