

Postoperative Care of the Cardiac Surgical Patient

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The subspecialty of interventional cardiology began in 1977. Since then, the discipline of interventional cardiology has matured rapidly, particularly with regards to ischemic heart disease. As a result, more patients are undergoing percutaneous catheter interventional therapy for ischemic heart disease and fewer patients are undergoing surgical myocardial revascularization. Those patients referred for surgical revascularization are generally older and have more complex problems. Furthermore, as the population ages more patients are referred to surgery for valvular heart disease. The result of these changes is a population of surgical patients older and sicker than previously treated. These patients require even more specialized postoperative care and pose unique challenges in critical care management. The clinical challenges are accompanied by the need to provide care in a cost-conscious manner and in an atmosphere that is carefully scrutinized and benchmarked. Managing postoperative cardiac patients is more challenging now than in the past and it is extremely important that those physicians providing critical care for the postoperative cardiac surgical patient have a clear knowledge of their unique problems. This chapter is designed to provide a basic understanding of the physiologic derangements of this group of patients and to offer treatment strategies for their successful care.

Pathophysiologic Consequences

The open-heart patient requires specialized care because physiologic systems are disrupted by cardiopulmonary bypass (CPB). CPB results in a generalized inflammatory response caused by blood contact with the synthetic surfaces of the bypass circuit.¹ The interface between blood elements and the surfaces of the circuit causes a generalized inflammatory response. This inflammatory response results in a series of complex reactions that activate the complement, clotting, and

fibrinolytic cascades causing bleeding, microemboli, fluid retention, and an altered hormonal response.²⁻⁵

CPB is a nonspecific activator of the inflammatory system.⁶ After the discontinuation of CPB, generalized complement activation occurs with elevations of C3a and C5a anaphylatoxins.⁷ The activation of these anaphylatoxins can result in pulmonary sequestration of leukocytes^{7,8} and the production of superoxides. There then occurs further leukocyte activation and the generation of leukotactic factors that further increase the local inflammatory response.^{9,10} Also, vasoactive amines from platelets are liberated in response to CPB or possibly from protamine administration, which can result in pulmonary hypertension and systemic hypotension.¹¹ Yet another result of the complement activation is an increase in vascular permeability that may predispose the patient to a capillary-leak syndrome with fluid sequestration in the third space, particularly the lung.¹² From a clinical perspective, the generalized inflammatory response results in postoperative pulmonary dysfunction, renal dysfunction, and a resetting of the hypothalamic thermoregulatory center.^{9,12}

The inflammatory response caused by CPB also has direct negative cardiac effects. The inflammatory state caused by CPB involves platelet–endothelial cell interactions and vasospastic responses resulting in low-flow states in the coronary circulation.¹³ The anaphylatoxin C5a is a potent molecule that is spasmogenic and has leukocyte-activating properties that cause degranulation and release of toxic oxygen free radicals. The complement-exposed leukocytes are attracted to adhere to the vascular endothelium and to aggregate, resulting in margination in blood vessels and leukoembolization. These inflammatory cells mediate injury by increasing their production and releasing oxygen free radicals or proteolytic enzymes.¹⁴ It is this release of oxygen free radicals that is generally accepted as the cause for transient postoperative ventricular dysfunction that manifests itself about 2 h after cessation of CPB and is

at its worse at 4–5 h after CPB.^{15,16} Recovery of ventricular function begins in 8–10 h and full recovery usually occurs by 24–48 h.¹⁶ The systemic vascular resistance rises as ventricular function worsens. This is a compensatory mechanism in an effort to maintain systemic blood pressure and perfusion in the face of depressed ventricular contractility. The oxygen free radicals and the proteolytic enzymes released by the neutrophils also damage endothelial cells increasing capillary permeability resulting in capillary leak during this period.¹⁷ The capillary leak may last from 1 to 2 days and is related to the duration of CPB. Hypothermia has multiple adverse effects on the postoperative open-heart patient. Regarding the circulatory status, it predisposes cardiac dysrhythmias, increases SVR, precipitates shivering and impairs coagulation.¹⁸ It also indirectly decreases cardiac output by increasing vasoconstriction and causing bradycardia. As a consequence of the inflammatory state after CPB, the postoperative open-heart patient is in a unique physiologic state where rules applicable to other physiologic situations may not apply, and a failure to recognize this concept results in management errors. Concerns about the short- and long-term effects of CPB has generated the recent concept of off-pump coronary artery bypass surgery. While there seems to be growing evidence that this off-pump approach to the surgical management of ischemic heart disease is advantageous, there does remain some debate.¹⁹ Despite the movement toward avoidance of CPB in selected patients with ischemic heart disease, the majority of these patients as well as virtually all patients with valvular heart disease are operated on using CPB. The CPB circuit is not the only factor responsible for this altered physiologic state. The time of ischemia and reperfusion, hypothermia, hypotension with nonpulsatile flow, altered coagulation, and the administration of blood and products are other factors contributing to the altered postoperative physiologic state.²⁰

Management of the Postoperative Open-Heart Patient

Initial Management

The patient after open-heart surgery presents with multiple, rapidly changing clinical problems. Initially, these patients are unstable and their clinical status is extremely fluid and dynamic. Caring for the postoperative open-heart patient requires bedside presence and the knowledge of general fundamental concepts of patient care as well as concepts specific to this set of patients. The initial management of these patients as they return from the operating room is critical, for it may well set the tone for the rest of the recovery period. Clinical errors at this time can have far-reaching implications. The initial management should begin even before the patient arrives in the intensive care unit (ICU). It is vital to review the chart noting indications for surgery, preoperative hemodynamic data, comorbid conditions, medications, and allergies.

Upon the patient's arrival in the ICU, perform a careful systematic assessment of the patient. Begin the assessment by speaking directly to the surgical and anesthesia team. Ascertain what procedure was done in the operating room and inquire as to any intraoperative events that might impact the patient's postoperative course. Then, physically examine the patient as part of this initial evaluation. During the initial assessment, avoid focusing on any one issue and attempt to get a global picture of the patient's clinical status. At this time, the patient is completely dependent on support systems, and dysfunction of any one of these can lead to disaster.²¹ The following points must be observed: heart rate and rhythm, blood pressure, temperature, right and left heart filling pressures, hemodynamic profile, pharmacologic support, ventilator status, chest drainage, neurologic status, laboratory results, EKG, and chest X-ray. A thorough knowledge of the specific monitoring and drug delivery lines is imperative as is knowledge of where the drains are placed. Once the initial assessment is complete, specific issues can be identified, prioritized, and addressed.

Basics of Cardiovascular Hemodynamic Management

The primary objective in managing the postoperative open-heart patient is achieving adequate hemodynamic performance by optimizing myocardial oxygen supply and demand.²² Optimal tissue oxygenation is essential to avoid organ dysfunction and can be determined by calculating oxygen delivery and oxygen demand. Oxygen delivery is a function of oxygen-carrying capacity and cardiac output. Oxygen demand is a function of oxygen consumption.²³

The most important concept in the optimization of myocardial oxygen supply and demand, and tissue oxygenation is an adequate cardiac output. *Cardiac output* is expressed as liters per minute and *cardiac index* as liters per minute per square meter. Normal cardiac index is between 2.0 and 4.4 L/min/m².²⁴ An uncomplicated recovery from cardiac surgery can be anticipated when the cardiac index is maintained greater than 2.0 and 2.2 L/min/m².^{24,25} Cardiac output is a function of stroke volume and heart rate, where cardiac output (CO) is the product of heart rate (HR) and stroke volume (SV). An optimal heart rate is usually between 80 and 110 beats per minute.²⁶ This rate allows for optimal filling of the heart at an economic level of myocardial oxygen consumption. Stroke volume is determined by preload, afterload, and contractility, and can be influenced by cardiac rhythm. Stroke volume is the end-diastolic volume minus the end-systolic volume and in normal states is 70 ml

Preload refers to left ventricular end-diastolic sarcomere fiber length and is a function of end-diastolic ventricular volume (LVEDV). It can be directly measured by echocardiography and is indirectly measured by left heart filling pressures; i.e., pulmonary artery diastolic pressure (PADP), pulmonary capillary wedge pressure (PCWP), and left atrial pressure (LAP). The former are all reflections of the left ventricular end diastolic pressure (LVEDP). The compliance of the left

ventricle is determined by the relationship between filling volumes and pressures, or LVEDV/LVEDP. Stiff ventricles have low compliances and require higher filling pressures to achieve adequate volumes. This scenario is almost universal after cardiac surgery.

Afterload is a reference to left ventricular wall tension during systole. It is determined by intraventricular systolic pressure and ventricular wall thickness.²⁷ Since there is minimal change in left ventricular wall thickness during cardiac surgery, intraventricular systolic pressure has the most impact on afterload. Systolic blood pressure (SBP) as a function of systemic vascular resistance (SVR) is the major determinant of afterload. An elevated SBP resulting from peripheral vasoconstriction and an elevation of the SVR negatively influences both stroke volume and myocardial oxygen demand. Myocardial oxygen demand is elevated because a major determinant of myocardial oxygen consumption is ventricular wall tension.

Contractility is the intrinsic strength of myocardial contraction at a constant preload and afterload. It is best assessed by echocardiography, and can be inferred from an analysis of cardiac output and filling pressures.

