Chapter

25 CARDIOVASCULAR DISEASE

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Cardiovascular disease is the leading cause of global death with an estimated 17 million deaths per year, and by 2030 this number could be more than 23 million. It is the leading cause of death in the United States.[1,2] Many of the risk factors identified to predict perioperative fatality are cardiovascular in origin. Coronary artery disease (CAD), peripheral vascular disease (PVD), and risk for CAD increase operative risk.[3,4] Recent myocardial infarction, the presence of congestive heart failure (CHF), and aortic stenosis are among the most important risk factors. Management of anesthesia for patients with cardiovascular disease requires an understanding of the pathophysiology of the disease process, appropriate preoperative testing, application of perioperative risk reduction strategies, and careful selection of anesthetic, analgesic, neuromuscular, and autonomic blocking drugs. The use of appropriate monitors to match the needs created by cardiovascular disease is very important.

CORONARY ARTERY DISEASE

CAD (ischemic heart disease), often asymptomatic, is a common accompaniment of aging in the American

population (also see Chapter 35). Of the adult patients who undergo surgery annually in the United States, about 40% will either have or be at risk for CAD.[1] The presence of CAD in patients who undergo anesthesia for noncardiac surgery may be associated with increased morbidity and mortality rates. History, physical examination with specific attention to cardiac and respiratory disease, and cardiac risk factors are very important. In addition, determination of the presence of the patient's exercise tolerance, cardiac symptoms, and electrocardiogram (ECG) are important components of the routine preoperative cardiac evaluation (also see Chapter 13).[5] The presence of symptoms of cardiac disease include shortness of breath with exercise in men and fatigue in women. People with severe CAD frequently state that they have no chest pain or shortness of breath with walking or activity. When asked about walking up stairs, they readily admit to shortness of breath. The presence of angina, angina at rest, orthopnea, paroxysmal nocturnal dyspnea, and dizziness or fainting can also be signals of cardiovascular disease.

More specialized procedures, such as ambulatory ECG monitoring (Holter monitoring), exercise stress testing, transthoracic or transesophageal echocardiography (TEE), radionuclide ventriculography (determination of ejection fraction), dipyridamole-thallium scintigraphy (mimics the coronary vasodilator response but not the heart rate response associated with exercise), cardiac catheterization, and angiography, are performed on selected patients. There is no evidence that invasive preoperative testing adds appreciably to the information provided by routine history and physical examination and electrocardiographic data for predicting adverse outcomes.[1] For example, echocardiographic determination of ejection fraction may not provide information that improves upon the ability to predict the presence of a preoperative myocardial infarction beyond that provided by a careful preoperative clinical evaluation.[6] Thallium scintigraphy, which evaluates adequacy of coronary blood flow, does not predict patients at risk for perioperative cardiac events.[7,8] Ultimately, the history and physical examination with specific attention to signs and symptoms of new onset of angina, change in anginal pattern, unstable angina, recent myocardial infarction, CHF, or aortic stenosis, and presence of appropriate medical therapy should determine whether patients are in the best medical condition possible before elective cardiac or noncardiac surgery.[6]

Patient History

Important aspects of the history taken from patients with CAD before noncardiac surgery include cardiac reserve, characteristics of angina pectoris, the presence of a prior myocardial infarction, and the medical, interventional cardiology, prior percutaneous coronary intervention (PCI), and cardiac surgical therapy for those conditions. Potential interactions of medications used in the treatment of CAD with drugs used to produce anesthesia must also be considered. Coexisting noncardiac diseases that are often present in these patients include hypertension, PVD, chronic obstructive pulmonary disease (COPD) from cigarette smoking, renal dysfunction associated with chronic hypertension, and diabetes mellitus. As stated previously, a thorough evaluation is especially important because patients can remain asymptomatic despite 50% to 70% stenosis of a major coronary artery.

Cardiac Reserve

Limited exercise tolerance in the absence of significant pulmonary disease is the most striking evidence of decreased cardiac reserve. Inability to lie flat, awakening from sleep with angina or shortness of breath, or angina at rest or with minimal exertion are evidence of significant cardiac disease. If a patient can climb two to three flights of stairs without symptoms, cardiac reserve is probably adequate. It is very common for patients with severe CAD requiring revascularization to state that they are able to walk as much as they would like but then admit to not being able to climb a single flight of stairs without shortness of breath. The ability to walk slowly on level ground requires only minimal exertion.

Angina Pectoris

Angina pectoris is considered to be stable when no change has occurred for at least 60 days in precipitating factors, frequency, and duration. Chest pain or shortness of breath produced with less than normal activity or at rest, or increasing in frequency, or lasting for increasingly longer periods is considered characteristic of unstable angina pectoris and may signal an impending myocardial infarction. Dyspnea following the onset of angina pectoris may be indicative of acute left ventricular dysfunction due to myocardial ischemia. Angina pectoris due to spasm of the coronary arteries (variant or Prinzmetal angina) differs from classic angina pectoris in that it may occur at rest and then be absent during vigorous exertion. Silent myocardial ischemia does not evoke angina pectoris (asymptomatic) and usually occurs at a heart rate and systemic arterial blood pressure less than those present during exercise-induced myocardial ischemia. About 70% of ischemic episodes are not associated with angina pectoris and as many as 15% of acute myocardial infarctions are silent. Women and diabetics are more likely to have painless myocardial ischemia and infarctions. The most common angina symptom in men is shortness of breath with exertion (e.g., stair climbing), and the most common symptom in women is fatigue.

The heart rate and systolic blood pressure at which angina pectoris or evidence of myocardial ischemia is indicated on the ECG are useful preoperative information. An increased heart rate is more likely than

hypertension to produce signs of myocardial ischemia (Fig. 25.1). Tachycardia increases myocardial oxygen requirements while at the same time decreases the duration of diastole, thereby decreasing left ventricular coronary blood flow, which occurs in diastole, and the delivery of oxygen to the left ventricle. Conversely, increased systolic and diastolic blood pressure, while increasing oxygen consumption, simultaneously increases coronary perfusion despite the presence of atherosclerotic coronary arteries.

Prior Myocardial Infarction

The incidence of myocardial reinfarction in the perioperative period is related to the time elapsed since the previous myocardial infarction (Table 25.1).[9-12] The incidence of perioperative myocardial reinfarction generally does not stabilize at 5% to 6% until 6 months after the prior myocardial infarction. Thus, a common recommendation is to delay elective surgery, especially thoracic, upper abdominal, or other major procedures, for a period of 2 to 6 months after a myocardial infarction.[6] The exact duration of suggested delay is not clear. Even after 6 months, the 5% to 6% incidence of myocardial reinfarction is about 50 times higher than the 0.13% incidence of perioperative myocardial infarction in patients undergoing similar operations but in the absence of a prior myocardial infarction.[13] Most perioperative myocardial reinfarctions occur in the first 48 to 72 hours postoperatively. However, if ischemia is initiated by the stress of surgery, there can be an increased risk of myocardial infarction for several months after surgery.[3,14]

Several factors influence the incidence of myocardial infarction in the perioperative period. For example, the incidence of myocardial reinfarction is increased in patients undergoing intrathoracic or intraabdominal operations lasting longer than 3 hours. Factors that do not predispose to a myocardial reinfarction include the (1) site of the previous myocardial infarction, (2) history of prior aortocoronary bypass graft surgery, (3) site of the operative procedure if the duration of the surgery is shorter than 3 hours, and (4) techniques used to produce anesthesia. In patients with CAD or PVD, appropriate use of β-adrenergic blocking drugs reduces the risk of cardiac morbidity (myocardial infarction or cardiac death) (also see Chapter 6).[6] Statin therapy with fluvastatin for 30 days before and after surgery, in addition to β-adrenergic blockade, reduces risk of myocardial infarction and death by an additional 50%.[15] Intensive hemodynamic monitoring using an intra-arterial catheter and prompt pharmacologic intervention or fluid infusion to treat physiologic hemodynamic alterations from the normal range may decrease the risk of perioperative cardiac morbidity in high-risk patients (see Table 25.1).[11]

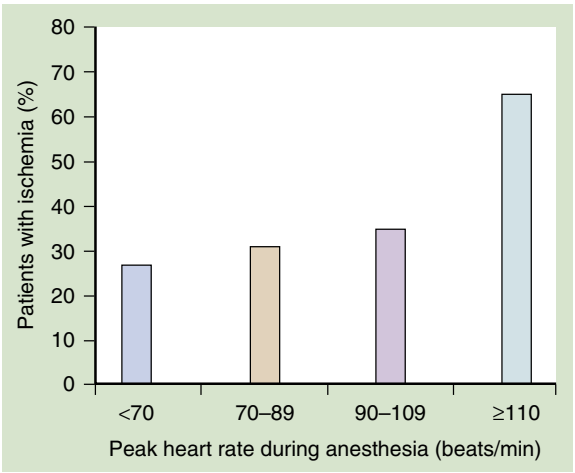

Fig. 25.1 The incidence of myocardial ischemia increases with heart rates with the greatest effect at heart rates above 110 beats/min. (From Slogoff S, Keats AS. Does chronic treatment with calcium entry blocking drugs reduce perioperative myocardial ischemia? *Anesthesiology.* 1988;68:676-680, used with permission.)

Current Medications

Drugs most likely to be taken by patients with CAD are β-adrenergic antagonists, nitrates, calcium channel blockers, angiotensin-converting enzyme inhibitors, drugs that decrease blood lipids, diuretics, antihypertensives, and platelet inhibitors. Knowledge of the pharmacology of these drugs and potential adverse interactions with anesthetics is an important preoperative consideration (see Chapters 6 and 8). Accordingly, patients with known CAD, known PVD, or those receiving β-adrenergic blocking drugs should be monitored throughout the perioperative

Table 25.1 Incidence of Perioperative Myocardial Infarction

Time Elapsed Since Previous Myocardial Infarction	Reported Incidence			
	Tarhan et al[9]	Steen et al[10]	Rao et al[11]	Shah et al[12]
0-3 months	37%	27%	5.7%	4.3%
4-6 months	16%	11%	2.3%	0
>6 months	5%	6%		5.7%

Table 25.2 Area of Myocardial Ischemia as Reflected by the Electrocardiogram

Electrocardiogram Leads	Coronary Artery Responsible for Myocardial Ischemia	Area of Myocardium That May Be Involved
II, III, aVF	Right coronary artery	Right atrium Sinus node Atrioventricular node Right ventricle
V_3-V_5	Left anterior descending coronary artery	Anterolateral aspects of the left ventricle
I, aVL	Circumflex coronary artery	Lateral aspects of the left ventricle

period.[6] Although COPD is not a contraindication to perioperative β-adrenergic blockade,[16,17] reactive asthma is. Patients with CAD or vascular disease should receive a statin type of drug unless there is a specific contraindication.[15] Despite the potential for adverse drug interactions, cardiac medications being taken preoperatively should be continued without interruption through the perioperative period. Discontinuation of β-adrenergic blockers,[18] calcium channel blockers, nitrates, statins, angiotensin-converting enzyme inhibitors,[19,20] or angiotensin receptor blockers[21] in the perioperative period can increase risk of perioperative morbidity and mortality and should not be discontinued.

Electrocardiogram

Preoperative evaluation of a resting 12-lead ECG is reasonable for patients with known coronary heart disease, significant arrhythmia(s), peripheral arterial disease, cerebrovascular disease, or other significant structural heart disease and may be indicated for some asymptomatic patients without known coronary heart disease (also see Chapter 20). Preoperative resting 12-lead ECG is not indicated in patients undergoing low-risk surgery.[6] The preoperative ECG should be examined for evidence of (1) myocardial ischemia, (2) prior myocardial infarction, (3) cardiac hypertrophy, (4) abnormal cardiac rhythm and conduction disturbances, and (5) electrolyte abnormalities. The exercise ECG simulates sympathetic nervous system stimulation as may accompany perioperative events such as direct laryngoscopy, tracheal intubation, surgical incision, postoperative pain, and recovery. The resting ECG in the absence of angina pectoris may be normal despite extensive CAD. Nevertheless, an ECG demonstrating ST-segment depression more than 1 mm, particularly during angina pectoris, confirms the presence of myocardial ischemia. Furthermore, the ECG lead demonstrating changes of myocardial ischemia can help determine the specific diseased coronary artery (Table 25.2). It is of particular importance that a prior myocardial infarction, especially if subendocardial, may not be accompanied by persistent changes on the ECG. The preoperative presence of ventricular premature beats may signal their likely occurrence intraoperatively. A prolonged PR interval on the ECG (longer than 200 ms) may be related to medication therapy such as amiodarone, digoxin, pregabalin, or dolasetron. Conversely, the block of conduction of cardiac impulses below the atrioventricular node (right bundle branch block, left bundle branch block, or intraventricular conduction delay) most likely reflects pathologic changes rather than drug effect.

Risk Stratification Versus Risk Reduction

One of the standard approaches to the perioperative care of patients with cardiac disease is risk stratification. Risk stratification consists of a preoperative history and physical examination followed by some series of tests thought to predict perioperative cardiac morbidity and mortality risks. These tests may include persantine thallium, echocardiography, Holter monitoring, dobutamine stress echocardiography, and angiography and may lead to angioplasty with or without an intracoronary stent or coronary artery bypass surgery. Yet, preoperative risk stratification with invasive testing may not be superior to a careful history and physical examination followed by prophylactic medical therapy.[6-8,17,22] Furthermore, combining the risk of angiography and an intracoronary stent or coronary artery bypass graft (CABG) to a surgical procedure may not reduce total risk.[6,23,24] The combined risk of two procedures may exceed that of the original operation.[23,25,26] Despite the lack of proven benefit of prophylactic invasive testing combined with either CABG or coronary angioplasty with stenting over medical therapy, the American College of Cardiology (ACC) and American Heart Association (AHA) have developed a protocol entitled ACC/AHA Guideline Perioperative Cardiovascular Evaluation for Noncardiac Surgery.[6,27-30] Fig. 25.2 provides a suggested protocol for preoperative evaluation. Unfortunately, the ACC/AHA protocol has been studied and found to be difficult to apply in practice with conflicting guidance on indications for testing with physicians ordering more tests than suggested by the guidelines.[31] Perioperative risk reduction therapy with β-adrenergic blockers and

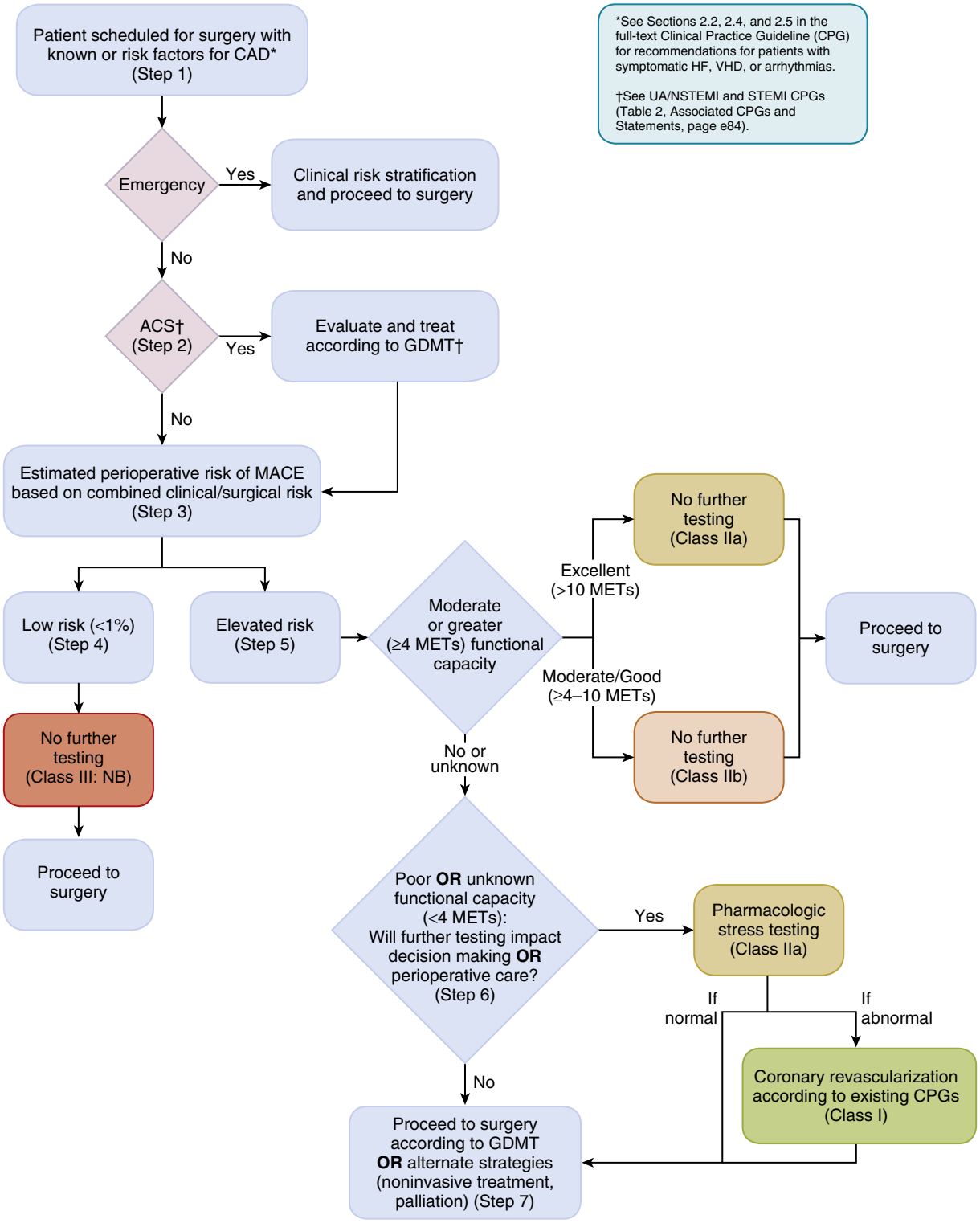

Fig. 25.2 Stepwise approach to perioperative cardiac assessment for coronary artery disease (CAD). *ACS*, Acute coronary syndrome; *CPG*, clinical practice guideline; *GDMT*, guideline-directed medical therapy; *HF*, heart failure; *MACE*, major adverse cardiac event; *MET*, metabolic equivalent; *NB*, no benefit; *STEMI*, ST-segment elevation myocardial infarction; *UA/NSTEMI*, unstable angina/non–ST-segment elevation myocardial infarction; *VHD*, valvular heart disease. (From Fleisher L, Fleischmann K, Auerbach AD, et al. 2014 ACC/AHA Guideline on Perioperative Cardiovascular Evaluation and Management of Patients Undergoing Noncardiac Surgery. A report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines. *J Am Coll Cardiol*. 2014;64(22):e77-e137.)