While cardiac output is an important component of oxygen delivery, it is not the only factor. Oxygen delivery is a function of cardiac output, hemoglobin, and arterial oxygen saturation (SaO_2). Most of the oxygen delivered to tissues is bound to hemoglobin. Low hemoglobin is a major factor adversely affecting oxygen delivery; therefore, maintenance of optimal hemoglobin is essential. Conversely, efforts should be made to limit transfusions, if possible, to avoid transfusion-related illnesses, immunologic compromise, and cost. A strategy should be in place to guide transfusions and should be based on criteria providing adequate oxygen delivery. The optimal postoperative hemoglobin is probably 22–24%.^{28,29} Red blood cell (RBC) transfusions should be considered in patients with hematocrits lower than 22–24% and those patients with poor LV function, marginal SaO_2 , ischemic findings on electrocardiogram (ECG), hypotension, tachycardia, and effort-related symptoms. Similarly, the optimal oxygen saturation is 95–100%, and maintaining an SaO_2 greater than 95% does not enhance oxygen delivery.

Mixed venous oxygen saturation (SvO_2) is a measure of the adequacy of oxygen delivery to the tissues. It can be measured from blood drawn from the distal port of a Swan–Ganz catheter or continuously using a fiber-optic oximetric pulmonary artery catheter. A diminished SvO_2 generally indicates decreased tissue perfusion and/or increased oxygen extraction by tissues. SvO_2 is an indirect correlate of the cardiac output. In the absence of factors that increase oxygen utilization, a 10% decrease in SvO_2 is an indication of a low cardiac output and can be seen before any change in other hemodynamic parameters. Other causes of a diminished SvO_2 are shivering, elevated temperature, anemia, alteration in inspired oxygen, and altered alveolar gas exchange. These conditions cause a diminished SvO_2 in the presence of a normal cardiac output by causing increased oxygen utilization. SvO_2 measurement can be of particular help in assessing adequate oxygen delivery

when thermodilution cardiac output is unreliable (e.g., tricuspid regurgitation, improperly placed Swan–Ganz catheter, malfunctioning Swan–Ganz catheter), when thermodilution cardiac output is unavailable because Swan–Ganz cannot be placed (e.g., mechanical prosthesis in the tricuspid position), or when the clinical situation is unstable requiring online, minute-to-minute cardiac evaluation.²²

Another important aspect in the appropriate management of the postoperative patient is minimizing the myocardial oxygen demand (MVO_2).³⁰ The MVO_2 is influenced by afterload, preload, heart rate, and contractility. Reducing afterload will reduce oxygen demand. Increasing preload, heart rate, and contractility will improve cardiac output but will also increase MVO_2 . Providing adequate myocardial oxygen supply is equally important to the postoperative patient. Myocardial oxygen supply is determined by coronary blood flow, duration of diastole, coronary perfusion pressure (systemic diastolic pressure minus LVEDP), hemoglobin level, and arterial oxygen saturation. Postoperatively, myocardial oxygen supply is optimized by avoidance of tachycardia, maintenance of adequate perfusion pressure (avoid hypotension and hypertension), avoiding ventricular distention and inappropriately elevated LVEDP, and by managing preload judiciously.

Low Cardiac Output in the Postoperative Period

The goal of postoperative management is the maintenance of a satisfactory cardiac output. Hemodynamically, the cardiac index (CI) should be greater than 2.2 L/min/m² at a pulmonary capillary wedge pressure (PCWP) of less than 20 mmHg or pulmonary artery diastolic pressure (PADP) of less than 22–27 mmHg with a heart rate less than 100 bpm. Clinically, the patient should be warm, well perfused, and with an appropriate urine output.²² By definition, a CI greater than 2.2 L/min/m² is satisfactory, a CI of 2.0–2.2 L/min/m² is marginal, and a CI below 2.0 L/min/m² is unacceptable and calls for intervention. Ninety percent of all postoperative open-heart patients demonstrate a transient low cardiac output (LCO) related to the release of oxygen free radicals in response to the induced inflammatory state of cardiopulmonary bypass, or from ischemic/reperfusion injury as a result of cardioplegic arrest.^{15,18,31,32} The ventricular function becomes depressed in 2 h and is at its worst at 4–5 h. Generally, there is significant recovery in about 8–10 h and full recovery by 24–48 h.³³ LCO is more common in patients with preoperative LV systolic dysfunction, diastolic dysfunction, prolonged cardiopulmonary bypass, and in women.^{34,35}

Clinical Manifestations of Low Cardiac Output

As cardiac output deteriorates, compensatory mechanisms develop and are the result of sympathetic autonomic stimulation and endogenous catecholamine production. These compensatory mechanisms result in an increased heart rate, increased contractility, and increased arterial and venous tone (resulting in elevation of preload and afterload). These compensatory

mechanisms may increase the cardiac output but at the expense of myocardium oxygen utilization, and consequently the myocardium may become more depressed. As the myocardium becomes depressed, the left ventricular function worsens and the systemic vascular resistance (SVR) increases in an attempt to maintain systemic blood pressure. This elevation in the SVR is compounded by the vasoconstriction seen with hypothermia.

The early clinical manifestations of low cardiac output may be subtle. The only findings may be cool extremities accompanied by progressive tachycardia. As the compensatory mechanisms fail, more advanced clinical manifestations occur. Overt findings of poor peripheral perfusion such as pale, cool extremities and diaphoresis, pulmonary congestion and poor oxygenation, oliguria secondary to poor renal perfusion, and metabolic acidosis will be manifest. Early intervention is indicated at the onset of the early manifestations to avoid the complications of prolonged hypoperfusion and progression to the advanced manifestations.

Etiology of Low Cardiac Output

The etiology of LCO can be abnormal preload, afterload, contractility, or heart rate and rhythm or a combination of these. The most common causes of LCO after surgery are related to decreased left ventricular *preload* caused by hypovolemia and bleeding, vasodilatation, rewarming, drugs, cardiac tamponade, right ventricular dysfunction, positive pressure ventilation, and a tension pneumothorax. Increased *afterload* is usually the result of acute vasoconstriction most often related to vasoactive drug therapy. It can also be from preexisting hypertension, pain or awareness, fluid overload, or hypothermia. Decreased *contractility* is causative of LCO in patients with preexisting LV dysfunction in association with perioperative ischemia. Perioperative ischemia is usually a consequence of poor intraoperative myocardial protection, incomplete revascularization, coronary artery or conduit spasm, coronary artery “trash” syndrome, graft closure, acute anemia, hypoxia, or acidosis of any etiology. *Tachyarrhythmias* adversely affect cardiac output by decreasing cardiac filling time and subsequently decreasing stroke volume coronary perfusion time. Tachyarrhythmias also increase myocardial oxygen demand. *Bradycardias* depresses cardiac output, especially when left ventricular dysfunction limits the compensatory mechanism of an increasing stroke volume. Bradycardias are particularly deleterious in association with aortic insufficiency of any degree. When atrial fibrillation occurs, there is a loss of atrial contribution to cardiac output and subsequent fall in the cardiac output. Finally, any ventricular arrhythmia adversely affects the cardiac output.

Diastolic dysfunction causes LCO in a specific set of patients. It is often seen in small women with hypertension, patients with long-standing aortic stenosis, or patients with hyperdynamic left ventricles. All of these situations are associated with left ventricular hypertrophy, poor ventricular relaxation, and near-oblivation of the left ventricular cavity during systole.^{36,37} Diastolic dysfunction presents with nor-

mal LV function and normal or elevated PCWP, but a LCO syndrome. These patients deteriorate quickly if sinus rhythm or atrial-ventricular synchrony is lost.

Miscellaneous noncardiac causes of LCO include anaphylaxis or anaphylactoid reaction, marked alterations in temperature, sepsis, adrenal insufficiency, and the various protamine reactions. When no obvious diastolic or systolic dysfunction is present, then consider *tamponade* from blood or clot within the confines of the mediastinum and pericardium.

Diagnosis of Low Cardiac Output

The diagnosis of low cardiac output begins with a *bedside physical examination*. The early clinical manifestations of LCO are apparent to the clinician with a heightened suspicion for their presence. The importance of a careful bedside assessment cannot be overstated. The examination should include the condition and appearance of skin and mucous membranes, breath sounds, murmurs, temperature of extremities, and a level of consciousness. The *EKG monitor* is a minimum level of monitoring after open-heart surgery. It is a screening device for ischemia and arrhythmias, both causes of LCO. All ischemic changes on monitors must be further assessed with a 12-lead EKG and it is prudent to confirm all but the most obvious arrhythmias with a 12-lead EKG. *Hemodynamic monitoring*, at a minimum, includes a central venous pressure (CVP) line and can be used to assess preload as well as right ventricular function. Clinical LCO and low CVP suggests inadequate preload as the cause of LCO. Clinical LCO and an elevated CVP are more complicated. This situation may be the result of right heart failure, volume overload, left heart failure, tamponade, or some preexisting problem such as severe chronic obstructive pulmonary disease (COPD). In this circumstance, the information from a Swan-Ganz catheter or transesophageal echocardiogram (TEE) can clarify the situation. Swan-Ganz catheters (pulmonary artery catheters) are used in all patients in some institutions and selectively in others. Oximetric Swan-Ganz catheters are optional and are used in highly selected situations when minute-to-minute cardiac assessments are necessary. Swan-Ganz catheters provide an assessment of right and left heart filling pressures, determine cardiac output, stroke volume, SVR, and SvO₂. The information acquired from these catheters confirm the diagnosis of clinical LCO and provide information as to the etiology. For example, low filling pressures suggest preload as the causative factor, whereas high filling pressures indicate a problem with contractility or afterload. A *Chest X-ray* is a valuable and essential tool in the postoperative period for multiple reasons, but it can also assess the lungs as a cause for low cardiac output. In particular, a chest X-ray can identify a pneumothorax, hemothorax, pleural effusion, adult respiratory distress syndrome, and the endotracheal tube position as potential causes of a low cardiac output. It also assesses the mediastinum for an enlarged mediastinal silhouette suggesting tamponade or incorrect position of intrathoracic monitoring lines.