statins may be superior to risk stratification with invasive testing, angioplasty, and CABG.[6,15-17,23,32-35]

Perioperative Cardiac Risk Reduction Therapy

There is some controversy after the publication of the POISE study on the use of prophylactic perioperative β-adrenergic blockade.[36,37] Continuation of anti-ischemic drugs in the perioperative period is recommended.[6,32,33] Perioperative use of β-adrenergic blockers in patients with known CAD or PVD is recommended.[6] Prophylactic addition of β-adrenergic blockers to patients at risk for CAD is recommended in patients with significant cardiac risk (revised cardiac risk index [RCRI] ≥ 3) and in those patients with intermediate- or high-risk preoperative tests.[6] If initiation of β-adrenergic blocker administration is planned, it should begin long enough in advance of surgery to assess safety and tolerability, preferably more than 1 day.[6] Large-dose β-adrenergic blocker[36,37] therapy should not be started on the day of surgery.[6,16,17] The following β-adrenergic blocker protocol[14,17] has been tested in 40,000 patients and has been shown to reduce risk.[32,33]

1. All patients who have either CAD, PVD, or two risk factors for CAD (age ≥ 60 years, cigarette smoking, diabetes, hypertension, cholesterol ≥ 240 mg/dL) should receive perioperative β-adrenergic blockade unless they have a specific intolerance to β-adrenergic blockers. Patients with renal failure or renal insufficiency may also benefit from therapy.
2. β-Adrenergic blockade should be started as soon as the patient is identified as having CAD, PVD, or risk factors. If the surgeon identifies the patient as having risk, the surgeon should start the medication. If the anesthesia preoperative clinic identifies the patient, it should be started in the preoperative clinic (also see Chapter 13). If the patient is not identified until the morning of surgery, intravenous atenolol or metoprolol should be used. If the drug is started prior to the day of surgery, atenolol 25 mg by mouth (PO) per day (qd) is an appropriate starting dose.
3. β-Adrenergic blockade should be continued until at least 30 days postoperatively, if not indefinitely, in patients with CAD or PVD. In patients with only risk factors, 7 days may be sufficient.
4. The optimal time to start β-adrenergic blockade is at the time of identification of the risk. This process should be multitiered to avoid missing patients. The following approach should be used to provide the maximum benefit at the minimum cost.
   a. The surgeon should give a β-adrenergic blocker if the patient has CAD, PVD, or two risk factors. Atenolol 25 mg PO daily is an appropriate starting dose.
   b. If a medical or cardiology consult is requested by surgery, the most common advice is: start a β-adrenergic blocker.
   c. The anesthesia preoperative clinic checks to see if the patients at risk are receiving a β-adrenergic blocker. If the patient is not getting adequate β-adrenergic blockade, the dose is increased.
   d. On the day of surgery, treatment with or increasing the dose of intravenously (IV) administered β-adrenergic blockers should be considered. Intravenous metoprolol in 5-mg boluses is used. Standard dose is 10 mg IV (withhold for heart rate less than 50 beats/min or systolic blood pressure less than 100 mm Hg). Intraoperative doses are used as needed. The patient should receive additional doses in the postanesthesia care unit as needed.
   e. The patient should receive the drug postoperatively for 30 days. If the patient is nil per os (NPO, or nothing by mouth), the patient receives intravenous metoprolol (10 mg IV q12h) unless systolic blood pressure is less than 100 mm Hg or heart rate is less than 50 beats/min. If the patient is taking oral medications, the patient receives atenolol 100 mg PO daily if the heart rate is more rapid than 65 beats/min and the systolic blood pressure is more than 100 mm Hg. If the heart rate is between 55 and 65 beats/min, the dose is 50 mg. There is a hold order for heart rate less than 50 beats/min or systolic blood pressure less than 100 mm Hg.
   f. The patient remains on the drug for at least 30 days postoperatively.
   g. Many patients should remain on the drug for life (patients with known CAD, known PVD, and hypertension).
5. Preoperative testing and revascularization[26] should only be used as needed for specific indications not prophylaxis.[38] If a patient is identified with new-onset angina, unstable angina, a change in the anginal pattern, or CHF, then further risk stratification is appropriate. If the patient is stable with known CAD, PVD, or two risk factors for CAD, the patient should receive a β-adrenergic blocker.[16,17,32,33]
6. Care should be taken with patients who have CHF, aortic stenosis, intracoronary stents on platelet inhibitors, or renal failure. All patients who have CHF should be evaluated by a cardiologist for the initiation of β-adrenergic blocker therapy. β-Adrenergic blocker therapy reduces the risk of death from CHF. Many patients with CHF are profoundly improved by β-adrenergic blockade; however, the dose must be titrated slowly and usually under the supervision of a cardiologist. Patients with aortic stenosis should be evaluated by cardiology and β-adrenergic blockade initiated with a cardiologist's supervision.
7. Patients with intracoronary stents on platelet inhibitors should be seen by a cardiologist. WARNING: Discontinuation of platelet inhibitors in patients with intracoronary stents can be lethal.[24,39,40] Patients with renal failure should be treated with appropriate drugs, but special attention is needed.

8. Patients with an indication for statin therapy and especially those with known CAD or PVD should be considered for statin therapy.[15] Therapy should be started 30 days prior to surgery and continued for at least 30 days after surgery,[15] possibly indefinitely.

Management of Anesthesia

Anesthesia care for patients with known CAD, known PVD, or two risk factors for CAD (age ≥ 60 years, hypertension, diabetes, significant smoking history, or hyperlipidemia) should begin as soon as the patient is identified as needing surgery.[16,17,32,33] All patients with new-onset angina, a change in anginal pattern, unstable angina, angina without medical therapy, aortic stenosis, CHF, or an intracoronary stent receiving a platelet inhibitor should be referred to cardiology. Patients with recently placed intracoronary stents receiving platelet inhibitors have a high risk of intracoronary thrombosis and death when the platelet inhibitors are discontinued for perioperative care.[24,39,40] Patients with bare metal stents may require 3 or more months of antiplatelet therapy.[40] Patients with drug-eluting intracoronary stents may require platelet inhibitors for a year or more.[39] Patients with stable coronary disease on medical therapy with no evidence of CHF or aortic stenosis should receive an oral β-adrenergic blocker (atenolol or metoprolol 25 mg/day PO) and a statin drug.[15] Patients with CHF should have β-adrenergic blockers initiated by cardiology over a prolonged period. The dose of β-adrenergic blockers should be increased as tolerated. β-Adrenergic blockers should be avoided in patients with a history of high-grade atrioventricular (AV) block without a pacemaker, reactive asthma, or an intolerance for β-adrenergic blockers. Diabetes is an indication for perioperative β-adrenergic blockade. For maximal effect, β-adrenergic blockers should be started as soon as the patient is identified as needing surgery.[14,17] Starting high-dose β-adrenergic blockers on the day of surgery is not indicated.[6,36,37] If a patient is identified on the day of surgery, intravenous atenolol or metoprolol can be started in the preoperative area (atenolol or metoprolol 10 mg IV if the heart rate is more rapid than 55 beats/min or systolic blood pressure is higher than 100 mm Hg) and continued postoperatively.[16] Perioperative β-adrenergic blockers should be continued for at least 7 days postoperatively.[16] In patients with higher risks (those with known CAD or PVD), β-adrenergic blockers should be continued at least 30 days if not indefinitely.[14,17] Esmolol boluses during surgery do not constitute perioperative β-adrenergic blockade and are not adequate to reduce perioperative cardiac risk.[41] Appropriate dosing of β-adrenergic blockers is prudent to avoid sequelae related to hypotension and bradycardia.[37]

The intraoperative anesthetic management as well as postoperative pain management (also see Chapter 40) of patients with CAD should permit the modulation of sympathetic nervous system responses and provide for the rigorous control of hemodynamic variables.[1] Management of anesthesia in these patients is based on a preoperative evaluation of left ventricular function and the maintenance of a favorable balance between myocardial oxygen requirements and myocardial oxygen delivery so as to prevent myocardial ischemia (Table 25.3 and Box 25.1). Any event associated with persistent tachycardia, systolic hypertension, arterial hypoxemia, or diastolic hypotension can adversely influence this delicate balance. Heart rate higher than 100 beats/min increases the risk of postoperative death in patients with risk for CAD; heart rates higher than 120 beats/min significantly increase risk.

Persistent and excessive changes in heart rate and systemic arterial blood pressure should be minimized (see Fig. 25.1).[42] Maintaining heart rate and systemic arterial blood pressure within 20% of the awake values is commonly recommended. Monitoring with an intra-arterial catheter greatly improves the ability to maintain stable systemic arterial blood pressures. Nevertheless, an estimated one half of all new perioperative ischemic episodes are not preceded by or associated with significant changes in heart rate or systemic arterial blood pressure.[43]

Table 25.3 Evaluation of Left Ventricular Function

Assessment Feature	Good Function	Impaired Function
Previous myocardial infarction	No	Yes
Evidence of congestive heart failure	No	Yes
Ejection fraction	>0.55	<0.4
Left ventricular end-diastolic pressure	<12 mm Hg	>18 mm Hg
Cardiac index	>2.5 L/min/m^2	<2 L/min/m^2
Areas of ventricular dyskinesia	No	Yes

Box 25.1 Determinants of Myocardial Oxygen Requirements and Delivery

Myocardial Oxygen Requirements
- Heart rate
- Systolic blood pressure
- Myocardial contractility
- Ventricular volume

Myocardial Oxygen Delivery
- Coronary blood flow
- Oxygen content of arterial blood

A single 1-minute episode of myocardial ischemia detected by a 1-mm ST-segment elevation or depression increases the risk of cardiac events 10-fold and the risk for death 2-fold.[3,4] Tachycardia for 5 minutes above 120 beats/min in the postoperative period can increase the risk of death 10-fold. The only clinically proven method to reduce the risk of perioperative myocardial ischemia and associated death is perioperative β-adrenergic blockade (atenolol or metoprolol).[16,17,32,33]

Monitoring (Also See Chapter 20)

Anticipation of problems and avoidance of potential disasters are key components for successful anesthetic management of patients with cardiovascular disease. Prophylactic therapy and more extensive monitoring reduce risk. Continuous intra-arterial pressure monitoring can reduce the risk of hemodynamic events by early identification of problems. Continuous ECG monitoring rapidly identifies arrhythmias, tachycardia, and myocardial ischemia. Monitoring should be continuous if possible. Rapid changes in hemodynamics can quickly lead to cardiac arrest; monitoring can quickly identify those changes and permits prompt therapy before further complications develop. When operations are completed, monitoring should be continued into the recovery room or intensive care unit (ICU). When patients are transferred from the operating room table to the gurney or ICU bed, or are turned from supine to prone or back to supine, monitoring should be as continuous as possible. Unconscious patients with cardiac disease may have rapid hemodynamic collapse with transfers from the operating room table to the gurney or ICU bed or when turned over and should be monitored during transfers. If arterial blood pressure, ECG, and saturation are monitored, the problem can be quickly identified and corrected prior to serious sequelae. Intravascular volume, vasoconstrictors, β-agonists, β-adrenergic blockers, anticholinergics, and vasodilator drugs should be immediately available. Loss of a pulse oximeter signal or desaturation can imply hypoxia or inadequate arterial blood pressure or cardiac output and should signal an immediate search for a cause and initiation of corrective action. The pulse oximeter is a monitor of both oxygen saturation and perfusion. If the pulse oximeter loses a signal, adequacy of perfusion should be assessed. Loss of the pulse oximeter signal may occur simply from the finger becoming cold, or much more importantly, may be the first warning of hemodynamic collapse. Continuous monitoring and prophylactic therapy can reduce the risk in patients with cardiovascular disease.

The intensity of monitoring in the perioperative period is influenced by the complexity of the operative procedure and the severity of the cardiovascular disease. The five-lead ECG serves as a noninvasive monitor of the balance between myocardial oxygen requirements and myocardial oxygen delivery in unconscious patients (also see Chapter 20). When this balance is unfavorably altered, myocardial ischemia occurs, as evidenced on the ECG by at least a 1-mm downsloping of the ST segment from the baseline. A precordial V_5 lead is a useful selection for detecting ST-segment changes characteristic of ischemia of the left ventricle during anesthesia. Intra-arterial pressure monitoring can speed the identification and treatment of hemodynamic changes. Monitoring should be continuous if possible. Ventricular wall motion abnormalities observed by TEE may be the most sensitive indicator of myocardial ischemia, but this monitor is expensive, is invasive, and requires additional training before its use as a routine method for detecting an imbalance between myocardial oxygen delivery and myocardial oxygen requirements. Intraoperative monitoring of pulmonary artery pressures or use of TEE should be reserved for selected high-risk patients (cardiac surgery, recent myocardial infarction, current CHF, unstable angina).[1] Continuous cardiac output monitoring with stroke volume variation (SVV) measurement of fluid responsiveness may improve intravascular fluid management.[44]

Induction of Anesthesia

Preoperative anxiety can lead to preoperative myocardial ischemia.[41] Myocardial ischemia predisposes to subsequent myocardial ischemia. Preoperative β-adrenergic blocker therapy reduces the incidence of myocardial ischemia.[17,41] Patients should receive their routine medications except for oral hypoglycemic drugs. Preoperative sedative medication is intended to produce sedation and reduce anxiety, which, if unopposed, could lead to secretion of catecholamines and an increase in myocardial oxygen requirements because of an increase in heart rate and systemic arterial blood pressure. Oral administration of benzodiazepines (diazepam or lorazepam PO) is an effective pharmacologic approach to allay severe anxiety. Supplemental oxygen may be needed if narcotics are combined with benzodiazepines for sedation.

Induction of anesthesia is acceptably accomplished with the intravenous administration of rapidly acting drugs. Preinduction placement of an intra-arterial catheter to monitor arterial blood pressure allows rapid pharmacologic manipulations and a very stable induction of anesthesia. An infusion of phenylephrine (0.2 to 0.4 μg/kg/min) started prophylactically stabilizes arterial blood pressure and can eliminate most hemodynamic changes with induction. Etomidate is a popular anesthetic to induce anesthesia because of its limited inhibition of the sympathetic nervous system and limited hemodynamic effects[45] (also see Chapter 8). The lack of inhibition of autonomic reflexes by etomidate may lead to hypertension with laryngoscopy and endotracheal intubation. Propofol is popular secondary to its antiemetic effects and rapid recovery, but the dose should be reduced to avoid hypotension with induction. Fentanyl and midazolam in combination with an infusion of phenylephrine and a

nondepolarizing muscle relaxant cause minimal associated changes in arterial blood pressure or heart rate.

Ketamine is not often used to induce anesthesia for patients with coronary disease because of the associated increase in heart rate and systemic arterial blood pressure, which may increase myocardial oxygen requirements. When giving desflurane, the inspired concentration should be slowly increased to avoid sympathetic stimulation and associated tachycardia, pulmonary hypertension, myocardial ischemia, and bronchospasm.[46] Tracheal intubation is facilitated by the administration of succinylcholine or a nondepolarizing neuromuscular blocking drug (also see Chapter 11).

Myocardial ischemia may accompany the tachycardia and hypertension that result from the stimulation of direct laryngoscopy as necessary for tracheal intubation. Adequate anesthesia and a brief duration of direct laryngoscopy are important in minimizing the magnitude of these circulatory changes. When the duration of direct laryngoscopy is not likely to be brief, or when hypertension coexists, the addition of other drugs to minimize the pressor response produced by tracheal intubation should be considered. For example, laryngotracheal lidocaine (2 mg/kg) administered just before placing the tube in the trachea produces rapid topical anesthesia of the tracheal mucosa and minimizes the magnitude and duration of the systemic arterial blood pressure increase. Alternatively, lidocaine (1.5 mg/kg IV), administered just before initiating direct laryngoscopy, is efficacious (also see Chapter 16).

Administration of opioids (fentanyl, sufentanil, alfentanil, or remifentanil) before initiating direct laryngoscopy reduces the stimulation produced by tracheal intubation. β-Adrenergic blockers are effective in attenuating heart rate increases associated with tracheal intubation. Tachycardia should be avoided in all patients with coronary disease, vascular disease, or risk factors for coronary disease.

Maintenance of Anesthesia

The choice of anesthesia is often based on the patient's left ventricular function (see Table 25.3). For example, patients with CAD but normal left ventricular function may develop tachycardia and hypertension in response to intense stimulation. Controlled myocardial depression produced by a volatile anesthetic with or without nitrous oxide may be appropriate if the primary goal is to prevent increased myocardial oxygen requirements. Equally acceptable for maintenance of anesthesia is the use of a nitrous oxide–opioid technique with the addition of a volatile anesthetic as necessary to treat acute increases in systemic arterial blood pressure as produced by a change in the level of surgical stimulation. When hypertension is treated with a volatile anesthetic (isoflurane, desflurane, sevoflurane), the drug-induced decrease in systemic vascular resistance (SVR) is more responsible for decreases in systemic arterial blood pressure than is drug-induced myocardial depression. The ability to rapidly increase the alveolar concentration of sevoflurane makes this drug uniquely efficacious for treating sudden increases in systemic arterial blood pressure. Abrupt and large increases in the delivered concentrations of desflurane may be accompanied by stimulation of the sympathetic nervous system and transient increases in systemic arterial blood pressure, heart rate, pulmonary hypertension, and myocardial ischemia[51] (also see Chapter 7).