Echocardiography has become a first-line tool in evaluating the postoperative patient suspected of having LCO. It can either be a transthoracic examination or a transesophageal examination. The surface echocardiography has limited value in the immediate postoperative period because of the presence of dressings and chest tubes, but can provide some information about LV function and recognize obvious tamponade. Transesophageal echocardiography is an extremely valuable tool in the postoperative period and can be carried out at the bedside. It provides excellent visualization of cardiac dynamics, the pericardial space, and the mediastinum. It is the best diagnostic modality for LV function, presence of tamponade, and the development of new valvular abnormalities. It is also good for right ventricular assessment.

Each of the previous diagnostic modalities has an important role in the assessment of the postoperative cardiac surgical patient with suspected LCO. Once the diagnosis of LCO is established and the etiology determined, appropriate treatment actions can be instituted.

Management of Low Cardiac Output

The management of low cardiac output begins by excluding tamponade as the cause. If there is no indication of tamponade, treat the correctable noncardiac abnormalities such as respiratory abnormalities, acid–base and electrolyte imbalances, and anemia. If LCO persists, direct therapy at treatable cardiac abnormalities such as ischemia with a nitroglycerine infusion and consider diagnostic catheterization with catheter or operative intervention if ischemia persists. Consider coronary spasm, but this is a difficult diagnosis. Suspect coronary spasm when the patient presents with hemodynamic instability and EKG changes, especially ST segment elevation. Coronary spasm usually responds to calcium channel blockers and is a particular threat in patients with arterial conduits as grafts. Arrhythmias can also cause LCO. Ideally, the patient should be in sinus rhythm at 70–90 bpm. In the presence of LCO, arrhythmia management should be aggressive and pacing support may be needed to maintain atrial–ventricular synchrony.

After the initial steps of correcting obvious noncardiac and cardiac abnormalities, the *volume status* should be assessed and preload optimized. It is helpful to know what filling pressures resulted in the best cardiac performance in the operating room or catheterization laboratory (cath lab) and adjust the volume accordingly. The cardiac performance should be followed closely as volume is administered, and if filling pressures increase without concomitant improvement of cardiac output, an inotrope will be needed. Be mindful that the injudicious use of volume administration will result in distention of the ventricle (right, left, or both) with a shift in the Frank–Starling curve. As the ventricular wall tension increases, the myocardial oxygen demand increases and contractility becomes impaired. If volume administration fails to improve filling pressures, there may be ongoing volume loss from hemorrhage, diuresis, capillary leak syndrome, or vasodilatation

from drugs, warming, or previous comorbid conditions. Volume should be given in doses of 10% of estimated blood volume (blood volume is estimated as $0.065 \times$ body weight in kg for adults). Orders for volume expansion should be written with a prescribed stop order when the optimal filling pressure is exceeded to prevent ventricular distension. The choice of the appropriate volume expander is important. If the hemoglobin is less than 9.5 g, give packed red blood cells (PRBCs); if the hemoglobin is 9.5–11.5 g, give PRBCs and a colloid of choice; and if the hemoglobin is 11.5 g or greater, give a colloid of choice or equivalent dose of crystalloid.³⁸

Pharmacologic Management of Low Cardiac Output

Pharmacologic support is considered when the cardiac output fails to improve after optimizing preload, afterload, rate and rhythm, and metabolic abnormalities. The threshold for using vasoactive agents should be low in patients with a preoperative history of compromised ventricular function. The choice of the agent depends on multiple factors: the hemodynamic profile of the patient; associated medical conditions; treating physician's understanding of the agent; and, to a lesser extent, cost. Of these factors, the most important is the hemodynamic profile of the patient. Inotropic agents must be chosen based on the specific hemodynamic abnormality most responsible for the current LCO state. Often, the causative factors are multifaceted and dynamic, making flexibility and vigilance key. It is not unusual to need a combination of agents to successfully treat LCO. At the initiation of therapy for LCO, a bedside presence is mandatory to respond minute-to-minute to hemodynamic changes. An understanding of the basic mechanism of action and of the inotropic agents comprises the basis for agent selection.

In general, each category of agents exerts their effects differently. Catecholamines affect α -adrenergic and β -adrenergic receptors. They elevate the levels of intracellular cyclic AMP (cAMP) by β -adrenergic stimulation of adenylate cyclase. The phosphodiesterase (PDE) inhibitors, inamrinone and milrinone, elevate cAMP by inhibiting cAMP degradation. Elevation of cAMP augments calcium influx into myocardial cells and increases contractility.³⁴ The stimulation of α_1 - and α_2 -adrenergic receptors results in elevation of SVR and PVR. Cardiac α_1 receptors increase contractility and decrease heart rate. Stimulation of β_1 receptors results in increased contractility, heart rate, and conduction. In contrast, β_2 stimulation results in peripheral vasodilatation and bronchodilatation. The overall hemodynamic effect of these agents is dose-related. The need to use these agents in combination is often beneficial and necessary to achieve the desired hemodynamic effect and lessen undesired sequelae.²²

When infusing vasoactive agents, several caveats are noteworthy. First, these agents have a lessened effect in an acid medium; therefore, it is important to maintain the patient in proper acid–base balance to achieve the full effect of the therapy. An increasing dose of the agent may be indicating a falling pH.

Secondly, the route of administration should always be through a central line and not peripherally. Thirdly, these agents should always be administered with a rate-controllable infusion pump. Finally, higher blood levels can be attained by infusing them directly into the left atrium to avoid partial deactivation or removal by the lungs. This method can also be employed to lessen the pulmonary vasoconstrictive effects and subsequent RV dysfunction of catecholamines such as epinephrine or norepinephrine. This method of infusion has its own inherent risks and should be reserved for extreme circumstances.³⁹

Epinephrine is the catecholamine of choice for low cardiac output in many institutions. It has potent β_1 inotropic effects and increases cardiac output by increasing contractility and heart rate. Some of its effects are dose-related. At doses lower than 2 mcg/min (<0.03 mcg/kg/min), its β_2 effects result in mild vasodilatation and a decrease in the SVR while maintaining an adequate blood pressure. Doses greater than 2 mcg/min (>0.03 mcg/kg/min) produce α effects that cause vasoconstriction with an increased SVR potentially decreasing cardiac output further as well as increasing myocardial oxygen demand. Epinephrine may cause tachycardia, but often less than that with dopamine or dobutamine at comparable doses. It can be arrhythmogenic, usually causing ventricular ectopy. Hyperglycemia and metabolic acidosis are not infrequently associated with its use. While epinephrine can be used as a first-line agent in patients with ventricular arrhythmias or brittle diabetes mellitus, it must be done so with care. In some institutions, it is used as a second-line agent if dopamine and/or dobutamine are not tolerated or ineffective. Secondary uses for epinephrine include stimulation of heart rate in patients with bradycardia, bronchospasm, anaphylaxis, and general resuscitation for cardiac arrest. Epinephrine is the least expensive of the commonly used inotropes. Epinephrine is begun at 1 mcg/min and titrated to effect or to 4–6 mcg/min.

Dopamine is also a first-line agent for low cardiac output in some institutions. It is indicated for LCO with a low SVR and diminished systemic blood pressure. It also may be beneficial in the face of decreased urine output. Aside from its inotropic and chronotropic effects, an added effect is the selective “dopaminergic” effect that increases renal perfusion, glomerular filtration rate, and urine production by directly reducing renal afferent arteriolar tone and indirectly increasing efferent arteriolar tone. The hemodynamic effects of dopamine are largely dose-dependent. Despite its ability to increase urine production in some instances, it has never been shown to prevent acute renal failure.^{40,41} At doses of 2–3 mcg/kg/min, the main effects are renal as described, although there can be a mild β_2 effect with a decrease in SVR and systemic blood pressure. At doses of 3–8 mcg/kg/min, β_1 effects are predominant increasing contractility. At this dose, there is also a chronotropic effect that increases heart rate and has the potential for arrhythmogenesis. Doses of dopamine of greater than 8 mcg/kg/min results in increasing inotropy, but also this dose causes a predominant α effect. This α effect occurs directly but also indirectly from

the release of norepinephrine. The SVR increases as do the filling pressures and myocardial oxygen consumption leading to ventricular dysfunction. These adverse effects can be somewhat mitigated by the concomitant use of vasodilator therapy. Its use may be limited by profound tachycardia even at low doses and excessive urine production. Dopamine is begun as an infusion at 2.5 mcg/kg/min and titrated to 10–20 mcg/kg/min if needed. If a β_1 favorable response is not achieved at 10 mcg/kg/min, it is unlikely that higher doses will result in hemodynamic improvement.

Dobutamine has similar effectiveness as dopamine, but does not have its renal dopaminergic effect. Dobutamine may augment myocardial perfusion better than dopamine.⁴² It is a positive inotrope with strong β_1 effect that increases contractility and also heart rate. Dobutamine has mild β_2 effect and decreases SVR; this effect is mild and may be offset by its mild α_1 vasoconstricting effect present in some specific circumstances.⁴³ Also, unlike dopamine, dobutamine reduces ventricular wall tension by reducing afterload and preload particularly in the presence of volume overload.^{44,45} There appears to be augmentation of myocardial blood flow and an improvement of the myocardial oxygen supply and demand curve, but this positive effect may be lessened by tachycardia.⁴² The usefulness of dobutamine may be limited by tachycardia that may be profound and may trigger atrial fibrillation. Because of its hypotension from the vasodilating effect, dobutamine should be used with caution in the hypotensive or hypovolemic patient and is contraindicated if tamponade is suspected. It is most commonly used for low cardiac output associated with a mildly elevated SVR and may have a synergistic effect when used with PDE inhibitors. It does have a moderate pulmonary vasodilatory effect and can improve RV dysfunction. It is more expensive than dopamine, yet only minimally more effective. Dobutamine is begun as an infusion at 5 mcg/kg/min and can be increased for effect up to 20 mcg/kg/min.

Inamrinone and *milrinone* are phosphodiesterase inhibitors known as “inodilators.”⁴⁶ These agents produce positive inotropic effects and vasodilation independent of β_1 adrenergic stimulation. They improve biventricular output by increasing stroke volume index, left ventricular contractility, and producing pulmonary vasodilation. These agents also produce vasodilation in arteriolar and venous smooth muscle, thus reducing preload and afterload, and their use is associated with decreased myocardial oxygen consumption, despite a modest positive chronotropic effect. Inamrinone and milrinone decrease coronary vascular resistance, improve coronary perfusion, and improve the myocardial oxygen supply/demand ratio.⁴⁷ PDE inhibitors have an additive effect when used with catecholamines because of their differing sites of action.^{48–50}

Catecholamines stimulate the production of cAMP whereas PDE inhibitors slow the hydrolysis of cAMP.⁵¹ Inamrinone and milrinone are generally considered second-line agents in the treatment of LCO. They are usually employed when first-line

agents like dopamine or epinephrine are not providing adequate hemodynamic improvement or if side effects are limiting their effectiveness. However, there is evidence that administering these agents preemptively, prior to separation from cardiopulmonary bypass in patients with preoperative LV dysfunction, may eliminate the need for inotropic therapy subsequently.^{52,53} Inamrinone and milrinone are particularly useful in patients with RV dysfunction secondary to pulmonary artery hypertension and elevated PVR. These agents are also useful in treating diastolic dysfunction as they have been shown to have relaxant or lusitropic properties. They also appear to have direct vasorelaxant effects on arterial graft conduits and may be useful in patients with evidence of internal mammary spasm or in the presence of radial artery grafts.^{54,55} These drugs have a relatively long half-life of 2–4 h; consequently, the loading dose will be effective for several hours after administration but the patient should be reassessed at that time for any ongoing need for therapy. Since the PDE-inhibitors are effective vasodilators, the systemic blood pressure may require support, usually with α agonists. Vasopressin may be an alternative drug to support the systemic blood pressure while reducing the need for catecholamine pressors.⁵⁶ Inamrinone is associated with thrombocytopenia, but this is rare with milrinone. There does not appear to be any significant hemodynamic difference between inamrinone and milrinone, but milrinone has largely replaced inamrinone in clinical use because of the latter's thrombocytopenic effects.⁵⁷ Both are relatively expensive compared to other inotropic agents. Inamrinone is given as a loading dose of 0.75 mg/kg over 10 min (may need 1.5 mg/kg if bolus given while on cardiopulmonary bypass) followed by an infusion of 10–15 mcg/kg/min. Milrinone is given as a loading dose of 50 mcg/kg over 10 min, then an infusion dose of 0.375–0.75 mcg/kg/min.

Norepinephrine is another naturally occurring catecholamine. It has a pronounced effect on peripheral α receptors resulting in peripheral vasoconstriction, elevated SVR, and elevated systemic blood pressure. Norepinephrine also is a β_1 agonist increasing myocardial contractility and heart rate. The increased afterload, contractility, and heart rate result in an increase in myocardial oxygen consumption. The overall increase in myocardial oxygen consumption may have a deleterious effect on ischemic myocardium. The primary effect of norepinephrine is elevation of blood pressure and mild-to-moderate elevation of the cardiac output. It also has been shown to cause regional redistribution of blood flow with reduced renal, mesenteric, and peripheral perfusion. The primary indication for norepinephrine is a low cardiac output associated with a low SVR. It is a reasonable choice of pharmacologic support if the SVR is low and the cardiac output is 2.0–2.5 L/min/m². If the SVR is low and the cardiac output greater than 2.5 L/min/m², a pure α agonist may be used. If the SVR is low and the cardiac output is less than 2.0 L/min/m², another inotrope should be used in addition to or in place of norepinephrine.³¹

Norepinephrine can be used in combination with afterload reduction to titrate the systemic blood pressures to acceptable

levels and to maintain a satisfactory systemic blood pressure. It can also be used in combination with epinephrine to augment the β_1 effect. The starting dose is 1 mcg/min (0.015 mcg/kg/min) and titrated to the desired systemic blood pressure. At doses greater than 20 mcg/min (0.2 mcg/kg/min), visceral and peripheral perfusion is reduced to such an extent the patient may become acidotic.

Isoproterenol is a β -adrenergic agonist. It has strong β_1 effect, some β_2 effect, and little α action. The β_1 effects increase cardiac output by its moderate increase in contractility and marked increase in heart rate. The β_2 effect reduces SVR. It has been shown to reduce pulmonary vascular resistance and may be effective in treating reactive pulmonary hypertension when right heart failure is contributing to low cardiac output. It can afterload reduce the right ventricle. Isoproterenol also has strong β_2 bronchodilator effect. The indications include right ventricular failure associated with elevated PVR and bronchospasm, and can be used to stimulate heart rate in patients with bradycardia and no functioning pacemaker wires. Its use is limited because it increases heart rate and myocardial oxygen demand. Since it is a nonselective β -adrenergic agonist, it will predispose to tachyarrhythmias, ventricular irritability, and ventricular dysrhythmias. As a result of the tachyarrhythmias, isoproterenol has been largely replaced by PDE inhibitors.⁵⁸

Phenylephrine has no direct cardiac effects. It is a pure α -agonist that increases SVR. It does have some usefulness in the treatment of LCO resulting from myocardial ischemia secondary to global hypoperfusion. If systemic blood pressure is reduced as a consequence of vasodilatation, coronary perfusion may be compromised leading to myocardial ischemia and ventricular dysfunction. Phenylephrine directly stimulates α -adrenergic receptors leading to an elevation of the coronary perfusion pressure and resolution of global myocardial ischemia. Systemic vasodilatation is most often seen immediately following CPB or in the early hours of recovery as the patient rewarms. In these circumstances, phenylephrine may be helpful. Since it provides no direct cardiac benefits, its role is limited. Phenylephrine can cause vasoconstriction of an arterial conduit and should be used with caution in patients with arterial conduit grafts. Its main indication is to increase SVR in patients with low SVR and normal or elevated cardiac output. It can also be used as a temporizing measure in a hypotensive, hypovolemic patient until the volume status is corrected. The usual starting dose is 5 mcg/min and the usual dosing range is 0.05–1.5 mcg/kg/min.

Nesiritide is a recombinant B-type natriuretic peptide. It is identical to the endogenous B-type natriuretic peptide secreted by the ventricles in response to increased cardiac volume and pressure overload.⁵⁹ Nesiritide decreases sympathetic stimulation and inhibits the neurohumoral responses seen in heart failure. It exerts its effects by inhibiting the renin–angiotensin–aldosterone system to decrease aldosterone, norepinephrine, and endothelin levels resulting in natriuresis and diuresis. The net effect is a balanced reduction in preload and afterload, and

relaxation of smooth muscle.⁶⁰ It indirectly improves cardiac output with no increase in heart rate and no increase in myocardial oxygen demand. Nesiritide is lusitropic and dilates native coronary arteries and arterial conduits. It is not proarrhythmic. It has been shown to dilate afferent and efferent renal arterioles increasing glomerular filtration resulting in natriuresis and diuresis. Like PDE inhibitors, it can be used synergistically with catecholamines to reduce dosages and side effects. While nesiritide has demonstrated favorable clinical results in nonsurgical patients with decompensated heart failure and it has pharmacologic effects possibly beneficial to the postoperative cardiac surgical patient, experience with nesiritide in surgical patients is limited. Early results indicated that it may not be any better than milrinone.⁶¹ One clinical trial did demonstrate a trend toward reduced length of stay without adverse effects.⁶² Its main indication in the surgical patient is in conditions of diastolic dysfunction or LCO states associated with elevated pulmonary artery pressures. It is also useful in conditions of fluid overload and postoperative renal failure.³¹ Nesiritide is given, a dose of a 2 mcg/kg over 1 min followed by an infusion of 0.01–0.03 mcg/kg/min.