Volatile anesthetics are vasodilators. Under unusual clinical circumstances, potent coronary vasodilators can divert blood flow from ischemic areas of myocardium (blood vessels already fully dilated) to nonischemic areas of myocardium supplied by vessels capable of vasodilation. Regional myocardial ischemia associated with drug-induced vasodilation is known as coronary artery steal. There are reports that the incidence of myocardial ischemia is either unchanged or increased in patients with CAD and anesthetized with isoflurane compared with those receiving a different volatile anesthetic or an opioid-based anesthetic.[47-49] Volatile anesthetics to varying degrees (halothane, isoflurane, sevoflurane, and desflurane) induce ischemic preconditioning and may protect the myocardium from subsequent ischemia.[50,51] All facts considered, volatile anesthetics may be either beneficial in patients with CAD because they decrease myocardial oxygen requirements and induce ischemic preconditioning, or detrimental because they decrease systemic arterial blood pressure and coronary perfusion pressure or produce coronary artery steal (isoflurane) or tachycardia (desflurane).[46] A large clinical trial in patients undergoing cardiac surgery failed to demonstrate a difference between halothane, enflurane, isoflurane, and narcotic-based anesthetics.[52] Avoiding tachycardia with the use of long-acting β-adrenergic blockers (metoprolol or atenolol) is more important than anesthetic choice.[16,17,32,33] Intraoperative bolus doses of short-acting β-adrenergic blockers (esmolol) have not been shown to be effective in reducing perioperative cardiac risk. Prophylactic perioperative administration of long-acting β-adrenergic blockers (metoprolol or atenolol) is needed to reduce perioperative risk.[41]

Patients with impaired left ventricular function, as associated with a prior myocardial infarction, may not tolerate direct myocardial depression produced by volatile anesthetics. In these patients, the use of short-acting opioids with nitrous oxide may be a more acceptable selection. Nitrous oxide, when administered to patients who have received opioids for anesthesia, may produce undesirable decreases in systemic arterial blood pressure and cardiac output. High-dose fentanyl (50 to 100 μg/kg IV) or equivalent doses of sufentanil or alfentanil as the primary anesthetic with benzodiazepines added to ensure amnesia may be useful for patients who cannot tolerate the myocardial depression from even low concentrations

of anesthesia. Yet, this technique is not clearly better than moderate dose narcotics with an inhaled or intravenous anesthetic.[52] Infusions of dexmedetomidine combined with smaller-dose fentanyl (1-10 μg/kg) and inhaled anesthetics work well and apparently reduce postoperative delirium in patients undergoing CABG.[53]

A regional anesthetic is an excellent technique in patients with CAD (also see Chapters 17 and 18). Regional anesthesia for peripheral surgery (orthopedic, podiatric, peripheral vascular) and lower abdominal surgery (gynecologic and urologic) is a very safe technique for patients with cardiac risk. However, flow through critically narrowed coronary arteries is pressure-dependent. Therefore, decreases in systemic arterial blood pressure associated with a regional anesthetic that are more than 20% of the preblock value probably should be treated with an intravenous infusion of crystalloid solutions or a vasoconstrictor such as phenylephrine. Phenylephrine improves coronary perfusion pressure but at the expense of increasing afterload and myocardial oxygen requirements. Nevertheless, the increase in coronary perfusion pressure is likely to more than offset any increase in myocardial oxygen requirements. Perioperative β-adrenergic blockers should be used in patients with cardiac risk undergoing surgery using regional anesthesia.

Neuromuscular Blocking Drugs (Also See Chapter 11)

The choice of nondepolarizing neuromuscular blocking drugs during maintenance of anesthesia for patients with CAD may be influenced by the circulatory effects of these drugs. Vecuronium, rocuronium, and cisatracurium do not evoke histamine release and associated decreases in systemic arterial blood pressure, even with the rapid intravenous administration of large doses. Likewise, the systemic arterial blood pressure lowering effects of atracurium and mivacurium are usually modest, especially if the drug is injected over 30 to 45 seconds to minimize the likelihood of drug-induced histamine release. None of these neuromuscular blocking drugs will adversely alter myocardial oxygen requirements. Pancuronium increases heart rate and systemic arterial blood pressure, but these changes are usually less than 15% above predrug values, making this drug a possible choice for administration to patients with CAD. Furthermore, circulatory changes produced by pancuronium can be used to offset negative inotropic or chronotropic effects of drugs being used for anesthesia. In contrast to pancuronium, the other nondepolarizing neuromuscular blocking drugs would not be expected to offset decreases in systemic arterial blood pressure or heart rate as associated with the administration of large doses of opioids. With the increased use of more selective neuromuscular blocking drugs (vecuronium, rocuronium, and cisatracurium), use of pancuronium has markedly decreased and in some cases has been eliminated.

Nondepolarizing neuromuscular blockade in patients with CAD can be safely antagonized with anticholinesterase drugs (i.e., neostigmine) combined with an anticholinergic drug. Glycopyrrolate has more titratable chronotropic effects than atropine. Tachycardia after reversal of nondepolarizing muscle relaxants can still occur. One of the common causes of postoperative myocardial ischemia and infarction is tachycardia after emergence, which may be the result of the combination of emergence, surgical pain, and reversal of nondepolarizing muscle relaxants. The addition of long-acting intravenous β-adrenergic blockers should be used to avoid tachycardia, which may lead to myocardial ischemia in this period.

Sugammadex has been used in many countries and now the United States (also see Chapter 11 for details). Sugammadex does not have significant cardiovascular effects. Readers are advised to read the Food and Drug Administration (FDA) prescribing information, which provides an excellent description of its pharmacology.

Treatment of Myocardial Ischemia

The appearance of signs of myocardial ischemia on the ECG supports the aggressive treatment of adverse changes in heart rate or systemic arterial blood pressure. Only 5% of perioperative myocardial ischemia found on Holter ECG is identified by clinicians. Prophylactic therapy with long-acting β-adrenergic blockers is essential to reduce perioperative risk.[16,17,32,33] Tachycardia is treated with the administration of atenolol, metoprolol, propranolol, or esmolol. Excessive increases in systemic arterial blood pressure respond to narcotics, increases in inhaled anesthetics, β-adrenergic blockers, or continuous intravenous infusion of nitroprusside. Nitroglycerin is a more appropriate choice than nitroprusside when myocardial ischemia is associated with a normal systemic arterial blood pressure. Hypotension should be treated with a phenylephrine infusion to rapidly restore pressure-dependent perfusion through atherosclerotic coronary arteries. In addition to drugs, the intravenous infusion of fluids to restore systemic arterial blood pressure can improve myocardial oxygen supply. A disadvantage of this approach is the time necessary for intravenous fluid treatment to be effective.

Although few or no data support the use of pulmonary artery catheters,[54,55] in selected patients a pulmonary artery catheter in combination with a TEE probe may be helpful for monitoring responses to intravenous fluid replacement and the therapeutic effects of drugs on left ventricular function and cardiac output. Continuous measurement of SVV or pulse pressure variation (PPV) can predict fluid responsiveness and be used to optimize fluid administration as part of goal-directed therapy. Right atrial (central venous) pressure does not predict left-sided heart volume status.[56] In healthy patients who have a reduced need for monitoring and in patients with CAD when the ejection fraction is higher than 0.5 and when there is no evidence of left ventricular dysfunction, right atrial pressure is more likely to correlate with pulmonary

artery occlusion pressure.[57,58] Pressures measured with pulmonary artery catheters correlate poorly with volume status in patients with diastolic dysfunction, myocardial ischemia, mitral regurgitation or stenosis, pulmonary hypertension, positive end-expiratory pressure (PEEP), pulmonary stenosis, or tricuspid regurgitation. Abrupt increases in the pulmonary artery pressure may also reflect acute myocardial ischemia or acute mitral regurgitation. When compared with TEE, monitoring with a pulmonary artery catheter is not a highly sensitive approach for detecting myocardial ischemia. TEE also provides an assessment of regional wall motion, global ventricular function, valvular function, intravascular fluid volume, and associated ventricular filling. TEE is more expensive than pulmonary artery catheterization, but the information is more accurate and useful than pulmonary artery catheter data.

Decreases in body temperature that occur intraoperatively may predispose to shivering on awakening, leading to abrupt increases in myocardial oxygen requirements. Attempts to minimize decreases in body temperature and provision of supplemental oxygen are of obvious importance. Postoperative pain relief is important as pain-induced activation of the sympathetic nervous system can increase myocardial oxygen requirements.

Postoperative Care

Postoperative care of the patient with CAD is based on provision of perioperative anti-ischemic drugs (β-adrenergic blockers, or statins), analgesia, and, if needed, sedation to blunt excessive sympathetic nervous system activity and facilitate rigorous control of hemodynamic variables (also see Chapter 39). Intensive and continuous postoperative monitoring is useful for detecting myocardial ischemia, which is often asymptomatic. Episodes of myocardial ischemia lead to increased risk and increasingly frequent occurrences.[3,17,59] Reducing the incidence of myocardial ischemia with β-adrenergic blockers reduces 30-day and 2-year mortality rates.[17,41] Patients with known CAD, known PVD, or two risk factors for CAD (≥60 years of age, hypertension, vascular disease, diabetes, significant smoking history, or hyperlipidemia) should be placed on a perioperative β-adrenergic blocker unless there is a specific contraindication.[16,17,32,33] They should receive β-adrenergic blockers as soon as they are identified as being at risk for cardiac complications.[6,16,17,32,33] Patients with a lower risk should take the drug for at least 7 days postoperatively.[16,17] Patients with known coronary disease or vascular disease should remain on the drug for at least 30 days if not permanently. COPD is not a contraindication to perioperative β-adrenergic blockade, but reactive asthma is. Diabetes is not a contraindication for perioperative β-adrenergic blockade; it is an indication. All medications have a therapeutic index and β-adrenergic blockers are no exception. The dose of perioperative β-adrenergic blockers should follow standard manufacturer guidelines to avoid hypotension, bradycardia, morbidity, and death.[37]

The major determinant of pulmonary complications (atelectasis, pneumonia) after cardiac surgery is poor cardiac function. Early mobilization and pain control are likely to minimize the incidence of clinically significant pulmonary complications.

VALVULAR HEART DISEASE

The most frequently encountered forms of valvular heart disease produce pressure overload (mitral stenosis, aortic stenosis) or volume overload (mitral regurgitation, aortic regurgitation).[60] The net effect of valvular heart disease is interference with forward flow of blood from the heart into the systemic circulation. TEE has revolutionized the evaluation and intraoperative management of valvular heart disease (Box 25.2). Selection of anesthetic drugs for patients with valvular heart disease is often based on the likely effects of drug-induced changes in cardiac rhythm, heart rate, systemic arterial blood pressure, SVR, and pulmonary vascular resistance (PVR) relative to maintenance of cardiac output in these patients. Although no specific general anesthetic is superior, when cardiac reserve is minimal, an anesthetic combination of opioids, an amnestic benzodiazepine, and an inhaled anesthetic is common. Dexmedetomidine infusions may be extremely useful in combination with other drugs. Patients with valvular heart disease should receive appropriate antibiotics in the perioperative period for protection against infective endocarditis. Monitoring intra-arterial pressure is helpful in patients with clinically significant valvular heart disease.

Mitral Stenosis

Mitral stenosis is characterized by mechanical obstruction of left ventricular diastolic filling secondary to a progressive decrease in the orifice of the mitral valve. The obstruction produces an increase in left atrial and pulmonary venous pressure. Increased PVR is likely when the left atrial pressure is chronically higher than 25 mm Hg. Distention of the left atrium predisposes to atrial fibrillation, which can result in stasis of blood, the formation

Box 25.2 Diagnosis: Echocardiography and Valvular Heart Disease

- Determine significance of cardiac murmurs (most often aortic stenosis).
- Identify hemodynamic abnormalities associated with physical findings (most often mitral regurgitation).
- Determine transvalvular pressure gradient.
- Determine cardiac valve regurgitation.
- Evaluate prosthetic valve function.

of thrombi, and systemic emboli. Chronic anticoagulation or antiplatelet therapy (or both) of patients with atrial fibrillation can reduce the risk of systemic embolic events. Mitral stenosis is commonly due to the fusion of the mitral valve leaflets during the healing process of acute rheumatic carditis. Symptoms of mitral stenosis do not usually develop until about 20 years after the initial episode of rheumatic fever. A sudden increase in the demand for cardiac output as produced by pregnancy or sepsis, however, may unmask previously asymptomatic mitral stenosis.

Patients with mitral stenosis who are being chronically treated with digitalis for the control of heart rate should continue to take this drug throughout the perioperative period. Adequate digitalis effect for heart rate control is generally reflected by a ventricular rate less than 80 beats/min. Because diuretic therapy is common in these patients, the serum potassium concentration should be measured preoperatively. Other common antiarrhythmic drugs such as β-adrenergic blockers should also be continued. The discontinuation of anticoagulant or antiplatelet therapy should be discussed with the surgeon and cardiologist. Patients should be switched from warfarin (Coumadin) therapy to heparin therapy prior to surgery depending on the type of case. Also, patients with mitral stenosis can be more susceptible than normal individuals to the ventilatory depressant effects of sedative drugs used for preoperative medication. If patients are given sedative drugs, supplemental oxygen may increase the margin of safety. Most medications that patients are taking, except anticoagulants, antiplatelet drugs, and oral hypoglycemic agents, should be continued throughout the preoperative period.

Management of Anesthesia

Preinduction of anesthesia placement of an intra-arterial pressure monitoring line can speed the identification and treatment of hemodynamic changes in patients with clinically significant valvular disease. Induction of anesthesia in the presence of mitral stenosis can be achieved with intravenous drugs, with the possible exception of ketamine, which may be avoided because of its propensity to increase the heart rate. Tracheal intubation is facilitated by the administration of a neuromuscular blocking drug. Drugs used for maintenance of anesthesia should cause minimal changes in heart rate and in SVR and PVR. Furthermore, these drugs should not greatly decrease myocardial contractility. No one anesthetic has been proved to be superior. These goals can be achieved with combinations of an opioid and low concentrations of a volatile anesthetic or intravenous anesthetics such as propofol or dexmedetomidine. Although nitrous oxide can increase PVR, this increase is not sufficient to justify avoiding this drug in all patients with mitral stenosis.[61] The effect of nitrous oxide on PVR, however, seems to be accentuated when coexisting pulmonary hypertension is severe. Avoiding the use of nitrous oxide allows higher inspired oxygen concentrations and may reduce pulmonary vasoconstriction. Rapid increases in the concentration of desflurane may cause tachycardia, bronchospasm, and pulmonary hypertension and should be avoided.[46] Control of arterial blood pressure with a prophylactic intravenous infusion of the vasoconstrictor phenylephrine can reduce hemodynamic changes with induction of anesthesia.

Nondepolarizing neuromuscular blocking drugs with minimal circulatory effects are useful in patients with mitral stenosis. The adverse effects of drug-induced tachycardia in response to drug-assisted antagonism of nondepolarizing neuromuscular blocking drugs should be avoided (Box 25.3). Sugammadex, which can replace neostigmine, does not cause cardiovascular changes. If cases are prolonged and neuromuscular blockade is not required for the conduct of the case, allowing the nondepolarizing neuromuscular blockade to be eliminated through metabolism may reduce the risk of tachycardia with drug-assisted antagonism. Intraoperative intravenous fluid therapy must be carefully titrated because these patients are susceptible to intravascular volume overload and to the development of left ventricular failure and pulmonary edema. Likewise, the head-down position may not be well tolerated because the pulmonary blood volume is already increased.

Monitoring intra-arterial pressure and SVV or PPV is a helpful guide to the adequacy of intravascular fluid replacement. If central pressures are measured, an increase in right atrial pressure could also reflect pulmonary vasoconstriction, suggesting the need to check for causes, which may include nitrous oxide, desflurane, acidosis, hypoxia, increased mitral regurgitation, or light anesthesia.

Postoperatively, patients with mitral stenosis are at high risk for developing pulmonary edema and right-sided heart failure. Mechanical ventilation may be necessary, particularly after major thoracic or abdominal surgery. The shift from positive-pressure ventilation to spontaneous ventilation with weaning and extubation may lead to increased venous return and increased central venous pressures with worsening of heart failure.

Box 25.3 Anesthetic Considerations in Patients With Mitral Stenosis

- Avoid sinus tachycardia or rapid ventricular response rate during atrial fibrillation.
- Avoid marked increases in central blood volume associated with overtransfusion or head-down position.
- Avoid drug-induced decreases in systemic vascular resistance.
- Avoid events such as arterial hypoxemia or hypoventilation that may exacerbate pulmonary hypertension and evoke right ventricular failure.

Mitral Regurgitation

Mitral regurgitation is characterized by left atrial volume overload and decreased left ventricular forward stroke volume due to the backflow of part of each stroke volume through the incompetent mitral valve back into the left atrium. This regurgitant flow is responsible for the characteristic V waves seen on the recording of the pulmonary artery occlusion pressure.[62] Mitral regurgitation secondary to rheumatic fever usually has a component of mitral stenosis. Dilated cardiomyopathy, which may be from ischemia, multiple myocardial infarctions, viral or parasitic infections, or other causes, may cause mitral regurgitation. Isolated mitral regurgitation may be acute, reflecting papillary muscle dysfunction after a myocardial infarction or rupture of chordae tendineae secondary to infective endocarditis.

Management of Anesthesia

Management of anesthesia in patients with mitral regurgitation should avoid decreases in the forward left ventricular stroke volume. Conversely, cardiac output can be improved by mild increases in heart rate and mild decreases in SVR (Box 25.4). Preinduction placement of intra-arterial pressure monitoring can speed the identification and treatment of hemodynamic changes in patients with clinically significant valvular disease.

A general anesthetic is the usual choice for patients with significant mitral regurgitation. Although decreases in SVR are theoretically beneficial, the rapid onset and uncontrolled nature of this response with a spinal anesthetic may detract from the use of this technique. Local or regional anesthesia may be used safely for surgery on peripheral body sites. Continuous spinal anesthetics may allow a slow titration of the regional block and can be a good choice of anesthetic. Maintenance of general anesthesia can be provided with volatile anesthetic, with or without nitrous oxide, or a continuous infusion of intravenous anesthetic. The concentration of volatile anesthetic can be adjusted to attenuate undesirable increases in systemic arterial blood pressure and SVR that can accompany surgical stimulation. Avoiding the use of nitrous oxide allows higher inspired oxygen concentrations and may reduce pulmonary vasoconstriction. Rapid increases in the concentration of desflurane may cause tachycardia, bronchospasm, and pulmonary hypertension and should be avoided.[46] Control of arterial blood pressure with a prophylactic intravenous infusion of the vasoconstrictor phenylephrine can reduce hemodynamic changes with induction. Intravascular fluid volume must be maintained by prompt replacement of blood loss to ensure adequate venous return and ejection of an optimal forward left ventricular stroke volume.

Box 25.4 Anesthetic Considerations in Patients With Mitral or Aortic Regurgitation

- Avoid sudden decreases in heart rate.
- Avoid sudden decreases in systemic vascular resistance.
- Minimize drug-induced myocardial depression.
- Monitor the magnitude of the V wave as a reflection of mitral regurgitant flow.
- Maintain sinus rhythm.
- Maintain diastolic pressure if possible.