Vasopressin is a peptide hormone synthesized in the hypothalamus and is released from the posterior pituitary upon stimulation by hyperosmolality, hypotension, and hypovolemia. It has two sites of action: kidney and blood vessels. The primary function of arginine vasopressin (AVP) is to regulate extracellular fluid volume by affecting renal tubular absorption of water. It acts on the renal collecting tubules by increasing water permeability and results in decreased urine formation. This is its antidiuretic function and is why it is commonly known as antidiuretic hormone (ADH). The antidiuretic effect increases blood volume and indirectly increases cardiac output and arterial blood pressure. A secondary function of AVP is vasoconstriction. It binds to vascular smooth muscle to cause vasoconstriction. AVP is a potent vasopressor even in patients with catecholamine-resistant hypotension. Loss of catecholamine pressor effect is a well-established phenomenon.⁶³ In acute shock states, vasopressin levels increase rapidly and then decrease in prolonged shock states leading to a relative deficiency of vasopressin.^{64,65} The deficiency of vasopressin is thought to contribute to hypotension refractory to catecholamines, especially in sepsis.^{65,66} Because vasopressin is a potent vasopressor, infusions of vasopressin leads to improved organ perfusion, increased mean arterial pressure, and improved neurological function.^{63,65,67} Vasopressin is indicated for the management of severe vasodilatory shock. In patients with “vasoplegia,” profound peripheral vasodilatation with preserved cardiac output, vasopressin may have a role. This condition is usually associated with patients on preoperative angiotensin-converting enzyme inhibitors or amiodarone. It may also be the consequence of leukocyte activation and release of proinflammatory mediators caused by the systemic inflammatory response to CPB.^{68,69} Vasopressin is usually successful in reversing the low SVR when phenylephrine and norepinephrine are not.^{68,70} Vasodilatory shock is not uncommon

in patients with a ventricular assist devices (VAD) and may benefit from the vasoconstrictive actions of vasopressin.⁷¹ Despite vasopressin’s effect in vasodilatory shock, it remains a second-line agent because there is no current evidence to support the use of vasopressin as a first-line agent instead of catecholamines.⁷² There is growing evidence that vasopressin may provide comparable or superior efficacy to epinephrine as a resuscitative agent for cardiac arrest and hemodynamic collapse when administered as a single bolus of 40 units intravenously.⁷³ The recommended infusion rate for vasopressin in the treatment of vasodilatory shock is 0.01–0.04 units/min. Doses greater than 0.04 units/min may lead to cardiac arrest.⁶⁴ Rapid rebound hypotension commonly occurs after vasopressin infusion is discontinued.⁷⁴ Potential adverse sequelae of vasopressin therapy include ischemic cutaneous necrosis, intestinal ischemia, and decreased hepatosplanchnic flow and cardiac output.⁷⁵

Ionized calcium is critical for excitation–contraction coupling in cardiac muscle.⁷⁶ Hypocalcemia depresses ventricular contractility and peripheral vascular resistance; the net effect is LCO and low systemic blood pressure. The hemodynamic effects of *calcium chloride* are more profound if the patient is hypocalcemic. Serum ionized calcium levels are low postoperatively, particularly just prior to weaning from CPB, and a bolus of calcium is frequently given just prior to weaning from CPB. The effect of a bolus of calcium is increased contractility and increased SVR. It has little effect on the heart rate. It is more effective when the patient is hypocalcemic, but is also efficacious even if the patient is normocalcemic. Calcium chloride provides ionized calcium, which acts as a strong but very evanescent inotrope. A continuous infusion of calcium does not sustain its hemodynamic effect. Ionized calcium is necessary for the effective action of catecholamines. The main indication for calcium chloride is at the termination of cardiopulmonary bypass to augment systemic blood pressure during separation from bypass. It is also used as an emergency resuscitation agent to support hemodynamics until a more complete evaluation can be performed and more specific measures utilized. The dose is in increments of 0.5–1.0 g slow IV bolus.

Cardiopulmonary bypass and hypothermic arrest results in low levels of circulating thyroid hormone.^{2,77,78} *Triiodothyronine* (T_3) has hemodynamic effects based on this reduction in the plasma-free level of T_3 following cardiopulmonary bypass. T_3 remains low for 24 h, but not low enough to cause symptoms of hypothyroidism. Augmenting the levels of T_3 can increase myocardial function and has been shown to increase cardiac output and lower SVR in patients with ventricular dysfunction.^{79–81} T_3 exerts its positive inotropic effect by increasing aerobic metabolism and synthesis of high-energy phosphates. It directly stimulates calcium adenosine triphosphatase (ATPase) in the sarcolemma and sarcoplasmic reticulum.⁸² The enhancement of calcium transport decreases intracellular calcium aiding myocardial relaxation, myocardial compliance, and diastolic function.^{2,77,82} T_3 also decreases

SVR.⁸³ Currently, there are conflicting results on the use of T_3 in the treatment of LCO. The current role for T_3 is salvage when cardiopulmonary bypass cannot be terminated despite maximum support including inotropic agents and intra-aortic balloon counterpulsation. There are no studies, to date, that show that T_3 favorably improves outcome in patients failing to separate from cardiopulmonary bypass even though hemodynamics have improved in patients with ventricular dysfunction.⁸⁴ The dosage is 0.05–0.8 mcg/kg as an IV bolus.

Mechanical Support for Low Cardiac Output

Pharmacologic support is the first-line therapy for LCO. *Mechanical support* should be considered for the management of LCO when there is need for more than two inotropic agents used at the upper range of their therapeutic efficacy, when there are complications from these agents, or when LCO progresses to cardiogenic shock. Other uses of mechanical support postoperatively include myocardial ischemia or the development of mitral regurgitation that cannot be managed medically. Finally, mechanical support is indicated for the patient experiencing acute deterioration and in need of a transplant. Available mechanical support devices are the intra-aortic balloon and circulatory assist devices such as left and/or right ventricular assist devices.

The *intra-aortic balloon pump* has been an effective tool for the management of LCO states, ongoing ischemia, valvular disease, and the complications of myocardial infarction since its development in 1968.⁸⁵ Intra-aortic balloon pump (IABP) counterpulsation provides hemodynamic support and control of ischemia before and after surgery.⁸⁶ It has been shown to be effective in improving the diastolic function of the left ventricle.⁸⁷ IABP counterpulsation is very effective in the management of low cardiac output states. Unlike most inotropic agents, it provides hemodynamic support to the failing heart by decreasing myocardial oxygen demand and improving coronary artery perfusion. IABP counterpulsation acts to improve the myocardial oxygen supply:demand ratio. It reduces the impedance of left ventricular ejection by rapidly deflating just before systole, thus unloading the LV, and in this way decreases myocardial oxygen demand. As it rapidly inflates just after aortic valve closure, it increases the diastolic coronary perfusion and improves myocardial oxygen supply. The survival rate of patients requiring postoperative IABP support is 60–70%.^{88,89} The indications for IABP counterpulsation are perioperative ischemia, mechanical complications of myocardial infarction (such as acute mitral regurgitation, ventricular septal defect, and cardiogenic shock), postoperative low cardiac output states not responsive to moderate doses of inotropic agents, and for the acute deterioration of myocardial function to provide temporary support or a bridge to transplantation. IABP counterpulsation is contraindicated in the presence of aortic insufficiency, aortic dissection, and severe aortic and peripheral vascular disease.

The IABP can be inserted percutaneously or surgically. The percutaneous approach is favored despite its somewhat higher

prevalence of vascular complications.⁹⁰ Percutaneous insertion is preferred because of ease of insertion and removal. The IABP is inserted percutaneously using the Seldinger technique and is positioned fluoroscopically. The balloon tip marker should be positioned just distal to the origin of the left subclavian artery. The surgical insertion requires the exposure of the femoral artery and creation of a sidearm to the femoral artery with a vascular graft, followed by the insertion of the balloon through the graft. An alternative open surgical approach is exposure of the femoral artery and then direct cannulation with a vascular sheath using a guide wire. A hemostatic suture is placed in the femoral artery around the stem of the IABP. The IABP can be inserted by an open supra-inguinal approach in cases of severe femoral arterial disease, or the transthoracic approach via the ascending aorta in cases of severe aortoiliac peripheral disease. Triggering of the device is timed using EKG or arterial waveform. If EKG is used, the inflation is set at the peak of T wave, the end of systole. Deflation is set just before or on the P wave. Arterial waveform triggering is more reliable and a better timing technique when outside electrical impulses (i.e., pacemaker, electrocautery) may interfere with interpretation of the EKG signal. With arterial triggering, the inflation should occur at the dicrotic notch and deflation just before the onset of the aortic upstroke. Proper timing will show an arterial waveform with augmentation of the diastolic portion of the curve.

Support with the IABP is instituted at a 1:1 ratio with ventricular systole based either on EKG monitoring or the arterial pressure pulse tracing. There is often immediate hemodynamic improvement and the patient requires less inotropic support. When the required inotropic support reaches moderate levels (generally half the doses required prior to IABP support) consideration for weaning is possible. The IABP is weaned by reducing the assist ratio from 1:1 to 1:3 or less depending on the system. The weaning process can usually begin after 12–24 h of support and completed by 24–48 h. If the device was placed percutaneously, it can be removed similarly with firm pressure to the groin for 30 min. Since the arterial puncture site is several centimeters proximal to the skin insertion site, a common mistake is to direct the pressure at the skin insertion site instead of the arterial puncture site. When this error occurs, a large hematoma develops in the groin proximally. If a hematoma occurs or if the perfusion to the distal limb is compromised, immediate exploration is required.⁹¹

At times, there is a failure to achieve augmentation from the counterpulsation with the IABP. This can be the result of tachycardia and arrhythmias, inadequate balloon volume, and/or balloon rupture. Arrhythmias effect augmentation by disrupting the normal inflation and deflation patterns of the device. Rapid heart rates, usually atrial fibrillation with ventricular responses greater than 150 bpm, interfere with the balloon's ability to inflate and deflate. In this circumstance, augmentation can be achieved by changing the triggering ratio to 1:2 (one IABP cycle for every second cardiac cycle). Inadequate gas volume in the balloon can also result in an inability to

augment. Volume loss from the balloon can result from a gas leak or from failure of the balloon to unwrap. Either circumstance necessitates the removal of the balloon. Of more immediate concern is a balloon rupture. This is heralded by blood in the balloon tubing. The balloon must be removed immediately as helium and blood can create a rock-hard thrombus making surgical removal necessary.

Vascular complications are the most commonly encountered complications of IABP counterpulsation. The most catastrophic complication is an aortic or iliac artery dissection or rupture. Fortunately, this is an uncommon occurrence. Equally catastrophic is paraplegia from a periaortic hematoma or as the consequence of embolization of atherosclerotic debris to the spinal cord. Embolization or altered perfusion to visceral vessels can also occur with IABP counterpulsation. The most common vessels involved are the renal arteries. This usually occurs in the presence of significant atherosclerotic disease in the aorta. Altered perfusion of the kidneys and renal failure can happen if the balloon is situated below diaphragm.⁹² The IABP can also restrict perfusion to the LIMA if it is advanced too far proximally into the subclavian artery.⁹³ Distal limb ischemia is the most common complication of the IABP. The occurrence rate is 5–10% and occurs more commonly with percutaneous placement, in women, and in patients with small femoral arteries. Heparin therapy is advisable if the IABP is in place more than 2–3 days after surgery. The management of compromised distal perfusion begins by knowing the preoperative vascular status of the patient as well as obtaining a baseline status of the distal extremities with physical examination and Doppler assessment as soon as possible after implantation of the IABP. Thereafter, the distal pulses or Doppler signals should be assessed hourly and recorded along with the vital signs of the patient. If the pulses or Doppler signals deteriorate, initially rule out peripheral vasoconstriction from hypothermia, low cardiac output, or as a result of vasoconstrictor agents. If limb ischemia persists, remove the sheath from the femoral artery if the IABP was inserted percutaneously. If distal perfusion remains compromised, then remove the balloon and place it on the contralateral side if counterpulsation remains necessary. Femoral artery exploration is necessary if IABP removal does not improve the vascular integrity of the threatened limb. If the patient remains dependent on the IABP and the femoral artery approach is not feasible any longer, consider the transthoracic approach.

Thrombocytopenia can occur from the mechanical destruction of the platelets by the IABP. Thrombocytopenia may also be related to drug interactions (heparin, amrinone, etc.) When the IABP is implanted, a platelet count should be checked daily and if a downward trend develops, then every 8–12 h.

Circulatory Assist Devices

Circulatory assist devices were introduced by Cooley and his associates in 1969.⁹⁴ These devices, commonly referred to as ventricular assist devices (VADs), are used as a bridge to transplantation, a bridge to recovery, and for support

after cardiac surgery. They are the ultimate therapy for low cardiac output. They are usually employed intraoperatively for failure to wean from cardiopulmonary, but can also be an option postoperatively if the patient fails to respond to vasoactive agents and the IABP. VADs should be considered if the patient does not respond to maximum medical therapy including the IABP.^{95,96} The therapeutic strategy of VADs is to provide sufficient flow to support the systemic and/or pulmonary circulation while the myocardium recovers. Short-term devices are used if there is a reasonable chance for recovery, whereas long-term devices are considered if the chances of recovery are remote and the patient is a suitable candidate for transplantation. Prior to committing to circulatory assist, a thorough investigation for correctable causes of LCO must be made. Transesophageal echocardiography is helpful in evaluating ventricular wall motion and excluding other structural conditions related to the cardiac procedure. Preload and afterload should be optimized, appropriate inotropic therapy instituted, and placement of the IABP accomplished before considering circulatory assist.⁹¹ Circulatory assist can be left or right heart bypass or combined biventricular bypass. The general indications for VAD implantation include a complete and adequate cardiac surgical procedure, the correction of all metabolic problems, the inability to wean from cardiopulmonary bypass, the inability to reverse deteriorating hemodynamic embarrassment despite maximum drug therapy and IABP, and a cardiac index less than 1.8–2 L/min/m².²²

Left ventricular assist devices (LVADs) provide systemic perfusion while the left ventricle recovers. The indications for LVAD support include those general indications for VADs as well as a systolic BP less than 80 mmHg, left atrial pressure greater than 20 mmHg, SVR greater than 21 dyne s/cm⁵, and urine output less than 20 mL/h.⁹⁷ LVADs require a left atrial cannula connected to an aortic cannula via a centrifugal pump. The LVAD flow is dependent on the intravascular volume and right ventricular function. The goal of management is a LVAD flow of 2.2 L/min/m². These devices reduce left ventricular wall stress by 80% and left ventricular myocardial oxygen demand by 40%. Monitoring mixed venous oxygen saturation can assess adequacy of tissue perfusion. After LVAD implantation, inotropic support should be discontinued to decrease myocardial oxygen demand. In some circumstances, an inotrope may be needed to support the right ventricle and vasoconstricting agents may be needed to maintain the SVR and a mean arterial pressure greater than 75 mmHg. Heparin therapy is necessary after postoperative bleeding stops and, particularly, when flow is decreased to less than 1.5 L/min. After 48 h of support, a TEE should be performed to assess the LV function. As the LVAD is weaned, a low-dose inotrope may be needed. Fifty percent of patients can be weaned successfully from LVAD and 25–30% survive to be discharged. Survival is improved in those patients with preserved right ventricles, no perioperative infarct, and a recovery of left ventricular function within 48–72 h. If ventricular function does not improve after 1 week of support, consideration should be made to

implant a long-term device as a bridge to transplantation if the patient is an appropriate candidate.⁹⁸

Right ventricular assist devices (RVADs) provide support to the right ventricle (RV) and allow recovery much the same as do LVADs. The main contributing factor to right ventricular failure is an elevated pulmonary vascular resistance; however, it can also be the result of an RV infarction, or inadequate intraoperative protection. Indications for an RVAD include the general indications for VADs as well as a right atrial pressure greater than 20 mmHg, left atrial pressure less than 15 mmHg, and no tricuspid regurgitation. Right heart bypass is established by connecting the right atrial cannula to a pulmonary artery cannula via a centrifugal pump. Despite the presence of an RVAD, adequate systemic flows depend on intact left ventricular function.⁹⁹ Management goals are an RVAD flow of 2.2 L/min/m² and an increase in left atrial pressure to 15 mmHg while maintaining a right atrial pressure of 5–10 mmHg. Impaired RVAD support may be the result of hypovolemia or inadequate cannula drainage. During RVAD support, if the patient becomes hypotensive it may be the result of hypovolemia, left ventricular dysfunction, or a decreased systemic vascular resistance. A TEE to assess the left ventricular function may be appropriate at this time as well as the use of an inotrope or vasopressor. Interval TEE examinations may be used to assess the recovery of the right ventricle, and weaning criteria are the same as those for an LVAD.²² From the standpoint of prognosis, generally patients requiring RVAD have a poor prognosis. Weaning is accomplished in only about 35% and survival to discharge in about 25%.⁹⁹

Biventricular failure occurs in 10–15% of patients requiring postoperative circulatory assist. *Biventricular assist devices* (BiVADs) support both pulmonary and systemic circulation and can even be used in periods of ventricular fibrillation. The indications for BiVAD implantation are a right atrial pressure greater than 20–25 mmHg, left atrial pressure greater than 20 mmHg, no tricuspid regurgitation, and inability to maintain LVAD flow greater than 2.0 L/min/m² with a right atrial pressure greater than 20 mmHg. It is not an unusual circumstance for LVAD implantation to unmask right ventricular dysfunction and the need for an RVAD.¹⁰⁰ BiVADs are managed to create a sequential adjustment of RVAD and LVAD flow achieving a systemic flow rate of 2.2 L/min/m². The heparin requirements, the assessment of recovery, and device weaning are the same as for the LVAD and RVAD.²² Weaning is accomplished in 35% of patients and survival to discharge in only 20%. This poor prognosis is a reflection of the adverse impact biventricular failure has on survival.⁹⁹

To be optimally effective, circulatory assist devices as support for LCO require adequate pulmonary function and gas exchange. In circumstances of compromised cardiac and pulmonary function, cardiopulmonary function support is also required. Cardiopulmonary support (CPS) is accomplished with a portable centrifugal pump, membrane oxygenator, heat exchanger, and heparin-coated tubing. This system is generally referred to as *extracorporeal membrane oxygenation* (ECMO). Indications for ECMO or CPS are those of VADs in association

with impaired oxygenation. ECMO can also be used for cath lab catastrophes or in support of high-risk angioplasty.^{101,102} Only two cannulae are required for ECMO/CPS support, a venous drainage cannula and arterial perfusion cannula. If the sternum is open, the cannulation technique is the right atrium and aorta. The percutaneous cannulation can also be used using the common femoral artery and vein or the jugular vein. Since this system does not completely divert all the blood from the LV (pulmonary venous return to the LV persists), the LV is not completely decompressed, and a beating heart and competent aortic valve is necessary. An IABP is frequently concomitantly used to provide augmented pulsatile coronary perfusion.¹⁰³ The management of the patient on ECMO/CPS is complicated and labor intensive. It requires an experienced, committed, and well-trained staff. Preload must be optimized and the SVR may need support with α -agonist agents or vasopressin. Pulmonary artery hypertension must be controlled and may require using inhaled nitrous oxide. If renal failure occurs, consider early continuous venovenous hemofiltration. Ventilation with low tidal volumes is helpful.²² Heparin-coated tubing may eliminate the need for full anticoagulation, but heparin anticoagulation is required to prevent excess fibrin formation in the oxygenator membrane. The activated clotting time (ACT) is maintained 160 s by continuous heparin infusion.⁹¹ The results of ECMO/CPS depend on the degree of organ dysfunction at the time of initiation and the indication for its use. If it was instituted for cardiac arrest, the survival is 31%.¹⁰⁴ Of those patients placed on ECMO/CPS for postcardiotomy cardiogenic shock, 40–50% will die on support and only half of those who do not will survive the hospitalization. Patients who survived 30 days had a 63% 5-year survival.^{105,106}

Currently, there are a variety of *mechanical assist drive devices* available for ventricular assist. Selection of the particular device depends on the length of support required. There are short-term devices and long-term devices.¹⁰⁷ The short-term devices are non-implantable and employed if recovery of ventricular function is expected. The long-term devices function as bridges to transplant and may be a long-term alternative to transplant. These devices are pulsatile, implantable, and provide total support of circulation. The selection of a long-term support device is rarely a consideration in the acute care management of the postoperative open-heart patient. However, a working understanding of the short-term devices may be required in the management of the postoperative patient with low cardiac output. The complications of these devices include mediastinal bleeding, mediastinal sepsis, thromboembolic events, renal failure, malignant ventricular arrhythmias, respiratory failure, refractory systemic vasodilatation, and immunocompromise.