Aortic Stenosis

Aortic stenosis is characterized by increased left ventricular systolic pressure to maintain the forward stroke volume through a narrowed aortic valve. The magnitude of the pressure gradient across the valve serves as an estimate of the severity of valvular stenosis. Hemodynamically significant aortic stenosis is associated with pressure gradients more than 50 mm Hg or valve areas less than 1.2 cm^2. A peak systolic gradient exceeding 50 mm Hg in the presence of a normal cardiac output or an effective aortic orifice less than about 0.75 cm^2 in an average-sized adult (i.e., 0.4 cm^2/m^2 of body surface area or less than approximately one fourth of the normal orifice) is generally considered to represent critical aortic stenosis. The combination of symptoms (angina, congestive failure, or fainting), signs (serious left ventricular dysfunction and progressive cardiomegaly), and a reduced valve area also indicate the diagnosis of critical aortic stenosis requiring surgical replacement. Increased intraventricular pressures are accompanied by compensatory increases in the thickness of the left ventricular wall. Angina pectoris occurs often in these patients in the absence of CAD, reflecting an increased myocardial oxygen demand because of the increased amounts of ventricular muscle associated with myocardial hypertrophy in combination with higher intraventricular pressures. There is a decrease in oxygen delivery secondary to the aortic valve pressure gradient in combination with an increase in oxygen requirements from the increase in left ventricular pressure and stroke work. Thus, aortic stenosis results in an increase in left ventricular stroke work and oxygen requirements (increased demand) while reducing coronary blood flow (reduced supply). The factors determining coronary blood flow are described by the following equation:

$$\text{Coronary blood flow} = (\text{aortic diastolic pressure} - \text{left ventricular end diastolic pressure}) / \text{coronary vascular resistance}.$$

Isolated nonrheumatic aortic stenosis usually results from progressive calcification and stenosis of a congenitally abnormal (usually bicuspid) valve. Aortic stenosis due to rheumatic fever almost always occurs in association with mitral valve disease. Likewise, aortic stenosis is usually accompanied by some degree of aortic regurgitation. Regardless of the cause of aortic stenosis, the natural

history of the disease includes a long latent period, often 30 years or more, before symptoms occur. Because aortic stenosis may be asymptomatic, it is important to listen for this cardiac murmur (systolic murmur in the second right intercostal space that may radiate to the right carotid) in patients scheduled for surgery. The incidence of sudden death is increased in patients with aortic stenosis.

Management of Anesthesia

With the advent of transcatheter aortic valve replacement (TAVR) the indications for aortic valve replacement (AVR) have changed, and many patients previously thought too high risk for surgical AVR (SAVR) are now considered candidates for TAVR. Patients with critical aortic stenosis or aortic stenosis with reduced left ventricular function or symptoms of angina or CHF should be evaluated for AVR prior to elective surgery.

Goals during management of anesthesia in patients with aortic stenosis are avoidance of arterial hypotension, maintenance of normal sinus rhythm, and avoidance of extreme and prolonged alterations in heart rate, SVR, and intravascular fluid volume (Box 25.5). Hypotension on induction can rapidly lead to myocardial ischemia from high myocardial oxygen requirements secondary to a constant load on the left ventricle from the stenotic valve combined with a decrease in coronary perfusion pressure secondary to an increase in left ventricular end-diastolic pressure and a relative diastolic hypotension. The most critical issue on induction of anesthesia is the avoidance of hypotension. Preservation of normal sinus rhythm is critical because the left ventricle is dependent on properly timed atrial contractions to ensure optimal left ventricular filling and stroke volume. Marked increases in heart rate (more than 100 beats/min) decrease the time for left ventricular filling and ejection and decrease coronary blood flow while increasing myocardial oxygen consumption. Coronary blood flow to the left ventricle occurs during diastole, and changes in heart rate primarily affect diastolic time. Bradycardia (less than 50 beats/min) can lead to acute overdistention of the left ventricle. Tachycardia may lead to myocardial ischemia and ventricular dysfunction. In view of the obstruction to left ventricular ejection, decreases in SVR may be associated with large decreases in systemic arterial blood pressure and coronary blood flow and result in myocardial ischemia. Intra-arterial pressure monitoring is essential prior to induction of anesthesia and throughout the anesthetic period and can speed identification and treatment of hemodynamic changes. Prophylactic infusions of vasoconstrictors such as phenylephrine started prior to induction, may reduce hemodynamic changes.

A general anesthetic may be preferred to a regional anesthetic because sympathetic nervous system blockade can lead to undesirable decreases in SVR. If surgery is peripheral, a regional anesthetic with careful intra-arterial pressure monitoring can be equally successful. Maintenance of general anesthesia can be achieved with both intravenous and volatile anesthetics. A potential disadvantage of volatile inhaled anesthetics is depression of sinus node automaticity, which may lead to junctional rhythm and decreased left ventricular filling due to loss of properly timed atrial contractions. Techniques with peripheral vasodilation should be used carefully. The most important aspect of management for patients with aortic stenosis is intra-arterial pressure monitoring with careful avoidance of hypotension.

Intravascular fluid volume must be maintained by prompt replacement of blood loss and liberal administration of intravenous fluids. If a pulmonary artery catheter is placed, it should be remembered that the occlusion pressure may overestimate the left ventricular end-diastolic volume because of the decreased compliance of the left ventricle that accompanies chronic aortic stenosis. It is difficult to demonstrate any benefit in patient outcomes with pulmonary artery catheter monitoring. A cardiac defibrillator should be promptly available when anesthesia is administered to patients with aortic stenosis because external cardiac compressions are unlikely to generate an adequate stroke volume across a stenosed aortic valve. Cardiopulmonary resuscitation (CPR) has a lower success rate in patients with aortic stenosis secondary to low coronary perfusion pressures as a result of the stenotic aortic valve.

Box 25.5 Anesthetic Considerations in Patients With Aortic Stenosis

- Intra-arterial pressure monitoring
- Rapid availability or prophylactic administration of intravenous vasoconstrictors (phenylephrine)
- Maintenance of normal sinus rhythm
- Avoidance of extreme bradycardia or tachycardia
- Avoidance of sudden decreases in systemic vascular resistance
- Optimization of intravascular fluid volume

Aortic Regurgitation

Aortic regurgitation is characterized by decreased forward left ventricular stroke volume due to regurgitation of part of the ejected stroke volume from the aorta back into the left ventricle through an incompetent aortic valve. A gradual onset of aortic regurgitation results in marked left ventricular hypertrophy and eventually dilation. Increased myocardial oxygen requirements secondary to left ventricular hypertrophy, plus a characteristic decrease in aortic diastolic pressure that decreases coronary blood flow, can manifest as angina pectoris in the absence of CAD. Coronary blood flow to the left ventricle occurs during diastole. In severe or acute aortic regurgitation with low diastolic pressures and elevated end-diastolic ventricular pressures, coronary blood flow can be

severely compromised. The combination of a low diastolic pressure from aortic regurgitation with the increase in left ventricular diastolic pressure substantially decreases the coronary perfusion pressure gradient. Acute aortic regurgitation is most often due to infective endocarditis, trauma, or dissection of a thoracic aortic aneurysm. Chronic aortic regurgitation is usually due to prior rheumatic fever. In contrast to aortic stenosis, the occurrence of sudden death in patients with aortic regurgitation is rare.

Management of Anesthesia

Management of anesthesia for noncardiac surgery in patients with aortic regurgitation is similar to the approach described for patients with mitral regurgitation (see Box 25.4). Preinduction intra-arterial pressure monitoring can speed the identification and treatment of hemodynamic changes and should be used for patients with significant aortic regurgitation. Anesthetics with minimal effects on SVR or cardiac function should be selected.

Mitral Valve Prolapse

Mitral valve prolapse (click-murmur syndrome, Barlow syndrome) is characterized by an abnormality of the mitral valve support structure that permits prolapse of the valve into the left atrium during contraction of the left ventricle.[63] Previous estimates that mitral valve prolapse was present in 5% to 15% of individuals are most likely erroneously high.[64] Transesophageal or transthoracic echocardiography can confirm the diagnosis of mitral valve prolapse, particularly in the absence of the characteristic systolic murmur. The incidence of mitral valve prolapse in patients probably increases with musculoskeletal abnormalities, including Marfan syndrome, pectus excavatum, and kyphoscoliosis.

Despite the prevalence of mitral valve prolapse, most patients are asymptomatic, emphasizing the usually benign course of this abnormality. Nevertheless, serious complications may accompany mitral valve prolapse (Box 25.6). For example, mitral valve prolapse is probably the most common cause of pure mitral regurgitation, which may progress to the need for surgical intervention. Infective endocarditis is a potential complication, and transient ischemic attacks in patients younger than 45 years of age are often associated with mitral valve prolapse. Sudden death is an extremely rare complication of mitral valve prolapse and, when it occurs, is presumed to be due to a ventricular cardiac dysrhythmia.

Box 25.6 Complications Associated With Mitral Valve Prolapse

- Mitral regurgitation
- Infective endocarditis
- Transient ischemic events
- Cardiac dysrhythmias
- Sudden death (extremely rare)

Management of Anesthesia

The important principle in the management of anesthesia in patients with mitral valve prolapse is the avoidance of events that can increase cardiac emptying and subsequently accentuate prolapse of the mitral valve into the left atrium.[65] Perioperative events that can increase cardiac emptying include (1) sympathetic nervous system stimulation, (2) decreased SVR, and (3) performance of surgery with patients in the head-up or sitting position. It is important to optimize intravascular fluid volume in the preoperative period. Although intravenous anesthetics can be used to induce anesthesia, a sudden prolonged decrease in SVR must be avoided. Also, preinduction placement of intra-arterial pressure monitoring can speed the identification and treatment of hemodynamic changes and should be used with patients who have clinically significant mitral valve prolapse. Prophylactic infusions of phenylephrine can reduce systemic vasodilation during anesthesia induction.

Maintenance of anesthesia is most often achieved with a volatile anesthetic with or without nitrous oxide, and a narcotic to minimize sympathetic nervous system activation because of noxious intraoperative stimulation. The dose of volatile anesthetic is titrated to avoid excessive decreases in SVR. A regional anesthetic could also produce undesirable decreases in SVR but can be used with careful monitoring and rapid hemodynamic therapy if needed. Prompt replacement of blood loss and generous administration of intravenous fluids will contribute to maintenance of an optimal intravascular fluid volume and decrease the potential adverse effects of positive-pressure ventilation of the patient's lungs. Lidocaine, amiodarone, metoprolol, and esmolol should be available to treat cardiac dysrhythmias. If a vasoconstrictor is needed to treat hypotension, an α-agonist, such as phenylephrine, should probably be used.

DISTURBANCES OF CARDIAC CONDUCTION AND RHYTHM

The ECG is a valuable tool for diagnosing disturbances of cardiac conduction and rhythm (also see Chapter 20). Ambulatory ECG monitoring (Holter monitoring) is useful in documenting the occurrence of life-threatening cardiac dysrhythmias and assessing the efficacy of antidysrhythmic drug therapy. The incidence of intraoperative cardiac dysrhythmias depends on the definition (benign versus life threatening), patient characteristics, and the type of surgery (frequent incidence during cardiothoracic

surgery).[65] The following questions should be asked when interpreting the ECG:

1. What is the heart rate?
2. Are P waves present, and what is their relationship to the QRS complexes?
3. What is the duration of the PR interval (normal 120 to 200 ms)?
4. What is the duration of the QRS complex (normal 50 to 120 ms)?
5. Is the ventricular rhythm regular?
6. Are there early cardiac beats or abnormal pauses after a preceding QRS complex?
7. Is there evidence of prior myocardial infarction or ventricular hypertrophy?
8. Is there evidence of myocardial ischemia?
9. Is there a conduction disturbance such as left bundle branch block, right bundle branch block, or intraventricular conduction delay?

Heart Block

Disturbances of conduction of cardiac impulses can be classified according to the site of the conduction block relative to the atrioventricular node (Box 25.7). Heart block occurring above the atrioventricular node is usually benign and transient. Heart block occurring below the atrioventricular node tends to be progressive and permanent.

A theoretical concern in patients with bifascicular heart block is that perioperative events, such as alterations in systemic arterial blood pressure, arterial oxygenation, or electrolyte concentrations, might compromise conduction in the one remaining intact fascicle, leading to the acute onset intraoperatively of third-degree atrioventricular heart block. However, surgery performed during general or regional anesthesia does not predispose to the development of third-degree atrioventricular heart block in patients with coexisting bifascicular block. Therefore, placement of a prophylactic artificial cardiac pacemaker is not required before anesthesia and surgery, but it should be available.

Box 25.7 Classification of Heart Block

- First-degree atrioventricular heart block
- Second-degree atrioventricular heart block
- Mobitz type I (Wenckebach)
- Mobitz type II
- Unifascicular heart block
- Left anterior hemiblock
- Left posterior hemiblock
- Right bundle branch block
- Left bundle branch block
- Bifascicular heart block
- Right bundle branch block plus anterior hemiblock
- Right bundle branch block plus posterior hemiblock
- Third-degree (trifascicular, complete) atrioventricular heart block

Third-degree atrioventricular heart block is treated by placement of an artificial cardiac pacemaker. An artificial cardiac pacemaker can be inserted intravenously (endocardial lead) or by the subcostal approach (epicardial or myocardial lead). An alternative to emergency transvenous artificial cardiac pacemaker placement is noninvasive transcutaneous or temporary esophageal cardiac pacing. A continuous intravenous infusion of isoproterenol acting as a pharmacologic cardiac pacemaker may be necessary to maintain an adequate heart rate until artificial electrical cardiac pacing can be established.

Sick Sinus Syndrome

Sick sinus syndrome is characterized by inappropriate sinus bradycardia associated with degenerative changes in the sinoatrial node. Frequently, bradycardia due to this syndrome is complicated by episodes of supraventricular tachycardia. Artificial cardiac pacemakers may be indicated when therapeutic plasma concentrations of drugs necessary to control tachycardia result in bradycardia. The increased incidence of pulmonary embolism in these patients may be a reason to initiate anticoagulation.

Ventricular Premature Beats

Ventricular premature beats, also known as premature ventricular complexes (PVCs), are recognized on the ECG by (1) premature occurrence, (2) the absence of a P wave preceding the QRS complex, (3) a wide and often bizarre QRS complex, (4) an inverted T wave, and (5) a compensatory pause that follows the premature beat. The primary goal with PVCs should be to identify any underlying cause (myocardial ischemia, arterial hypoxemia, hypercarbia, hypertension, hypokalemia, mechanical irritation of the ventricles) if possible and correct it. PVCs can be treated with lidocaine (1 to 2 mg/kg IV) when they (1) are frequent (more than 6 premature beats/min), (2) are multifocal, (3) occur in salvos of three or more, or (4) take place during the ascending limb of the T wave (R on T phenomenon) that corresponds to the relative refractory period of the ventricle.

Ventricular Tachycardia

Ventricular tachycardia is defined as the appearance of at least three consecutive wide QRS complexes (longer than 120 ms) on the ECG occurring at an effective heart rate more rapid than 120 beats/min. Ventricular tachycardia not associated with hypotension is initially treated with the intravenous administration of amiodarone, lidocaine, or procainamide. Torsades de pointes responds to

magnesium. Symptomatic ventricular tachycardia is best treated with external electrical cardioversion. The presence of ventricular tachycardia should elicit an immediate search for a cause such as myocardial ischemia, hypoxia, electrolyte abnormalities, or myocardial stimulation by the surgeons.

Preexcitation Syndromes

Preexcitation syndromes are characterized by activation of a portion of the ventricles by cardiac impulses that travel from the atria via accessory (anomalous) conduction pathways. These pathways bypass the atrioventricular node such that activation of the ventricles occurs earlier than it would if impulses reached the ventricles by normal pathways.

Wolff-Parkinson-White Syndrome

The Wolff-Parkinson-White syndrome is the most common of the preexcitation syndromes, with an incidence that may approach 0.3% of the general population. The lack of physiologic delay in transmission of cardiac impulses along the Kent fibers results in the characteristic short PR interval (less than 120 ms) on the ECG. The wide QRS complex and delta wave on the ECG reflect the composite of cardiac impulses conducted by normal and accessory pathways. Paroxysmal atrial tachycardia is the most frequent cardiac dysrhythmia associated with this syndrome. An increasing number of patients with Wolff-Parkinson-White syndrome are being treated by catheter ablation of accessory pathways as identified by electrophysiologic mapping. Supraventricular tachycardias such as atrial fibrillation or atrial flutter with one-to-one conduction may lead to hemodynamic collapse in patients with Wolff-Parkinson-White syndrome.

Management of Anesthesia

The goal during management of anesthesia in the presence of a preexcitation syndrome is to avoid events (anxiety) or drugs (anticholinergics, ketamine, pancuronium) that might increase sympathetic nervous system activity and predispose to tachydysrhythmias.[65] All cardiac antidysrhythmic drugs should be continued throughout the perioperative period. Anesthesia can be induced with intravenous drugs, with the possible exception of ketamine. Tracheal intubation should be performed only after a sufficient concentration or dose of anesthetic has been given to reliably blunt sympathetic nervous system stimulation evoked by instrumentation of the upper airway. Intravenous β-adrenergic blockers (atenolol, metoprolol, propranolol, or esmolol) can be used to avoid tachycardia during induction of anesthesia. Neuromuscular blocking drugs with minimal effects on heart rate should be used.

The onset of paroxysmal atrial tachycardia or fibrillation in the perioperative period can be treated with the intravenous administration of drugs that abruptly prolong the refractory period of the atrioventricular node (adenosine) or lengthen the refractory period of accessory pathways (procainamide). β-Adrenergic blockers may be used for heart rate control. Digitalis and verapamil may decrease the refractory period of accessory pathways responsible for atrial fibrillation, resulting in an increase in ventricular response rate during this dysrhythmia and should be avoided. Electrical cardioversion is indicated when tachydysrhythmias are life threatening.

Prolonged QT Interval Syndrome

A prolonged QT interval (longer than 440 ms on the ECG) syndrome is associated with ventricular dysrhythmias, syncope, and sudden death. Treatment should include β-adrenergic antagonists or left stellate ganglion block. The effectiveness of a left stellate ganglion block supports the hypothesis that this syndrome results from a congenital imbalance of autonomic innervation to the heart produced by decreases in right cardiac sympathetic nerve activity. Management of anesthesia includes avoidance of events or drugs that are likely to activate the sympathetic nervous system and availability of β-antagonists (metoprolol, atenolol, propranolol, or esmolol) or electrical cardioversion to treat life-threatening ventricular dysrhythmias.[65] The effect of inhaled and intravenous anesthetics can prolong the QT interval on the ECG in normal patients. Fortunately, these anesthetics do not produce additional prolonged QT interval in those patients with this syndrome in a predictable manner.[66] Many medications have the potential to prolong the QT interval (e.g., droperidol)[67,68] and should be avoided, if possible, in patients with prolonged QT syndrome.

ARTIFICIAL CARDIAC PACEMAKERS

Preoperative evaluation of the patient with an artificial cardiac pacemaker in place includes determination of the reason for placing the pacemaker, assessment of its present function, as well as the brand, model, magnet mode, and availability of a programmer for this specific device and a person who knows how to operate the programmer.[69] Many implanted electrical devices can be used. A device under the skin may not be a pacemaker. Implanted devices include deep brain stimulators, automatic implantable cardiac defibrillators, intravenous pumps, spinal stimulators for chronic pain, bladder stimulators for neurogenic bladder, gastric stimulators for the treatment of obesity, intravenous ports, and vagal stimulators for sleep.

Special considerations are necessary for devices when the patient's life depends on the device. If a device is a cardiac pacemaker placed for third-degree heart block, special considerations for the continuous operation of that device and monitoring of its operation should be taken.

If a pacemaker implanted for third-degree heart block is to be disconnected to change the stimulator, transvenous pacing may be needed. If the device is an automatic defibrillator, it will need to be inactivated during electrical-surgical cautery to avoid the device erroneously detecting ventricular dysrhythmias and defibrillating, which would waste battery life and possibly cause R-on-T phenomenon and ventricular fibrillation. The device should be reactivated after the surgical procedure and interrogated for proper function. The magnet mode of many implanted devices is now programmable. The magnet mode cannot automatically be assumed to be "safe." The specific magnet mode for a patient's device should be identified as some magnet modes change with device state or are programmable. Magnet mode for many pacemakers is asynchronous at 99 beats/min. If the patient has a spontaneous heart rate of 60 to 80 beats/min, the asynchronous mode at 99 beats/min would be safe. However, in some devices, the magnet mode shifts to asynchronous at 50 beats/min at the end of battery life. Asynchronous pacing at 50 beats/min may lead to R-on-T phenomenon if the patient has a spontaneous heart rate above 50 beats/min. The specific magnet mode should be identified and used only when needed given the circumstances of the case.

Intraoperative monitoring of patients with artificial cardiac pacemakers includes the ECG and possible intra-arterial pressure monitoring so as to detect the appearance of asystole promptly. Atropine, isoproterenol, and an external pacemaker should be available if the artificial cardiac pacemaker ceases to function. If electrocautery interferes with the ECG, monitoring the intra-arterial pressure, or arterial oxygenation, auscultation through an esophageal stethoscope or a palpable pulse confirms continued cardiac activity. Monitoring systemic arterial blood pressure with an intra-arterial catheter provides immediate evidence of loss of pacemaker function and should be considered in patients with third-degree heart block. Inhibition of pulse generator activity by electromagnetic interference most commonly from electrosurgical cautery, which is interpreted as spontaneous cardiac activity by the artificial cardiac pacemaker, is most likely when the ground plate for electrocautery is placed too near the pulse generator or unipolar cautery is used. For this reason, the ground plate should be placed as far as possible from the pulse generator. Bipolar electrocautery may also reduce interference between electrosurgical cautery and the pacemaker. If surface pads are placed for external pacing or defibrillation, they should be placed away from the implanted device to reduce current passing down the pacing lead and hyperpolarizing a small segment of myocardium, which could interfere with pacemaker capture after defibrillation. Automatic implantable cardioversion devices sense ventricular fibrillation or ventricular tachycardia. They provide a cardioversion shock through implanted cardiac leads. Electrocautery signals can be misinterpreted as ventricular dysrhythmias, thus triggering unnecessary shocks and decreasing battery life. These devices should be reprogrammed to the standby mode prior to elective surgery and returned postoperatively to full function with interrogation of proper operation (also see Chapter 13).

Selection of drugs or techniques for anesthesia is not influenced by the presence of artificial cardiac pacemakers as there is no evidence that the threshold and subsequent response of these devices is altered by drugs administered in the perioperative period. However, patients with artificial cardiac pacemakers or implanted cardioversion devices have a frequent incidence of coexisting cardiac disease and should be monitored carefully and anesthetized with care. Patients with defibrillators frequently have poor ventricular function. Insertion of a pulmonary artery catheter will not disturb epicardial electrodes but might dislodge recently placed (less than 2 weeks) transvenous endocardial electrodes.[70]

ESSENTIAL HYPERTENSION

Essential hypertension is arbitrarily defined as sustained increases in systemic arterial blood pressure (systolic blood pressure higher than 160 mm Hg or a diastolic blood pressure higher than 90 mm Hg) independent of any known cause. Treatment of essential hypertension with appropriate drug therapy decreases the incidence of stroke and CHF. Hypertension is a risk factor for CAD, and the longer the patient has hypertension the higher the risk of end organ damage.

Management of Anesthesia

Management of anesthesia for patients with essential hypertension includes preoperative evaluation of drug therapy and the extent of the disease plus a consideration of the implications of exaggerated systemic arterial blood pressure responses elicited by preoperative anxiety and painful intraoperative stimulation.[71]

Preoperative Evaluation

Preoperative evaluation of patients with essential hypertension begins with a determination of the adequacy of systemic arterial blood pressure control and a review of the pharmacology of the antihypertensive drugs being used for therapy (see Chapters 6 and 13). Antihypertensive drugs should be continued throughout the perioperative period. Evidence of major organ dysfunction (CHF, CAD, cerebral ischemia, renal dysfunction) must be sought. Patients with essential hypertension have an elevated risk of CAD. Evidence of PVD should be recognized, as all patients with PVD have some degree of CAD. It can be assumed that nearly one half of patients with

evidence of PVD will have more than 50% stenosis of one or more coronary arteries even in the absence of angina pectoris and the presence of a normal resting ECG. Additional monitoring, including intra-arterial catheter monitoring, is justified for significant operations. Patients with increased pulse pressure have increased perioperative and long-term complications.[72] Essential hypertension is associated with a shift to the right of the curve for the autoregulation of cerebral blood flow, emphasizing that these patients are more vulnerable to cerebral ischemia should perfusion pressures decrease. Detection of renal dysfunction due to chronic hypertension may influence the selection of drugs, particularly if elimination from the plasma depends on renal clearance or metabolites of the drugs are known potential nephrotoxins (e.g., fluoride from metabolism of sevoflurane).

Hypertension should be treated preoperatively because the incidence of hypotension and evidence of myocardial ischemia on the ECG during the maintenance of anesthesia is increased in patients who remain hypertensive before the induction of anesthesia.[57] Patients who are treated with antihypertensives prior to surgery should be continued on those medications in the perioperative period. Discontinuation of antihypertensive and antianginal medications in the perioperative period increases operative risk.[6,19,21,32,33] Prophylactic cardiac risk reduction therapy with β-adrenergic blockers of patients with CAD, PVD, or two risk factors (age ≥ 60, hypertension, cholesterol > 240 mg/dL, diabetes, or smoking) reduces risk of perioperative death.[14,32,33,41] Appropriate dosing of β-adrenergic blockers is important to avoid sequelae.[6,37]

Despite therapy, systemic arterial blood pressure increases during the intraoperative period are more likely to occur in patients with a history of essential hypertension regardless of the degree of pharmacologic control of systemic arterial blood pressure established preoperatively. Furthermore, the incidence of postoperative cardiac complications is not increased when hypertensive patients undergo elective operations as long as the preoperative diastolic blood pressure is not more than 110 mm Hg and heart rate is controlled. Pretreatment with a β-adrenergic blocker may be useful in blunting exaggerated sympathetic nervous system responses and reduces perioperative mortality risk.[16,17,41]

Induction of Anesthesia

Induction of anesthesia with intravenous drugs is acceptable, remembering that an exaggerated decrease in systemic arterial blood pressure may occur, particularly if hypertension is present preoperatively. Thiopental, propofol, midazolam, synthetic opioids (fentanyl, sufentanil, alfentanil, remifentanil), and etomidate all have been used to induce anesthesia. Any anesthetic is acceptable if used with appropriate dosing and careful monitoring. Etomidate or combinations of midazolam and fentanyl are frequently used for induction because of their limited hemodynamic effects. Ketamine is rarely selected for induction of anesthesia in patients with essential hypertension because it can increase systemic arterial blood pressure and cause tachycardia, which may lead to myocardial ischemia. Placement of an intra-arterial pressure monitor prior to induction of anesthesia and prophylactic infusions of the vasoconstrictor phenylephrine can reduce hemodynamic perturbations with induction of anesthesia. Hemodynamic changes with induction most likely reflect unmasking of decreased intravascular fluid volume due to chronic hypertension combined with a stiffening of the arterial vasculature.

Hypertension can occur during direct laryngoscopy for tracheal intubation in patients with essential hypertension but may be attenuated with administration of opioids and β-adrenergic blockers. Tachycardia may lead to episodes of myocardial ischemia. A single 1-minute episode of myocardial ischemia increases the risk of perioperative cardiac morbidity 10-fold and death 2-fold. The risk of myocardial ischemia can be reduced by prophylactic therapy with β-adrenergic blockers.[16,17,41]

Maximal attenuation of sympathetic nervous system responses should be attempted during direct laryngoscopy by administering anesthetics, intravenous opioids, and β-adrenergic blockers before attempting tracheal intubation. Careful attention to the airway is critical in all anesthetics, and the risks are greater in patients with cardiac disease. If the patient has a recognized difficult airway precluding direct laryngoscopy, hemodynamic control with specific attention to heart rate control must be observed while securing the airway with alternative approaches such as fiberoptic intubation. It is important to prevent hypoxia, tachycardia, hypotension, hypertension, and myocardial ischemia. Regardless of the drugs administered before tracheal intubation, however, it must be recognized that an excessive concentration of anesthetic drugs can produce decreases in systemic arterial blood pressure that are as undesirable as hypertension. An important concept for limiting pressor responses elicited by tracheal intubation is to limit the duration of direct laryngoscopy to less than 15 seconds if possible. In addition, the administration of laryngotracheal lidocaine immediately before placement of the tube in the trachea will minimize any additional pressor response.

Maintenance of Anesthesia

The goal during maintenance of anesthesia is to adjust the concentrations of anesthetics to avoid tachycardia and minimize wide fluctuations in systemic arterial blood pressure (Box 25.8). No single anesthetic technique has been shown to be superior. Combinations of volatile anesthetics with or without nitrous oxide and a narcotic are commonly used. Changes in the concentration of volatile anesthetics allow rapid adjustments in the depth of

Box 25.8 Management of Anesthesia for Patients With Essential Hypertension

Preoperative Evaluation
- Determine the adequacy of systemic arterial blood pressure control.
- Review the pharmacology of antihypertensive drugs.
- Evaluate associated organ dysfunction (cardiac, central nervous system, renal).
- Consider the administration of prophylactic anti-ischemic therapy (perioperative β-adrenergic blockade).
- Choose appropriate monitors and consider intra-arterial pressure monitoring.

Induction of Anesthesia and Tracheal Intubation
- Anticipate exaggerated systemic arterial blood pressure changes.
- Consider initiation of prophylactic infusion of phenylephrine to reduce hemodynamic perturbation with induction.
- Minimize the pressor response during tracheal intubation by limiting the duration of direct laryngoscopy to <15 seconds.

Maintenance of Anesthesia
- Use a volatile anesthetic and vasoconstrictors to control systemic arterial blood pressure.
- Monitor the electrocardiogram for evidence of myocardial ischemia (avoidance is better than detection).
- Anticipate excessive increases in systemic arterial blood pressure with emergence.

Postoperative Management
- Ensure effective pain control.
- Patient's arterial blood pressure will return to preoperative level or greater after emergence from anesthesia, be ready to treat as needed.
- Continue perioperative anti-ischemic therapy for at least a week in low-risk patients, 30 days in those at higher risk, and permanently in patients with known coronary artery disease or vascular disease.

anesthesia in response to increases or decreases in systemic arterial blood pressure. Changes in surgical stimulation may lead to changes in arterial blood pressure and heart rate. Additional doses of narcotics, β-adrenergic blockers, and changes in the dose of volatile anesthetics can be used to control hemodynamics. Heart rate control is the most critical element for preventing cardiac morbidity and fatality. Heart rates above 120 beats/min increase mortality rate. Volatile anesthetics are useful for attenuating activity of the sympathetic nervous system, which is responsible for these pressor responses. The ability to rapidly increase the alveolar concentration of sevoflurane (because of its low solubility) makes this volatile anesthetic uniquely efficacious for treating sudden increases in systemic arterial blood pressure (see "Maintenance of Anesthesia" under "Coronary Artery Disease"). Rapid changes in desflurane concentration may lead to tachycardia, hypertension, pulmonary hypertension, and myocardial ischemia and should be avoided.[46] A positive feedback situation can occur with desflurane anesthetics whereby a surgical stimulus can raise arterial blood pressure, the anesthesia provider rapidly raises the desflurane concentration, which stimulates the sympathetic system causing the arterial blood pressure to increase, which causes the anesthesia provider to further increase the desflurane concentration, which further increases the arterial blood pressure.[46]

A nitrous oxide–opioid technique is also acceptable for the maintenance of anesthesia, but the addition of a volatile anesthetic is often necessary to control undesirable increases in systemic arterial blood pressure, particularly during periods of maximal surgical stimulation. Total intravenous anesthesia (combinations of dexmedetomidine, propofol, narcotics, and benzodiazepines) can also be used with effect. Continuous intravenous infusions of phenylephrine, nitroprusside, nitroglycerin, or esmolol can be used to maintain normotension during the intraoperative period. Combinations of narcotic, benzodiazepine, and inhaled anesthetics are commonly used. Hypotension that occurs during maintenance of anesthesia is often treated by decreasing the concentrations of volatile anesthetics while infusing fluids intravenously to increase intravascular fluid volume. Sympathomimetics, such as ephedrine, or vasoconstrictors such as phenylephrine may be necessary to restore perfusion pressures until the underlying cause of hypotension can be corrected.

The choice of intraoperative monitors for patients with coexisting essential hypertension is influenced by the complexity of the surgery. The ECG is monitored with the goal of recognizing changes suggestive of myocardial ischemia. Invasive monitoring with an intra-arterial pressure monitor is commonly used. Continuous cardiac output monitors with calculation of SVV or PPV can be used to monitor intravascular fluid status as a part of goal-directed therapy. Pulmonary artery catheters may be considered if major surgery is planned and there is evidence preoperatively of left ventricular dysfunction, although there is no evidence that demonstrates improved outcomes with pulmonary artery catheter monitoring. Monitoring with TEE is an alternative to placement of a pulmonary artery catheter.

A regional anesthetic is an excellent choice for patients with multiple medical conditions who are scheduled for peripheral surgery. Whatever the choice of anesthetic, β-adrenegic blockers and sedatives can be used to reduce sympathetic nervous system stimulation. Patients with cardiac disease who are scheduled for elective surgery can have episodes of myocardial ischemia in the days prior to surgery. The night before surgery is stressful, and prophylactic β-adrenergic blockade can reduce the risk of sympathetic stimulation resulting in tachycardia and subsequent myocardial ischemia. There is the erroneous belief that minor surgery causes minor stress. Patients scheduled for ophthalmic surgery, a minor outpatient procedure, commonly have sympathetic stimulation resulting

in preoperative hypertension. Prophylactic therapy with β-adrenergic blockers can reduce the preoperative hypertensive episodes and myocardial ischemia. Appropriate dosing of all medications is essential and inappropriate dosing may lead to hypotension, bradycardia, and increased morbidity and mortality rates.[37] All medications have a therapeutic index. Withholding antihypertensive medications may lead to withdrawal phenomena and increase the morbidity and mortality rates.[19,21,32,33]

Postoperative Management

Hypertension in the early postoperative period is a frequent occurrence in patients with a preoperative diagnosis of essential hypertension. Prophylactic or therapeutic administration of β-adrenergic blockers can reduce these episodes of hypertension and reduce risk of perioperative ischemia and death. If hypertension persists despite β-adrenergic blockers and adequate analgesia, it may be necessary to pharmacologically decrease systemic arterial blood pressure utilizing a continuous intravenous infusion of nitroprusside, nitroglycerin, or intermittent injections of hydralazine (5 to 20 mg IV) or labetalol (0.1 to 0.5 mg/kg IV). Tachycardia in the postoperative period must be actively avoided as it increases morbidity and mortality rates (also see Chapter 39). A heart rate of 120 beats/min raises the risk of postoperative death. Clearly the arterial blood pressure needs to be controlled during the entire perioperative period. The patient needs preoperative, intraoperative, and postoperative hemodynamic and autonomic control to prevent associated cardiac morbidity and death. Anesthesia care for patients with cardiac disease truly needs to be perioperative for optimal outcomes. If medication is needed to control arterial blood pressure and heart rate while at home, the patient will likely need it during surgery and postoperative care. Withdrawal of antihypertensive and anti-ischemic medications in the perioperative period increases cardiac risk.[27,29,30]

CONGESTIVE HEART FAILURE

Elective surgery should not be performed in patients with untreated CHF unless optimally treated. The preoperative presence of CHF is often associated with significant postoperative morbidity or mortality rates. Cardiology consultation is frequently helpful in patients with congestive failure as consideration of surgical or interventional revascularization and optimization of medical therapy can improve cardiac function. Preoperative initiation of β-adrenergic blockers and vasodilator therapy with angiotensin-converting enzyme inhibitors can improve ventricular function and reduce operative risk. These drugs should be started by physicians with expertise in treating CHF and the doses increased slowly as tolerated over 3 to 6 months as the heart function recovers.

Management of Anesthesia

When surgery cannot be delayed, however, the drugs and techniques chosen to provide anesthesia must be selected with the goal of minimizing detrimental effects on cardiac output. Optimal cardiac output can be obtained when the impedance of the vasculature (preload and afterload) matches the impedance of the heart and can be achieved by careful preload and afterload management.

Etomidate may be useful for the induction of anesthesia in the presence of CHF because of its limited effect on the sympathetic nervous system. Small doses of volatile anesthetics can maintain anesthesia, but must be used carefully to avoid cardiac depression. In the presence of severe CHF, the use of opioids in large doses as the primary anesthetic in combination with amnestic benzodiazepines (midazolam) may be justified, although no evidence supports this approach over the use of a primary volatile anesthetic combined with narcotics.[52] Positive-pressure ventilation of the lungs may be beneficial by decreasing pulmonary congestion, improving arterial oxygenation, and eliminating the work of breathing. Care must be taken on extubation of patients with CHF as the resumption of negative intrathoracic pressures with spontaneous ventilation can lead to increased filling pressures and worsening heart failure. Invasive monitoring of intra-arterial blood pressure is helpful for hemodynamic management of patients undergoing both regional and general anesthetics. Use of pulmonary artery catheters can be helpful in hemodynamic management, but no evidence exists to suggest that they reduce operative risk or improve outcome. Maintenance of arterial blood pressure with vasoconstrictors (phenylephrine) should precede increasing myocardial contractility with continuous intravenous infusions of inotropic drugs such as epinephrine, dopamine, and dobutamine. The use of β-adrenergic agonists in patients with CHF may decrease the chance of survival and should be used only when necessary.