Common Postoperative Hemodynamic Problems

Most patients return to the intensive care unit following open-heart surgery with an arterial line, Foley catheter, and usually a thermodilutional Swan–Ganz catheter. The hemodynamic

status of the patient can be determined by careful assessment of data provided by these monitoring devices. With information collected by these monitoring devices, an accurate and real-time profile of the patient's hemodynamic status can be calculated and appropriate therapeutic interventions prescribed. The following is a discussion of commonly encountered hemodynamic situations in the postoperative open-heart patient.

Hypotension with Normal Cardiac Output

This is a very common postoperative occurrence. It usually occurs with rewarming and responds well to volume expansion. If hypotension persists despite volume expansion, or if presenting hypotension is severe, consider temporizing with a vasopressor such as phenylephrine or norepinephrine. The systemic vascular resistance (SVR) and cardiac output/index must be followed closely when using either drug. The hemodynamic effects of *phenylephrine* are purely α -adrenergic and act to increase the systemic vascular resistance. It has no cardiac effects. The indirect cardiac effects include a decrease in cardiac output caused by an increasing afterload as well as a potential increase in the cardiac output by raising perfusion pressure in coronary arteries. Patients may become refractory to the therapeutic effects of phenylephrine after several hours and may require a change to norepinephrine. The starting dose of phenylephrine is 5 mcg/min and increase to effect up to 500 mcg/min, with the usual dosage range of 0.05–1.5 mcg/kg/min. If there is inadequate therapeutic response to phenylephrine, switching to *norepinephrine* may prove effective. Norepinephrine has powerful α -adrenergic properties and some weaker β -adrenergic effects. The α -adrenergic stimulation will increase the systemic blood pressure by increasing the SVR. The β -adrenergic effects will increase contractility and heart rate. Clinically, the α -adrenergic effects predominate and will increase myocardial oxygen demand and may cause a fall in cardiac output despite its β -adrenergic effect on contractility. The vasoconstrictive effects of norepinephrine may increase organ perfusion pressure but decrease absolute blood flow and result in visceral ischemia; this is an important potential adverse effect of this agent. The initial dose of norepinephrine is 1 mcg/min (0.015 mcg/kg/min) and titrate to effect. Recall that at doses greater than 20 mcg/min (0.2 mcg/kg/min), visceral and peripheral perfusion is reduced to such an extent the patient may become acidotic.

Hypertension and a Normal Cardiac Output

This is another common occurrence and is seen in patients with normal left ventricular function. It is related to an increased arterial resistance secondary to hypothermia and increased levels of circulating catecholamines, plasma renin-angiotensin, and vasopressin.^{22,108,109} Postoperatively, systemic hypertension is more commonly seen in patients with normal left ventricular function, preoperative hypertension, preoperative use of β -blockers, and patients having aortic valve

replacement.¹¹⁰ The adverse sequelae of systemic hypertension include exacerbation of any latent myocardial ischemia by increasing afterload, stresses on suture lines, a predisposition to bleeding, and an increased potential for stroke and aortic dissection.^{22,111} Hypertension may be the result of hyperdynamic cardiac function or peripheral vasoconstriction, or both; and a hemodynamic profile must be ascertained before initiating therapy so as to direct therapy at the appropriate cause. The usual criterion for pharmacologic treatment is a mean arterial pressure 10% above the upper level of the normal patient-specific mean arterial pressure (MAP), usually greater than 96 mmHg, or arbitrarily, a systolic blood pressure greater than 140 mmHg (MAP greater than 110 mmHg). In managing the postoperative hypertensive patient, a few caveats are important to keep in mind. First, a patient with a history of longstanding hypertension or critical carotid stenosis may require a higher perfusion pressure to maintain adequate cerebral and renal perfusion. Secondly, a patient with a tenuous aorta or thin-walled vein grafts may require a lower pressure to avoid suture line dehiscence and catastrophic hemorrhage.

The treatment goal in this scenario is to lower the SVR and reduce myocardial oxygen demand without adversely affecting coronary artery perfusion. The treatment of systemic hypertension in the early postoperative period is vasodilator therapy. This can be augmented with β -blocker therapy, calcium channel blocker therapy, angiotensin converting enzymes (ACE) inhibitor therapy, and sedation, depending on the clinical circumstances.

The vasodilator of choice for systemic hypertension postoperatively is *sodium nitroprusside* (SNP). SNP has a rapid onset of action and can produce rapid and excessive hypotension, but it has a short half-life. It is imperative that filling pressures are optimized before beginning SNP, or a hypotensive collapse will occur. SNP relaxes smooth muscle and as such decreases arterial resistance in the systemic and pulmonary circuit. It also relaxes venous capacitance vessels. It should be used with caution in the setting of myocardial ischemia as it can produce a coronary steal phenomenon. It has the potential for either short-term cyanide toxicity or thiocyanate toxicity with prolonged use.¹¹² SNP can also cause hypoxemia by opening intra-pulmonary shunts. The dosage is initiated at 0.1–0.25 mcg/kg/min and titrated to a maximum dose of 8 mcg/kg/min.

Nitroglycerine (NTG) is primarily a venous dilator that lowers blood pressure by reducing preload, filling pressures, stroke volume, and cardiac output. Since its primary action is on venous vessels, it usually maintains arterial diastolic pressure, but at high doses can produce arterial dilatation of varying degree and lower coronary artery perfusion pressure. NTG must be used with care if the patient is hypovolemic or the cardiac output is marginal, as reducing preload further will reduce cardiac output further and produce a reflex tachycardia. NTG works best in the hypertensive patient with active ischemia and high filling pressures.¹¹³ The major adverse effect of NTG is methemoglobinemia and impaired oxygen

transport. The dosage begins at 0.1 mcg/kg/min and can be titrated up to 10 mcg/kg/min.

Hydralazine is a direct arterial vasodilator that can be used to unload the left ventricle and treat systemic hypertension. It produces arterial vasodilatation and usually a compensatory tachycardia. In the immediate postoperative period, it is used as a supplement to other agents and not as the primary drug for the management of hypertension. Hydralazine most commonly is used in the hemodynamically stable patient that remains hypertensive several days postoperatively but is unable to take oral medications. The dosage is 5–10 mg IV bolus every 4 h as needed.

Calcium channel blockers primarily produce antihypertensive effects by relaxing vascular smooth muscle. They are very effective for managing postoperative hypertension, but do have a variety of cardiovascular hemodynamic effects and conduction alterations specific to each particular agent. Calcium channel blockers are also used for the treatment of coronary spasm and rapid atrial tachycardias as well as for hypertension.

Nicardipine is a strong systemic and coronary vasodilator that does not cause coronary steal or tachycardia. It has little or no effect on the venous system and can be used without great concern for altering preload. The onset of action is rapid and has a relatively long half-life of 40 min. Nicardipine is not a negative inotrope and has no effect on AV conduction. The dosage is an initial IV bolus of 2.5 mg over 5 min and repeat every 10 min to a total dose of 12.5 mg, then begin an infusion of 2–4 mg/h.

Diltiazem also acts as a peripheral vasodilator that reduces SVR; however, it decreases cardiac output as a result of its negative inotropic and chronotropic (slows AV conduction) effect. Diltiazem is a good choice when hypertension is associated with coronary spasm because it is a potent coronary artery vasodilator. It is also a good option if hypertension is associated with atrial fibrillation and a rapid ventricular response. The dosage is 0.25 mg/kg IV bolus over 2 min and a repeat dose in 15 min of 0.35 mg/kg, then an infusion of 5–15 mg/h.

Verapamil is a peripheral vasodilator with moderate negative inotropic and chronotropic effects. Its indications for usage are similar to diltiazem. The dosage is 0.1 mg/kg IV bolus initially, then 2–5 mcg/kg/min infusion.

Nifedipine, like all calcium channel blockers, lowers blood pressure by reducing the SVR. It has potent vasodilatory actions. It causes a slight increase in heart rate and inotropy. When compared to SNP, an infusion of nifedipine has a more positive effect on cardiac output and a greater decrease in SVR. It has no effect on venous capacitance and preload.¹¹⁴ Nifedipine is a potent coronary vasodilator and is an effective agent for managing suspected coronary spasm or arterial conduit spasm.¹¹⁵ While an intravenous form is available, it is primarily given sublingually or orally at a dose of 10–30 mg every 4 h.

Amlodipine acts on the SVR as do all other calcium channel blockers and may result in an increased cardiac output as a result of decreasing afterload. It has no negative inotropic

or chronotropic properties by virtue of its lack of effect on the SA and AV nodes. Amlodipine exerts its antihypertensive effect gradually over a 24-h span and is used mainly for the long-term management of hypertension. The dose of amlodipine is 2.5–10 mg daily.