Regional anesthesia (also see Chapters 17 and 18) should be considered for patients with CHF requiring peripheral or minor surgery. Anesthetics with minimal hemodynamic effects are optimal. If the surgery precludes such a choice, general anesthesia with careful hemodynamic control with intra-arterial pressure monitoring, infusions of vasoconstrictors, and possibly inotropic drugs, with the careful avoidance of tachycardia, should be used.

HYPERTROPHIC CARDIOMYOPATHY

Hypertrophic cardiomyopathy (idiopathic hypertrophic subaortic stenosis) is characterized by obstruction to left ventricular outflow produced by asymmetric hypertrophy of the intraventricular septal muscle.[73] Associated left ventricular hypertrophy in an attempt to overcome the

Box 25.9 Events That Decrease Left Ventricular Outflow Obstruction in the Presence of Hypertrophic Cardiomyopathy

Decreased Myocardial Contractility
- β-Adrenergic blockade (atenolol, metoprolol, propranolol, esmolol)
- Volatile anesthetic (sevoflurane or isoflurane)

Increased Preload
- Increased intravascular fluid volume
- Bradycardia (fentanyl or sufentanil)

Increased Afterload
- α-Adrenergic stimulation (phenylephrine infusions)

obstruction may be so massive that the volume of the left ventricular chamber is decreased. Despite these adverse changes, the stroke volume remains normal or increased owing to the hypercontractile state of the myocardium. This disease is often hereditary, and the genetic defect seems to be an increased density of calcium channels manifesting as myocardial hypertrophy.

Management of Anesthesia

The goal during management of anesthesia for patients with hypertrophic cardiomyopathy is to decrease the pressure gradient across the left ventricular outflow obstruction (Box 25.9). Decreases in myocardial contractility and increases in preload (ventricular volume) and afterload will decrease the magnitude of left ventricular outflow obstruction. Volatile anesthetics are useful for maintenance of anesthesia, providing mild depression of myocardial contractility. Theoretically, isoflurane, desflurane, and sevoflurane would be less ideal choices than halothane because these drugs decrease SVR more than does halothane. Rapid increases in desflurane may cause sympathetic stimulation with tachycardia, hypertension, bronchospasm, and pulmonary hypertension and should be avoided.[46] Primary opioid anesthetics may not be optimal as they do not produce myocardial depression and can decrease SVR. High potency opioids stimulate the vagus nerve, lower heart rate, and can decrease sympathetic stimulation improving hemodynamics. Combinations of volatile drugs (sevoflurane or isoflurane) with an opioid are commonly selected.

Intraoperative hypotension is generally treated with intravenous fluids or an α-agonist such as phenylephrine. Drugs with β-agonist activity are not likely to be used to treat hypotension because any increase in cardiac contractility or heart rate could increase left ventricular outflow obstruction. When hypertension occurs, an increased delivered concentration of isoflurane or sevoflurane can be used. Vasodilators, such as nitroprusside or nitroglycerin, should be used with caution because decreases in SVR can increase left ventricular outflow obstruction.

PULMONARY HYPERTENSION AND COR PULMONALE

Cor pulmonale is the designation for right ventricular hypertrophy and eventual cardiac dysfunction that occurs secondary to chronic pulmonary hypertension. Elective operations in patients with cor pulmonale should not be performed until any reversible components in the coexisting pulmonary vascular disease have been treated.

Management of Anesthesia

Goals during management of anesthesia in patients with cor pulmonale are to avoid events or drugs that could increase PVR. Volatile anesthetics are useful for relaxing vascular smooth muscle and attenuating airway responsiveness to stimuli produced by a tracheal tube. Pulmonary vasodilation with prostaglandins (epoprostenol, treprostinil, iloprost, beraprost), endothelin receptor antagonists (bosentan, sitaxentan, ambrisentan), inhaled nitric oxide, inhaled milrinone, type 5 phosphodiesterase inhibitors (sildenafil, vardenafil), or soluble guanylate cyclase activators (cinaciguat, riociguat) have been tried with variable success. Patients with pulmonary hypertension have significant increased risk and should be treated with extreme care. Nitrous oxide may increase PVR and should be avoided.[61] Another disadvantage of nitrous oxide is the associated decrease in the inspired concentration of oxygen necessitated by the administration of this drug.

Intra-arterial pressure monitoring is very helpful for hemodynamic management. Monitoring of pulmonary arterial or right atrial pressure (or both) may be helpful to detect any adverse effect on pulmonary vasculature. TEE monitoring can be very helpful in blood volume management. In severe cor pulmonale, inotropic support with β-agonists can improve cardiac function. Therapy should be chosen based on the hemodynamic problem (volume, SVR, chronotropy, inotropy, and pulmonary hypertension). β-Agonists must be used carefully to avoid myocardial ischemia. In severe right ventricular failure, combinations of β-agonists and phosphodiesterase inhibitors (amrinone or milrinone) can provide synergistic improvements in ventricular function and vasodilation (amrinone or milrinone), thus improving cardiac output. The cyclic guanosine monophosphate–dependent phosphodiesterase inhibitors (sildenafil and vardenafil) can be used to vasodilate the pulmonary vasculature with minimal effects on SVR.

CARDIAC TAMPONADE

Cardiac tamponade is characterized by (1) decreases in diastolic filling of the ventricles, (2) decreases in stroke volume, and (3) decreases in systemic arterial blood pressure due to increased intrapericardial pressure from

Box 25.10 Manifestations of Cardiac Tamponade

- Primary diastolic dysfunction from increased pericardial pressure
- Hypotension
- Tachycardia
- Increased systemic vascular resistance
- Low cardiac output
- Equalization of left and right diastolic filling pressures
- Exaggeration of arterial blood pressure variation with respiration
- Fixed and reduced stroke volume (cardiac output and systemic arterial blood pressure dependent on heart rate)
- Failure to respond to volume and multiple inotropes with cardiogenic shock

accumulation of fluid in the pericardial space (Box 25.10). Decreased stroke volume from inadequate ventricular filling results in activation of the sympathetic nervous system (tachycardia, vasoconstriction) as the cardiovascular system attempts to maintain the cardiac output. Cardiac output and systemic arterial blood pressure are maintained only as long as the pressure in the central veins exceeds the right ventricular end-diastolic pressure. Institution of general anesthesia and positive-pressure ventilation of the lungs in the presence of cardiac tamponade can lead to immediate and profound hypotension or death, reflecting anesthetic-induced peripheral vasodilation, direct myocardial depression, and decreased venous return from positive-pressure ventilation. When percutaneous pericardiocentesis cannot be performed using local anesthesia, the induction and maintenance of general anesthesia are extremely dangerous but may be achieved while carefully maintaining spontaneous respiration. Potential adverse effects of increased intrathoracic pressure from controlled respiration on venous return must be taken seriously. If possible, positive-pressure ventilation of the lungs should be avoided until drainage of the pericardial space is imminent. With this in mind, tracheal intubation with topical anesthesia has been suggested.

Management of Anesthesia

Prior to the induction of general anesthesia in patients with significant cardiac tamponade, the patient should be positioned on the operating room table. Intra-arterial monitoring is helpful if time permits. The chest and abdomen should be prepped and draped for surgery. The surgeons should be scrubbed, gowned, gloved, and at the operating room table ready for incision prior to anesthetic induction. It is optimal if anesthetic induction, intubation, incision, and drainage of the pericardial tamponade can occur in extremely rapid succession (less than 60 seconds). Although continuous intravenous infusions of catecholamines (epinephrine, norepinephrine, dopamine, dobutamine, or isoproterenol) and vasoconstrictors may be necessary to maintain cardiac output and arterial blood pressure, the primary therapy is pericardial drainage. A common sign of cardiac tamponade is hemodynamic collapse and cardiogenic shock unresponsive to fluids and inotropes. Systolic ventricular function is not the problem; diastolic dysfunction from increased pericardial pressure is the primary problem. Once the pericardium is drained, venous return can enter the heart and hemodynamics will rapidly normalize.

ANEURYSMS OF THE AORTA

Aneurysms of the aorta most often involve the abdominal aorta but may involve any part including thoracic or abdominal. Most patients are hypertensive, and many have associated atherosclerosis. A dissecting aneurysm denotes a tear in the intima of the aorta that allows blood to enter and penetrate between the walls of the vessel, producing a false lumen. Ultimately, the dissection may reenter the lumen through another tear in the intima or rupture through the adventitia.

Elective repair of an abdominal aneurysm is often recommended when the estimated diameter of the aneurysm is more than 5 cm. The incidence of spontaneous rupture increases dramatically when the size of the aneurysm exceeds this diameter. Extension of the abdominal aneurysm to include the renal arteries occurs in about 5% of patients.

Management of Anesthesia

All surgery patients with vascular disease should be considered for prophylactic β-adrenergic blocker and statin therapy. Perioperative administration of β-adrenergic blockers reduces perioperative mortality rate 50% to 90%. β-Adrenergic blocking drugs should be started as soon as patients are identified as needing surgery.[6] Perioperative statin use reduces risk an additional 50% over the benefits of β-adrenergic blockers and should be started 30 days preoperatively and continued at least 30 days postoperatively, if not indefinitely.[15]

The surgical approach certainly influences the anesthetic. Endovascular aneurysm repair is less invasive and may require only regional anesthesia, although in prolonged cases general anesthesia is preferred. Open procedures for aortic aneurysm surgery are major procedures and require general anesthesia. All patients undergoing anesthesia for resection of an abdominal aortic aneurysm should have monitoring of intra-arterial pressures. Epidural catheter placement may be helpful for the management of postoperative pain. Continuous cardiac output monitoring with calculation of SVV or PPV can be used to direct goal-directed therapy of volume replacement. The use of pulmonary arterial pressure monitoring is controversial and not supported by improved survival data.[57,58]

Patients with coexisting CAD are likely to develop evidence of myocardial ischemia during cross-clamping of the abdominal aorta. TEE may be useful in evaluating the adequacy of intravascular volume replacement and in the recognition of cardiac wall motion abnormalities associated with myocardial ischemia, although no data support its use as a risk reduction strategy. Intraoperatively, myocardial ischemia is treated by decreasing heart rate with β-adrenergic blockers and maintaining systemic arterial blood pressure and filling pressures to acceptable levels by pharmacologic interventions, which may include continuous intravenous infusion of phenylephrine (for hypotension), nitroprusside, or nitroglycerin (for hypertension). Preoperative hydration with a balanced salt solution and prompt intraoperative replacement of blood loss as guided by data obtained from echocardiography or continuous cardiac output devices are considered useful for maintaining intravascular fluid volume and thus renal function. Diuresis is often facilitated by intraoperative administration of a diuretic (mannitol, furosemide, or both) with or without dopamine. Despite these interventions, glomerular filtration rate and renal blood flow are not predictably improved.[74]

Hypotension can accompany unclamping of the abdominal aorta, presumably reflecting sudden decreases in vascular resistance and increases in venous compliance with reperfusion. Systemic arterial blood pressure decreases can be minimized by infusing intravenous fluids prior to cross-clamp release. Gradual removal of the aortic cross-clamp minimizes decreases in systemic arterial blood pressure by allowing time for return of pooled venous blood to the circulation.

CARDIOPULMONARY BYPASS

Cardiopulmonary bypass (extracorporeal circulation) support is used to stabilize the myocardium reducing motion during coronary artery bypass surgery and allow ascending aortic and intraventricular procedures (valve repair or replacement) (also see Chapter 26). Cardiopulmonary bypass is characterized by gravity drainage of blood from the vena cava into a reservoir, followed by its pumping through a heat exchanger, oxygenator, and filter followed by its return to the arterial system, usually the ascending aorta, by means of a centrifugal or roller pump (Fig. 25.3).[75] In the presence of a competent aortic valve, the heart is excluded from the patient's circulation by either a single venous cannula inserted into the right atrium (see Fig. 25.3) and advanced into the inferior vena cava, or by dual catheters placed into the superior and inferior venae cavae so that all returning blood enters the large cannulas in these vessels. If the aortic valve is not competent, venting of the left ventricle may be necessary (1) through a drain placed from the right superior pulmonary vein into the left ventricle, (2) by aspirating from the antegrade cardioplegia line placed in the proximal ascending aorta, or (3) via a pulmonary venous drain. Otherwise, retrograde blood flow through the incompetent aortic valve could cause distention of the left ventricle and damage ventricular function. Venting of blood returning via thebesian or bronchial veins may also be necessary. An aortic cross-clamp is placed between the antegrade cardioplegia catheter and the arterial inflow catheter to separate the heart from the circulation and allow cardioplegic arrest. The ventricle should not be overdistended in any situation in which it is not pumping. If the aortic cross-clamp is removed and ventricular contraction has not returned, the ventricle may become overdistended in situations with aortic valve insufficiency. When the heart is isolated from the circulation, total cardiopulmonary bypass is present, and ventilation of the lungs is no longer necessary to maintain oxygenation. However, in any situation where there is a pulsatile pulmonary pressure detected by pulmonary arterial catheter measurement, there is partial pulmonary bypass, and the lungs should be ventilated to avoid pumping desaturated blood systemically. Gravity-dependent venous drainage to the cardiopulmonary bypass machine can be improved by raising the level of the operating table or placing a small vacuum on the cardiotomy reservoir.

The use of extracorporeal circulatory support is dangerous and requires special precautions. Prior to going on cardiopulmonary bypass it is important to review a checklist of required items. Checklists are effective in improving anesthetic care. The checklist prior to going on cardiopulmonary bypass can be recalled by using the mnemonic HADDSUE, pronounced HAD TO SUE, making each item easy to remember (Box 25.11).

Components of the Cardiopulmonary Bypass Circuit

The bypass pump produces nonpulsatile flow into the patient's aorta by either a centrifugal or roller pump. The centrifugal pump has three disks rotating at 3000 to 4000 rpm that use blood viscosity to pump blood. Centrifugal pumps are superior to roller pumps because they are less traumatic to blood cells, do not pump air bubbles secondary to air being less dense than blood, and are afterload-dependent, avoiding the risk of line rupture with clamping of the arterial inflow circuit. Roller pumps compress the fluid-filled tubing between the roller and curved metal back plate and are able to pump air and can have tube rupture with arterial inflow clamping. The necessary cardiac index delivered by the bypass pump is determined by the patient's body temperature and oxygen consumption. For normothermia or mild hypothermia, a cardiac index of 2 to 4 L/min/m^2 is satisfactory, although flows of about half these levels have been used successfully. Low flows have the advantage of less blood trauma and less noncoronary collateral blood flow, which might

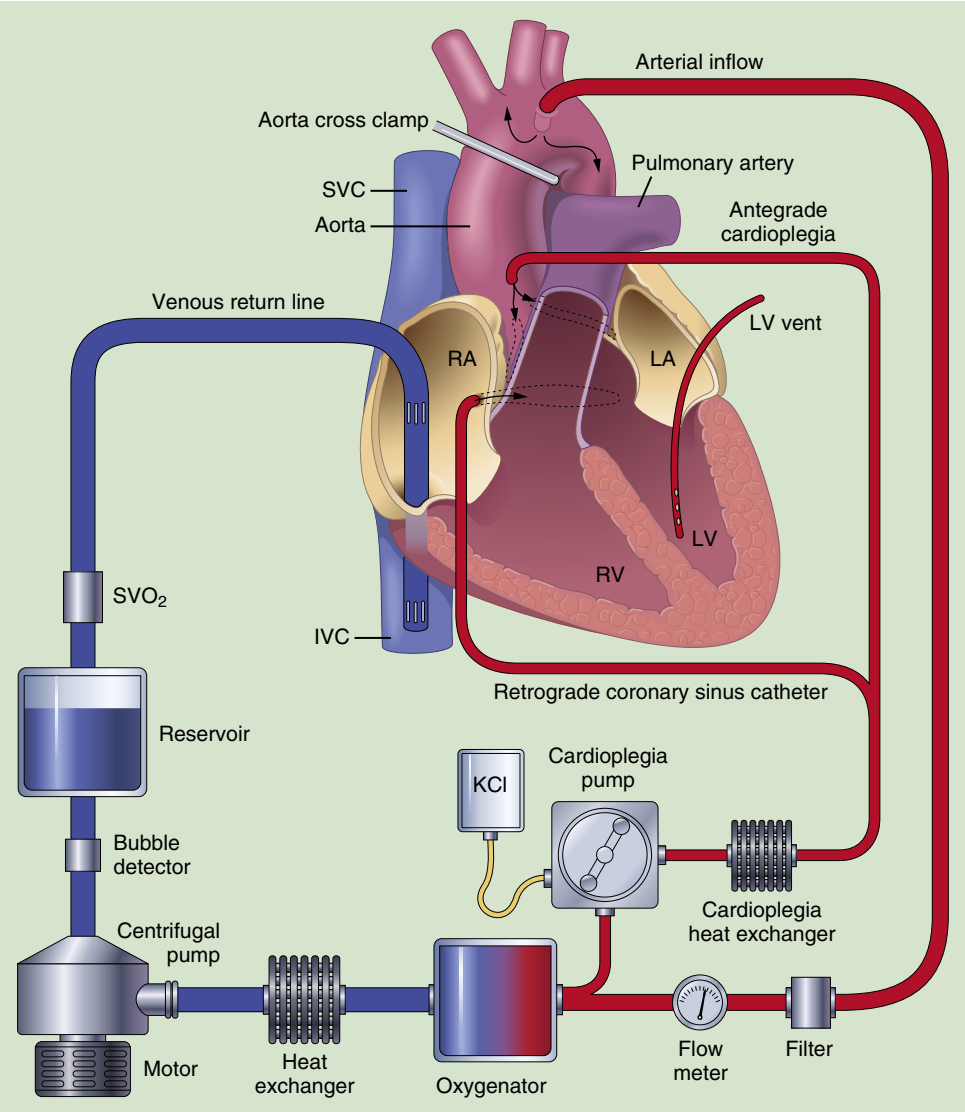

Fig. 25.3 Schematic diagram of a cardiopulmonary bypass circuit. Blood from cannulas placed through the right atrium (RA) and into the inferior vena cava (IVC) drains by gravity into a reservoir and then is pumped by a centrifugal pump through a heat exchanger, oxygenator, and filter prior to return to the ascending aorta. Blood mixed with cardioplegia solution is pumped alternatively into the proximal ascending aorta or into the coronary sinus. Venting can be from a cannula placed through the right superior pulmonary vein into the left ventricle, or from the ascending aorta antegrade cardioplegia cannula, or the pulmonary artery. *LA,* Left atrium; *LV,* left ventricle; *RV,* right ventricle; *SVC,* superior vena cava.

result in better myocardial protection. Blood is oxygenated by a membrane or bubble oxygenator. Membrane oxygenators use a blood-membrane-gas interface rather than a blood-gas interface and produce less trauma to the blood compared with bubble oxygenators. Because membrane oxygenators cause less trauma to blood components than bubble oxygenators, membrane-based oxygenator systems are the norm. Bubble oxygenators consisted of an oxygenator column, a defoaming section to remove air bubbles, and an arterial reservoir. They are not commonly used today. With either form of oxygenator Pao_2 is maintained by adjusting the concentration of oxygen into the oxygenator. Air-oxygen mixing may be used to avoid hyperoxia. Carbon dioxide levels are controlled between 35 and 45 mm Hg by controlling the sweep (the total free gas flow through the oxygenator). In the past, carbon dioxide was added to maintain $Paco_2$ and pH at levels considered normal for 37° C. Carbon dioxide

Box 25.11 Protocol to Initiate Cardiopulmonary Bypass: HADDSUE

*H*eparin	Was heparin administered? If the surgeon is placing sutures in the aorta for aortic cannulation, ask about heparin. Do not allow a surgeon to initiate cardiopulmonary bypass without heparin administration or alternative profound anticoagulant; the results will immediately be fatal.
*A*CT	Did the heparin increase the ACT to 450 seconds or greater? Were antifibrinolytics given?
*D*rugs	Were additional nondepolarizing muscle relaxants or anesthetics administered to prevent inspiration during venous cannula placement, which could result in gas emboli?
*D*rips	Did you discuss any infusions with the perfusionist that may interfere with hemodynamic management during bypass? Arterial blood pressure on cardiopulmonary bypass depends on flow and resistance. Drugs that affect resistance will affect arterial blood pressure. Drugs that affect venous capacity will reduce venous return to the reservoir and force a reduction in pump flow.
*S*wan	Pull back the pulmonary arterial catheter 5 cm to avoid pulmonary arterial injury or pulmonary infarction during bypass.
*U*rine	Measure the total urine output so that the urine produced during bypass can be tabulated. Urine output can be quite variable during bypass depending on the extracorporeal circulatory prime, volume administered, intrinsic hormonal response to cardiopulmonary bypass, and renal function.
*E*moli	Check the aortic cannula visually to detect any emboli.

ACT, Activated clotting time.

is no longer added to cardiopulmonary bypass circuits to maintain blood gases. Bypass circuits are flushed with carbon dioxide prior to priming to speed priming and reduce gas emboli in the circuit. Carbon dioxide is also continuously flushed into the pericardial cavity to replace air during bypass in an effort to reduce the significance of gas emboli during bypass. Carbon dioxide is more easily absorbed than the nitrogen in air reducing the duration that gas emboli take to be resorbed.

Heat exchangers are incorporated into bypass circuits to control the patient's body temperature by heating or cooling blood as it circulates. Hot or cold water entering the unit at one end with blood entering at the other provides an efficient countercurrent flow system. Metabolic requirements are decreased about 8% for every degree Celsius decrease in body temperature below 37° C. The optimal temperature management for cardiopulmonary bypass is not entirely clear. Eighteen degrees (18° C) is used prior to circulatory arrest and 28° C is common during aortic cross-clamping with rewarming to 37° C prior to weaning from bypass. Newer protocols maintain temperature between 31° C and 33° C. Normothermic (37° C) bypass is associated with an increase in cerebrovascular accidents.[76]

Blood from the pericardial cavity and the opened heart, as during a valve replacement, is returned to a cardiotomy reservoir, where it is filtered, defoamed, and pumped to the oxygenator for recirculation. The cardiotomy suction may be a major cause of hemolysis and emboli during cardiopulmonary bypass. Filters are incorporated in the cardiotomy reservoir and the arterial circuit to act as traps for particulate debris (e.g., blood clot, latex, talc, fat, Silastic, polyethylene) that could act as systemic emboli.

The tubing used for the cardiopulmonary bypass system is flushed with carbon dioxide, then filled (primed) with crystalloid. Additives to the circuit may include albumin, hetastarch, blood, bicarbonate, heparin, and antibiotics. The goal is a predetermined solution that is calculated to produce a specific hematocrit with institution of total cardiopulmonary bypass. Because whole body hypothermia (18° C to 28° C) may be utilized, the pump prime often contains little or no blood, such that the hematocrit of blood during cardiopulmonary bypass is 20% to 30%. Hemodilution is important for decreasing viscosity during hypothermia. It is mandatory that all air be cleared from the arterial side of the circuit before institution of cardiopulmonary bypass. Indeed, pumping of air into the patient by the cardiopulmonary bypass machine is an ever-present hazard. Carbon dioxide flushing prior to priming and continuous flushing of the pericardium reduce gas emboli risk. Patients who suffer gas emboli can be treated with hyperbaric oxygen with improvements in neurologic function even 24 hours after embolization.[77] Early treatment may have better results.

Heparin-induced anticoagulation of the patient is mandatory before placement of the venous and aortic cannulas used for cardiopulmonary bypass. The usual initial dose of heparin administered intravenously is 300 to 400 units/kg. The adequacy of anticoagulation is subsequently confirmed by determination of the activated coagulation time, which is typically maintained at greater than 450 seconds during cardiopulmonary bypass (when baseline normal is 90 to 120 seconds).[75]

Monitoring During Cardiopulmonary Bypass

Institution of cardiopulmonary bypass is often associated with decreases in mean arterial pressure, presumably reflecting the dramatic decreases in viscosity that result from infusion of prime solutions and activation of systemic inflammatory response. In addition, peripheral vasodilation may accompany decreased oxygen delivery that occurs in the early period of hemodilution. Administration of an α-agonist, such as phenylephrine, to increase perfusion pressures to higher than 40 mm Hg in the early period after institution of cardiopulmonary bypass may

be recommended on the assumption that perfusion pressure is important for maintenance of cerebral blood flow. The correct arterial blood pressure during bypass is debatable. Lower pressures may reduce cerebral blood flow and reduce emboli load to the brain. Higher pressures may improve cerebral blood flow and reduce watershed infarction, but higher pressures come from higher flows and more emboli per unit time. Pressures below 40 mm Hg are avoided if possible in adults. Pressures higher than 60 mm Hg are used during rewarming. Pressures up to 80 to 90 mm Hg may be used in patients with cerebral vascular disease. Evidence to support these recommendations is limited.

After the initial decrease, mean arterial pressure during cardiopulmonary bypass often begins to increase spontaneously, perhaps reflecting activation of the renin-angiotensin system or sympathetic nervous system. Mean arterial pressures higher than 100 mm Hg can lead to impairment of tissue perfusion as well as the risk of intracranial hemorrhage. Furthermore, noncoronary collateral blood flow is likely to be increased as mean arterial pressure increases, resulting in perfusion of the heart with blood at higher temperatures than desired for optimal cellular protection. Hypertension is often treated by decreasing SVR with volatile anesthetics administered through the oxygenator or the continuous intravenous administration of nitroprusside. Nitroglycerine has reduced effect on cardiopulmonary bypass because its action is predominantly venodilation and arterial pressures during bypass are primarily dependent on SVR.

An increasing central venous pressure with or without facial edema (eyelids and scleras) may reflect improper placement of the vena cava cannula resulting in obstruction to venous drainage. For example, insertion of a cannula too far into the superior vena cava can obstruct the right innominate vein, leading to an increase of cerebral venous pressure with associated cerebral edema. Placement of a cannula too far into the inferior vena cava results in abdominal distention. Confirmatory evidence of misplacement of a vena cava cannula is inadequate venous return from the patient to the cardiopulmonary bypass machine. Prompt withdrawal of the vena cava cannula to a more proximal position should immediately improve venous drainage.

A pulmonary artery catheter detects increases in pulmonary artery pressures caused by malfunction of the left ventricular vent and the associated inadequate decompression of the left ventricle. Persistent left ventricular distention can result in damage to the contractile elements of the myocardium.

Blood gases and pH are monitored frequently during cardiopulmonary bypass. A mixed venous Po_2 less than 30 mm Hg associated with metabolic acidosis may indicate inadequate tissue perfusion. Temperature correction of $Paco_2$ and pH is probably not necessary. Urine output may serve as a guide to the adequacy of renal perfusion, with an output of 1 mL/kg/h being a common expectation. Continuous cerebral oximetry with infrared spectroscopy can detect poor cerebral perfusion and may reduce risk.

During total cardiopulmonary bypass, the lungs are left quiescent with or without moderate continuous positive airway pressure. The best composition of gases in the lungs during this period is unsettled. Continued ventilation of the lungs with oxygen may be appropriate when there is some pulmonary blood flow, as evidenced by a pulsatile pulmonary artery trace. If there is a pulsatile pulmonary arterial pressure or systemic arterial pressure, the lungs should be ventilated because there is only partial cardiopulmonary bypass.

Esophageal, rectal, bladder, and blood temperatures are monitored routinely. Rapid rewarming caused by a high blood-to-body temperature gradient is avoided to prevent gas emboli. Drug-induced vasodilation as produced by a volatile anesthetic or nitroprusside may speed the rewarming process, as reflected by a more rapid approach of the rectal (core) to esophageal (blood) temperature, but should be used carefully. Measurement of urinary bladder temperature may be a superior alternative to monitoring rectal temperature, as bladder temperature may reflect core temperatures better than rectal.

Myocardial Preservation

The goal of myocardial preservation is to decrease myocardial damage introduced by the period of ischemia associated with cardiopulmonary bypass. This goal is achieved by decreasing myocardial oxygen consumption by infusing cardioplegia solutions containing potassium into the aortic root, which in the presence of a distally cross-clamped aorta, and competent aortic valve ensures diversion of the solution into the coronary arteries. Alternatively, the cardioplegia solution may be administered retrograde through a cannula placed into the coronary sinus. Monitoring of coronary sinus pressures during retrograde administration is used to assess catheter placement. If the pressure at the distal tip of the coronary sinus catheter during cardioplegia administration at 200 mL/min is equal to central venous pressure, the catheter is not in the coronary sinus but is most likely in the right atrium. If the pressure is very high (more than 100 mm Hg), the coronary sinus catheter is up against a vascular wall. If the pressure in the coronary sinus catheter is 40 to 60 mm Hg during a 200 mL/min infusion, the catheter is correctly positioned. Positioning of the coronary sinus catheter should be checked with TEE and manual feel by the surgeon. If the catheter is in too deep, cardioplegia to the right ventricle will be compromised, resulting in poor right ventricular protection. An additional route for infusion of cardioplegia solutions is directly into newly placed bypass grafts.

Potassium in the cardioplegia solution blocks the initial phase of myocardial depolarization, resulting in cessation

of electrical and mechanical activity. The cold solution produces selective hypothermia of the cardiac muscle. At 30° C, the normally contracting heart muscle consumes oxygen at a rate of 8 to 10 mL/100 g/min. Oxygen consumption in the fibrillating ventricle at 22° C is 2 mL/100 g/min. The electromechanically quiet heart at 22° C consumes oxygen at a rate of 0.3 mL/100 g/min. The effectiveness of cold cardioplegia is monitored by measuring heart temperature with a temperature probe placed into the left ventricular muscle plus the absence of any visible electrical activity on the ECG. Cold cardioplegia infusions are supplemented by total-body hypothermia and localized epicardial surface cooling using ice or cold irrigation solutions placed into the pericardial space. Cardioplegia solutions may also contain many additives including blood, insulin, glucose, aspartate, glutamate, calcium, magnesium, nitroglycerin, and superoxide dismutase, at the discretion of the surgeon. None of these additives is definitively better than cold blood cardioplegia with a short cross-clamp time. Adequate myocardial preservation is suggested by good myocardial contractility without the need for inotropic drugs at the conclusion of cardiopulmonary bypass.

A side effect of cardioplegia solutions is an increased incidence of atrioventricular heart block due to intramyocardial hyperkalemia. This heart block usually resolves in 1 to 2 hours and can be treated temporarily by use of an artificial cardiac pacemaker. Intramyocardial hyperkalemia also produces decreased myocardial contractility. Systemic hyperkalemia is likely to occur when coronary sinus blood containing cardioplegia solution is returned to the oxygenator for subsequent circulation. Decreased renal function during cardiopulmonary bypass will also contribute to hyperkalemia. If hyperkalemia persists at the conclusion of cardiopulmonary bypass, regular insulin (10 to 20 units IV) can be given in combination with glucose (25 to 50 mg IV) in an attempt to shift potassium into the cells. The perfusionists can also add crystalloid solutions to the bypass circuit and then use a hemoconcentrator to ultrafiltrate the blood thereby eliminating potassium.

Management of Anesthesia

Drugs selected for maintenance of anesthesia in patients undergoing cardiopulmonary bypass are influenced by the patient's cardiac disease. Patients with diabetes or those who develop glucose intolerance during surgery should have infusions of insulin with a target of glucose between 120 and 180 mg/dL. Avoidance of hypoglycemia is essential to avoid neurologic injury. Hyperglycemia may lead to increased risk of infections and neurologic sequelae. Infusions of dexmedetomidine are associated with reduced risk of delirium.[53] Institution of cardiopulmonary bypass may produce a sudden dilution of circulating drug concentrations. For this reason, supplemental anesthetics, such as benzodiazepines or opioids, may be needed. Likewise, skeletal muscle paralysis may be supplemented with additional nondepolarizing neuromuscular blocking drugs. An additional dose of nondepolarizing muscle relaxant should be administered just prior to placement of the venous cannula to avoid inspiratory efforts entraining air. Anesthetic depth can also be increased by volatile anesthetics from vaporizers incorporated into the cardiopulmonary bypass circuit. The effect of hemodilution on drug concentrations is likely to be offset by a decreased need for drugs during hypothermia. Anesthetic requirements seem to be minimal following rewarming to a normal body temperature at the conclusion of cardiopulmonary bypass. Therefore, additional anesthesia is not routinely required during rewarming or the early period after the conclusion of cardiopulmonary bypass. However, additional anesthetic will be needed to maintain tracheal intubation for transfer and postoperative ventilation in the ICU. An intravenous anesthetic infusion (propofol or dexmedetomidine) with minimal hemodynamic effects should be given in the procedure and continued into the ICU. Dexmedetomidine-induced sedation may reduce the risk of postoperative delirium after cardiac surgery.[53]

Discontinuation of Cardiopulmonary Bypass

Optimal anesthetic care can be achieved with checklists. The checklist for weaning from cardiopulmonary bypass consists of the mnemonic WRMVP (Box 25.12), as in Wide Receiver Most Valuable Player (a wide receiver is an American football position for our non–United States readers):

1. Warm: Is the patient at 37° C?
2. Rhythm: Does the patient have a stable cardiac rhythm?
3. Monitors: Are the monitors turned back on? How about the pulse oximeter? The pulse oximeter is essential postoperatively both as a monitor of arterial oxygen

Box 25.12 Checklist for Weaning From Cardiopulmonary Bypass: WRMVP

*W*arm	Body temperature (37° C) is likely to decrease rapidly after cardiopulmonary bypass if patient is not adequately rewarmed, with resultant metabolic acidosis and poor myocardial contractility.
*R*hythm	Confirm that the patient has a stable cardiac rhythm.
*M*onitors	Confirm that the monitors are turned on; pulse oximeter is essential for arterial oxygen saturation and cardiac output.
*V*entilator	Confirm that it is turned on.
*P*erfusion	Confirm heart beating, presence of vasodilation.

saturation and cardiac output. If the pulse oximeter is not working, it may be that perfusion is inadequate. The pulse oximeter is an excellent low cardiac output alarm.

4. Ventilator: Is the ventilator back on? It is easy to forget this, and rapid desaturation after bypass detected from the pulse oximeter should be quickly identified.
5. Perfusion: Is the heart beating, is the vasculature appropriate for the cardiac function? Very few hearts following cardiopulmonary bypass are adequate to maintain an arterial blood pressure in the face of profound systemic vasodilation. The SVR should be normal (not profoundly vasodilated or constricted). Cardiopulmonary bypass is discontinued when the patient is hemodynamically stable and normothermia has been reestablished. In the absence of adequate rewarming before discontinuation of cardiopulmonary bypass, body temperature is likely to decrease rapidly in the post–cardiopulmonary bypass period, resulting in metabolic acidosis and poor myocardial contractility. When the left side of the heart has been opened, as during valve replacement surgery, it is mandatory to remove all air from the cardiac chambers and pulmonary veins before permitting the heart to eject blood into the aorta. Otherwise, systemic air emboli can occur with disastrous cardiac and central nervous system effects. The presence of air can be checked with TEE. Unrecognized air in the coronary arteries may be a cause of sudden onset of poor myocardial contractility after discontinuation of cardiopulmonary bypass. Air embolization with neurologic defects can be treated with hyperbaric oxygen even 24 hours after surgery with improvements in neurologic outcome.[77] Measurement of cardiac filling pressures, determination of thermodilution cardiac outputs, and calculation of systemic and PVR are helpful for guiding intravenous fluid replacement and the appropriate selection of drugs in the early post–cardiopulmonary bypass period (Table 25.4). Alternatively, TEE can be used to estimate the adequacy of intravascular fluid volume and myocardial contractility. TEE is also useful for evaluating cardiac valve function and intracardiac blood flow patterns, particularly following surgical repair or replacement.

The most common hemodynamic abnormality after cardiopulmonary bypass is inadequate SVR. It is very difficult to wean the patient from cardiopulmonary bypass with an SVR that is low. SVR can be calculated as follows:

$$\text{Mean arterial pressure (mm Hg)} - \text{central venous pressure (mm Hg)} / \text{pump flow (L/min)} \times 80$$

SVR should be between 1200 and 1400 prior to weaning from bypass. The units of SVR are dyne-seconds/centimeters^5 (dyn-s/cm^5). SVR can be normalized with a vasoconstrictor prior to weaning from cardiopulmonary bypass. The goal should be to match the vascular input impedance to the cardiac output impedance to optimize energy transfer. It is much easier to adjust the vasculature to match the heart than to force the heart to tolerate a dilated vasculature. On occasion, an inotropic drug, such as epinephrine, norepinephrine, dopamine, or dobutamine, is needed. In cases of severe ventricular dysfunction, a combination of drugs (epinephrine or norepinephrine and amrinone or milrinone) with an intra-aortic balloon pump or left ventricular assist device is necessary to maintain optimal cardiac output. The use of combinations of β-agonists and phosphodiesterase inhibitors produces synergistic increases in cardiac function. The vasoconstriction of epinephrine or norepinephrine is counterbalanced by the vasodilation of the

Table 25.4 Diagnosis and Treatment of Cardiovascular Dysfunction After Cardiopulmonary Bypass

Systemic Blood Pressure	Atrial Pressure	Cardiac Output	Diagnosis	Therapy
Decreased	Decreased	Decreased	Hypovolemia	Administer volume
Decreased	Decreased	Increased	Vasodilation Low blood viscosity	Vasoconstrictor Erythrocyte transfusion
Decreased	Increased	Decreased	Left ventricular dysfunction	Inotrope Inodilator Vasodilator Mechanical assistance
Increased	Increased	Decreased	Vasoconstriction Left ventricular dysfunction	Vasodilator Inotrope
Increased	Decreased	Increased	Hyperdynamic	Volatile anesthetic β-Antagonist

phosphodiesterase inhibitor. Careful measurement of SVR and supplementation with a vasoconstrictor, such as phenylephrine, are frequently needed to maintain a normal SVR. If β-agonists are needed, frequent attention must be given to measurement and control of potassium, glucose, calcium, pH, and the presence of arrhythmias. Gas emboli to the coronary arteries may suddenly and profoundly reduce ventricular function. Posterior papillary muscle dysfunction at the conclusion of cardiopulmonary bypass may result in mitral regurgitation as evidenced by the presence of prominent V waves on the pulmonary artery occlusion pressure tracing. This dysfunction may reflect less than optimal cardioplegic protection of the posterior myocardium, which is most vulnerable to warming effects from blood in the adjacent descending aorta, as well as perfusion with warm blood representing noncoronary collateral circulation. Acute mitral regurgitation can also occur with volume overload from excessive fluid administration; it can be managed simply by the use of reverse Trendelenburg position to reduce venous return to the heart.

A mechanical complement to inotropic support of cardiac output is the intra-aortic balloon pump. The intra-aortic balloon pump (a 25-cm long balloon mounted on a 90-cm stiff plastic catheter) is typically inserted percutaneously through the femoral artery and advanced so that the tip is just distal to the left subclavian artery. The balloon is timed to inflate during diastole to augment diastolic blood pressure and increase the gradient for coronary perfusion improving coronary blood flow. The balloon deflates immediately before systole, thus decreasing afterload and lowering oxygen requirements. Coronary blood flow is increased, with little or no increase in cardiac work, which may result in improvements in cardiac output. Aortic insufficiency may be worsened by intra-aortic balloon inflation. Rapid heart rates and cardiac dysrhythmias interfere with proper balloon timing and optimal augmentation of cardiac output. Temporary ventricular assist can also be provided by catheters with impellers that rely on the Archimedes screw technology. The impeller device comes in two sizes capable of 2.5 or 5.0 L/min flow.

When an adequate systemic arterial blood pressure and cardiac output have been maintained for several minutes, the vena cava cannula is removed and protamine administration is begun to reverse heparin anticoagulation. Protamine administration is dangerous and frequently is associated with hypotension from release of histamine. Occasionally there is severe pulmonary hypertension or even anaphylaxis from protamine administration. Protamine should be administered after a test dose and given slowly to avoid catastrophic hemodyamic collapse. Administration of the vasoconstrictor phenylephrine can be used to maintain arterial blood pressure. In cases of hemodyamic collapse even epinephrine boluses will be inadequate, and return to cardiopulmonary bypass after emergency reheparinization can be lifesaving. Isophane (NPH) insulin is made with protamine. Diabetics who use NPH insulin may be at increased risk for protamine reactions. Protamine allergic reactions may be reduced with a combination of histamine blockade (H_1 [diphenhydramine] and H_2 blocker [ranitidine]) and a steroid (hydrocortisone). The aortic cannula is removed after protamine administration is safely concluded. Pharmacologic measures to decrease bleeding include administration of antifibrinolytics (aminocaproic acid, tranexamic acid, and formerly aprotinin) and desmopressin (improves platelet function in patients with von Willebrand disease). Blood loss throughout the procedure as well as the blood in the bypass tubing can be salvaged, washed, and retransfused using "cell saver" devices.

Administration of nitrous oxide after cardiopulmonary bypass is not recommended because this gas could unmask the presence of air in the heart or coronary arteries. For this reason, anesthesia is most often supplemented, when necessary, by the intravenous administration of propofol, dexmedetomidine, opioids, benzodiazepines, or alternatively with low inhaled concentrations of volatile anesthetics. The blood and fluid that remain in the cardiopulmonary bypass circuit are washed and collected into sterile plastic bags as packed cells for possible reinfusion to the patient. High resistance to blood flow in the arm induced by vasoconstriction may result in a falsely low systemic arterial blood pressure reading from the radial artery in the early period after cardiopulmonary bypass. If there is a question of inadequate arterial blood pressure, direct pressure measurement from the ascending aorta can be instantly obtained. Placement of a femoral arterial catheter is needed if there is a gradient between central and radial pressure. Any gradient between central aortic and radial artery blood pressure usually disappears within 60 minutes.

Intravenous anesthetics such as propofol infusions,[78] dexmedetomidine infusions,[53] or opioids and benzodiazepines are continued after bypass and continued into the ICU to provide sedation prior to tracheal extubation. Dexmedetomidine-induced sedation may reduce postoperative delirium after cardiac surgery.[53] The time to tracheal extubation is shortening after cardiopulmonary bypass but some period of time of postoperative intubation is common after leaving the operating room. Once oxygenation is adequate (Pa_{O_2} above 80 mm Hg on 40% oxygen), the bleeding is controlled, the patient is awake, and neuromuscular function has recovered, extubation can be considered. There is no benefit from prolonged postoperative ventilation in cardiac surgery.

The large financial cost of cardiac surgery is due in part to the duration of intensive care required for these patients. Improvements in anesthetic, surgical, and perfusion techniques serve to decrease the need for prolonged care of these patients in an ICU. The concept known as "fast track" as applied to cardiac surgical patients includes early postoperative awakening and tracheal extubation.[79]

Off-Pump Coronary Artery Bypass Graft Surgery

In an effort to minimize postoperative morbidity, CABG surgery may be accomplished in selected patients without institution of cardiopulmonary bypass and in the presence of a spontaneously beating heart and normothermia. Cardiopulmonary bypass using extracorporeal circulatory support was developed because it is difficult to safely produce a high-quality anastomosis between a vessel and a coronary artery while the heart is beating. Off-pump CABG was developed to reduce the sequelae of extracorporeal circulatory support, which may include stroke, global encephalopathy, renal failure, pulmonary injury, and death. Off-pump CABG surgery is limited by several considerations including the quality of the distal anastomosis and long-term graft patency is of primary concern. There are several problems with off-pump CABG or "beating heart" surgery. The first is motion of the coronary artery, making suture placement for the anastomosis difficult. Anticoagulation with heparin is achieved and activated clotting time (ACT) is measured. There is some debate on the appropriate ACT levels of an off-pump CABG with some surgeons using standard doses appropriate for cardiopulmonary bypass (300 to 400 units/kg ACT > 450 s) and others using smaller dose heparin (200 unit/kg). Antifibrinolytics (aprotinin, aminocaproic acid, or tranexamic acid) are sometimes not used if the patient is not going on extracorporeal circulatory support. The ability to immediately go on extracorporeal circulatory support must be available during the conduct of off-pump CABG should the patient have circulatory collapse or cardiac arrest. Blood flow in the target coronary artery is usually stopped by placement of a proximal and distal latex suture, which is lifted up, consequently arresting flow. Alternatively, a silicon stent can be placed in the target coronary artery during production of the anastomosis to maintain coronary flow. The silicon stent is removed just prior to tightening the suture. Stopping the coronary blood flow in the target coronary may cause myocardial ischemia, ventricular arrhythmias, ventricular dysfunction, heart block, hemodynamic collapse, and cardiac arrest. When flow is resumed in the coronary artery, reperfusion arrhythmias may occur. Prophylactic antiarrhythmic therapy should be administered prior to off-pump CABG. Magnesium (2 g IV slowly) combined with lidocaine (100-mg bolus followed by 2 mg/min) infusion works well. Intravenous amiodarone should be used in patients who demonstrate a tendency toward ventricular tachycardia or fibrillation.

The technology for the off-pump CABG was developed in the 1990s and initially stabilized the heart with a retractor that simply pushed on the myocardium while it was lifted into the retractor with stay sutures. This system was difficult to use because ventricular diastolic filling was compromised by external pressure on the heart. The development of a retractor that used a vacuum foot (Octopus) to stabilize the heart eliminated the external pressure on the myocardium and improved ventricular diastolic function during the distal anastomosis. Coronary grafts to the inferior and lateral circulation were difficult to perform because retraction of the heart reduced diastolic filling and caused hemodynamic collapse. The use of suction retractors (Starfish and Urchin) for lateral and anterior displacement of the heart during production of the lateral and inferior anastomosis in combination with steep Trendelenburg positioning greatly stabilized hemodynamics.

Careful cooperation between the cardiac surgeon and cardiac anesthesiologist is essential for off-pump CABG. Surgical positioning must be performed in conjunction with anesthesia. The surgeon must not open the coronary artery for a distal anastomosis without ensuring that the patient will hemodynamically tolerate the 10- to 15-minute anastomosis. Communication between the cardiac surgeon and cardiac anesthesiologist is especially critical during this process. Some surgeons use a 5-minute period of ischemic preconditioning prior to a 5-minute recovery period followed by the anastomosis. The 5-minute preconditioning period can be used to optimize hemodynamics and test to see if the patient will tolerate the anastomosis. Ischemic preconditioning may reduce ischemic injury at the cost of a longer operative time.

Anastomosis of the left internal mammary artery (LIMA) to the left anterior descending (LAD) coronary artery was the first off-pump bypass and is technically the simplest and most important for reducing myocardial ischemia. The LIMA to LAD anastomosis is usually conducted first, which improves coronary blood flow to the LAD circulation. Saphenous vein grafts are then placed to the obtuse marginal (OM) branches off the circumflex artery and finally to the posterior descending artery (PDA), which usually branches from the right coronary artery. Placement of the lateral wall grafts to the obtuse marginal requires shifting the heart to the right, which may be better tolerated by opening the right pleural space and placing lifting-stay sutures into the inferior pericardium. Steep Trendelenburg positioning with right tilt will improve hemodynamics. Intravascular administration of colloid and vasoconstriction with phenylephrine should be used to maintain arterial blood pressure. The ECG amplitude may diminish dramatically making ST segments difficult to observe secondary to myocardial positioning. TEE of the ventricle may be impossible secondary to lifting of the ventricle off the esophagus. Anastomosis to the posterior descending coronary artery can be produced with steep Trendelenburg position, volume loading, and vasoconstriction with phenylephrine. Low cardiac outputs can be tolerated for the brief period of the distal anastomosis. Completion of the proximal aortic anastomosis for the saphenous vein grafts requires placement of a side biter clamp on the ascending aorta.

Devices that staple the proximal anastomosis are available and may reduce the use of side biter clamps with less aortic trauma. Arterial blood pressure can be decreased to assist placement of this clamp with increasing inspired concentrations of volatile anesthetics or cardiac manipulation to reduce venous return. Once the distal and proximal anastomoses are complete, any air in the saphenous vein graft must be removed to avoid coronary gas emboli. Removal of the aortic side biter should only be done once any remaining air is removed from the saphenous vein grafts to avoid systemic gas emboli. Heparin anticoagulation should then be carefully reversed with protamine. Protamine reactions, which include hypotension, pulmonary hypertension, and anaphylaxis, are more difficult to treat in off-pump CABG because rapid return to extracorporeal circulatory support will require full reheparinization, bypass circuit priming, followed by proximal aortic cannula and right atrial venous cannula placement. If hypotension occurs following protamine administration, rapid treatment with the vasoconstrictor phenylephrine is frequently needed. Severe reactions to protamine may be treated with intravenous epinephrine, diphenhydramine, H_2 blockade, steroids, intravascular fluid administration, and if necessary reheparinization, and initiation of extracorporeal circulatory support. The use of off-pump CABG is becoming less frequent after the publication of the ROOBY (*r*andomized *o*n/*o*ff *by*pass) trial, which showed a reduction in graft patency and poorer outcomes in the off-pump group.[80]

Management of Anesthesia

Anesthesia for off-pump CABG is very similar to anesthesia for on-pump CABG with a few notable exceptions. Patients for off-pump CABG have similar medical conditions, medical therapies, and requirements for care as those receiving on-pump CABG. All preoperative medications with the exception of oral hypoglycemic agents should be continued in the perioperative period. Patients with diabetes should be managed with intravenous insulin infusions and frequent blood glucose determinations. Coumadin (warfarin) should be stopped at least 7 days prior to an operation. Platelet inhibitors, with the exception of aspirin, should be discontinued preoperatively depending on clearance. Preoperative heparin infusions can be continued into the operating room and discontinued after full heparinization. Preoperative sedation with a benzodiazepine and nasal cannula oxygen is effective at reducing sympathetic stimulation but is rarely used in the current era.

Induction of anesthesia should have the goal to maintain arterial blood pressure within 10% to 20% of baseline. Baseline measurements of heart rate, arterial blood pressure, pulmonary artery pressures, central venous pressures, and cardiac output can be obtained using intra-arterial and pulmonary arterial catheters allowing preinduction optimization of hemodynamics. If severe pulmonary hypertension or low cardiac output is identified, a discussion of the case with the cardiac surgeon is warranted. An infusion of the vasoconstrictor phenylephrine may be started prior to induction of anesthesia and then titrated to maintain arterial blood pressure. Any intravenous anesthetic can be used to induce anesthesia, but benzodiazepines (midazolam) and narcotics (fentanyl) are common. Sufentanil decreases heart rate more than fentanyl, which may or may not be advantageous. Dexmedetomidine can be used to supplement other drugs and may reduce stress response and postoperative delirium.[53] Etomidate, propofol, and sodium thiopental are also effective for induction of anesthesia, but doses should be reduced in patients at risk for hypotension.

Once anesthetic induction is complete, nondepolarizing muscle relaxants (rocuronium, vecuronium, cisatracurium) or succinylcholine can be used to facilitate tracheal intubation. Bradycardia (heart rates between 45 and 60 beats/min) is helpful during conduct of the distal anastomosis. If reflux is a concern, a modified rapid sequence induction with cricoid pressure is warranted. If the patient is thought to have a difficult airway, the standard difficult airway protocols should be used with special attention to avoid tachycardia and sympathetic stimulation. Intubation of cardiac surgery patients should follow the standard protocols for airway management, the only difference being that the tolerance for tachycardia, hypotension, or hypertension is greatly reduced and myocardial ischemia, ventricular arrhythmias, and hemodynamic collapse are the possible rapid sequelae of complications.

Maintenance of anesthesia is usually with a volatile anesthetic (isoflurane or sevoflurane) in combination with an opioid (fentanyl or sufentanil). Nitrous oxide should be avoided secondary to reduction in F_{IO_2}, potential for pulmonary vasoconstriction, and potential to increase the volume of gas emboli. Maintenance infusions of propofol, dexmedetomidine, or remifentanil are also commonly used. If remifentanil is chosen, inadvertent discontinuation of the infusion should be avoided because the metabolism is rapid. Cardiac depression may be greater with remifentanil than fentanyl or sufentanil, making its use more difficult in patients with limited cardiac reserve. Prophylactic antiarrhythmic therapy (lidocaine and magnesium or amiodarone) is appropriate to avoid arrhythmias from manual manipulation of the heart, from ischemia during the distal anastomosis, and upon reperfusion after completion of the anastomosis. Anticoagulation is achieved with heparin and monitored with ACT or heparin assay. Hemodynamic stability during the distal anastomosis is achieved with careful surgical manipulation and retraction of the heart, table positioning, infusions of vasoconstrictors, and volume. Inotropic stimulation with β-agonists has the potential to raise the heart rate, making completion

of the distal anastomosis more difficult and lowering the threshold for ventricular arrhythmias. If β-agonists are needed to support cardiac output during conduct of the distal anastomosis, use of extracorporeal circulatory support should be considered. Heparin anticoagulation is reversed with protamine after completion of the proximal and distal anastomoses and is confirmed by measurement of an ACT near baseline (120 to 140 seconds).

The duration and requirements for postoperative ventilation and sedation may be reduced in off-pump CABG and extubation of the trachea should be performed once hemodynamics are stable, bleeding is controlled, oxygen requirements are reduced (F_{IO_2} = 0.40 with P_{O_2} more than 80 mm Hg), neuromuscular blockade is reversed, and the patient is awake and breathing spontaneously with the help of continuous positive-pressure ventilation. Postoperative administration of β-adrenergic blockade may reduce the incidence of atrial fibrillation and myocardial ischemia and should be started as soon as hemodynamics will tolerate. Aspirin therapy should be resumed once bleeding is controlled. Discontinuation of anti-ischemic and vasodilator drugs (β-adrenergic blockers, calcium channel blockers, nitrates, and angiotensin inhibitors) should be avoided because withdrawal phenomena may lead to increased morbidity and mortality rates.

Cardiac surgery is continually advancing with hybrid operations, off-pump CABG, minimal access, surgical ventricular restoration, left ventricular assist devices, artificial hearts, and robotic mitral and coronary artery bypass surgery. Vigilance, cooperation, team work, and a very clear understanding of the surgical plans and hemodynamic consequences of procedures are essential to reduce the morbidity and mortality rates of these operations.

QUESTIONS OF THE DAY

1. How does risk stratification for cardiac disease differ from risk reduction?
2. How have the results of the POISE study impacted recommendations for perioperative cardiac risk reduction therapy?
3. A patient with severe aortic stenosis requires general anesthesia. What are the hemodynamic goals for the patient? What are the risks of hypotension during induction of anesthesia?
4. What is the "magnet mode" of a programmable cardiac pacemaker? Why should the specific magnet mode be known during the perioperative period?
5. A patient with hypertrophic cardiomyopathy develops intraoperative hypotension. What interventions are most likely to be effective?
6. A patient with cardiac tamponade is scheduled for a pericardial window in the operating room. What precautions should be taken before and during anesthesia induction to minimize the chance for cardiac arrest?
7. What are the major components of a cardiopulmonary bypass circuit? What principles are relevant in determining appropriate perfusion pressure during cardiopulmonary bypass?

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