β-blockers reduce pressure by negative inotropic and chronotropic actions. They reduce contractility, lower stroke volume and cardiac output, and lower heart rate. These agents are used to control hypertension associated with normal or hyperdynamic cardiac output, especially if the patient is tachycardic.

Esmolol is an ultrafast, short acting, cardioselective agent. Because it is so short acting, it is the β-blocker of choice for transient hypertension in a hemodynamically unstable patient. It should be used with caution in a patient with marginal cardiac output. The reduction in blood pressure is generally greater than the reduction in heart rate. It is cardioselective and can be used in a patient with bronchospasm. The dosage is an initial dose of 0.25–0.5 mg/kg over 1 min, followed by 50 mcg/kg/min over 4 min followed by a continuous infusion titrated to effect. If an adequate response is not obtained after the initial dose, another loading can be given followed by 100 mcg/kg/min over 4 min. There is little to be gained by cumulative doses of more than 200 mcg/kg/min.

Labetalol has α-adrenergic and β-adrenergic blocking effects as well as a direct vasodilatory effect. The α-adrenergic blocking effect prevents reflex vasoconstriction.¹¹⁶ This agent is used when a longer-acting antihypertensive effect is needed because its duration of action is 6 h. Labetalol has a rapid onset of action resulting in a blood pressure response within 5 min. The dosage is 0.25 mg/kg IV bolus over 2 min, with subsequent dosing at 0.5 mg/kg every 15 min until desired effect is reached or a total dose of 300 mg is administered.

Metoprolol is a cardioselective β-blocker used mainly to control ischemia or to slow ventricular response in atrial fibrillation, but rarely can it be used to treat postoperative hypertension. The onset of action is 2 min and duration of action is about 5 h. The dosage is 5 mg IV bolus every 15 min until the desired effect is reached or a total dose of 15 mg.

Propranolol is a non-cardioselective agent with a long duration of action and has negative inotropic effect and as such is rarely used to treat postoperative hypertension. The dosage is in 0.5 mg increments given every 2–5 min until desired effect is reached or a total dose of 0.1 mg/kg.

Enalaprilat is an ACE inhibitor that reduces blood pressure by inhibiting the activation of the renin–angiotensin system. It causes a balanced arterial and venous dilatation and acts to reduce myocardial oxygen consumption by its action on preload and afterload. It generally does not cause a reflex tachycardia. Enalaprilat can be used alone or as a supplement in situations requiring high doses of nitroprusside or nicardipine. The onset of action is 15 min and usually has a 4-h duration of action. The dosage is 0.625–1.25 mg IV over 15 min every 6 h. It can be used as a continuous infusion of 1 mg/h with a doubling of the dose every 30 min until the desired effect is reached or a total dose of 10 mg.¹¹⁷

Fenoldopam mesylate is a dopamine receptor agonist that is a rapid-acting peripheral and renal vasodilator. It is indicated for the short-term management of severe hypertension. Fenoldopam mesylate causes a rapid fall in blood pressure and a reflex tachycardia. Other hemodynamic effects include increase in stroke volume index and cardiac index attributed to the fall in SVR. There is also an associated fall in pulmonary vascular resistance that may make its use beneficial in patients with pulmonary artery hypertension and RV failure. These properties make it an option for the management of postoperative hypertension in the cardiac surgical patient.¹¹⁸ It also has a beneficial effect on the kidneys. It dilates renal afferent arterioles and increases renal blood flow. The dosage of fenoldopam mesylate is an initial infusion of 0.05–0.1 mcg/kg/min and increases at increments of 0.05 mcg/kg/min to the desired effect or a maximum of 0.8 mcg/kg/min. The renoprotective dose is 0.1 mcg/kg/min and is usually not associated with hypotension. While it has been shown to be effective in the management of postoperative hypertension in the cardiac surgical patient, it is not cost-effective and should be reserved for instances when other agents are ineffectual.

Low Cardiac Output and Normal Left Ventricular Function

The two most common causes of this scenario are right ventricular failure and diastolic dysfunction. *Right ventricular failure* is rarely an isolated clinical situation. When it is, it is the result of poor intraoperative protection or a right ventricular infarct. More commonly, it is associated with pulmonary artery hypertension, either preexisting or the result of infused vasoconstricting adrenergic agents, administration of blood products, a type III protamine reaction, hypoxemia, acidosis, or a tension pneumothorax. The hemodynamic hallmark of RV failure is a central venous pressure (CVP) higher than the pulmonary artery diastolic pressure (PAD) or pulmonary capillary wedge pressure (PCWP). TEE is an excellent mode of RV assessment and diagnosis of RV failure.¹¹⁹ The treatment of RV dysfunction begins by optimizing preload to a CVP of 18–20 mmHg. Pushing the CVP higher may result in RV dilatation and exacerbation of RV dysfunction. Also, a distended RV can have an adverse effect on the LV by shifting the intraventricular septum into the LV and impairing LV filling and stroke volume. Hypoxemia, hypercarbia, and acidosis must be corrected as these adversely affect RV function. There must be active transport of volume from the right atrium to the RV, so it is imperative that atrioventricular (AV) conduction be maintained or established using sequential AV pacing if necessary. The addition of inotropic support is often necessary. Inotropes that support biventricular function and are pulmonary vasodilators should be selected. The phosphodiesterase inhibitors are reasonable agents, but their action on the SVR may necessitate the use of α -adrenergic agents and lead to further vasoconstriction of the pulmonary vasculature. Isoproterenol may improve RV contractility, but its proarrhythmic effects may not be well tolerated.

When RV failure is associated with an elevated pulmonary vascular resistance (PVR), it is mandatory to decrease RV afterload by using a *pulmonary vasodilator*. The pulmonary vasodilators have no direct effect on RV or LV inotropy. Their effect is indirect by afterload reduction of the RV. *Nesiritide* (see prior description) is a synthetic β -type natriuretic peptide that reduces pulmonary artery pressure and unloads the RV. It also has vasodilatory effects on the SVR and renal arterioles resulting in improved cardiac output and a synergistic effect with loop diuretics.^{120,121} *Inhaled nitric oxide* (iNO) is a selective pulmonary vasodilator and decreases RV afterload. This results in enhanced RV performance. It has little, if any, effect on the SVR.¹²² Inhaled nitric oxide is administered through a ventilator circuit designed to mix O₂ and NO. This generates a low level of NO₂, which must be monitored as it is toxic to lung parenchymal tissue. Inhaled nitric oxide is quite effective, but it is cumbersome and expensive. The usual dose is 10–40 ppm administered through a ventilator circuit. *Prostaglandin E₁* and its analogs, *epoprostenol* and *iloprost*, are potent pulmonary vasodilators effective in the treatment of pulmonary hypertension. These agents are most frequently used in cardiac transplantation, but have been used effectively after mitral valve surgery.^{58,123,124}

Diastolic dysfunction is a function of impaired myocardial relaxation. In the postoperative period, it results in LCO with normal or elevated filling pressures in patients with normal or hyperdynamic LV function. It is commonly seen in small women with left ventricular hypertrophy from hypertensive cardiovascular disease or aortic stenosis. Severe diastolic dysfunction is associated with reduced left ventricular compliance exacerbated by edema often associated with ischemic cross-clamping, reperfusion, and CPB. Inotropic agents used to treat the LCO in the postoperative period will worsen diastolic dysfunction. Diastolic dysfunction is frequently associated with tachycardia.¹²⁵ The filling pressures are high and stroke volume reduced because the impaired left ventricular relaxation leads to impaired filling of the LV and a decreased LV end-diastolic volume (LVEDV). Swan–Ganz monitoring confirms high left-sided filling pressures and LCO. The SVR is elevated as a compensatory mechanism. TEE is diagnostic. It confirms a hypertrophic LV with decreased compliance and filling. The LV may be so hyperdynamic as to obliterate the LV cavity at end-systole. Diastolic dysfunction is difficult to manage. If not managed successfully, end-organ dysfunction is inevitable. The initial steps in management are to assure AV synchrony and adequate preload. Volume should be infused until the PCWP is 20–25 mmHg to increase LVEDV. Intuitively, it may seem inappropriate to give volume in the setting of elevated filling pressures, but the elevated filling pressures are the consequence of impaired LV compliance and not volume overload. Inotropic agents should be replaced with lusitropic agents. ACE inhibitors may improve diastolic compliance. Calcium channel blockers also have some lusitropic and may be of benefit. Finally, inamrinone and milrinone have lusitropic properties as does nesiritide. There is no one agent

shown to be better than the others and often management requires courses of therapy and observation. If the patient can be guided through the first few days, the cardiac output gradually improves.²²

Arrhythmias

Cardiac arrhythmias carry a source of morbidity and mortality in the postoperative surgical patient. These arrhythmias are usually an indicator of some underlying abnormality and should alert the clinician to closely evaluate the patient. In addition to standard electrocardiograms (EKG), the temporary atrial and ventricular pacing wires are useful in the diagnosing and treatment of postoperative arrhythmias.¹²⁶ The ideal postoperative rhythm is sinus rhythm at 70–110 bpm.¹²⁷ *Sinus tachycardia* is frequently seen in the early postoperative period and is most commonly caused by vasodilatation secondary to rewarming, reperfusion injury to the left ventricle secondary to cardiopulmonary bypass, sympathomimetic drugs, pain and anxiety as the patient awakens from anesthesia, normovolemic anemia, withdrawal from β -blocker therapy, occasionally fever, and idiopathic.

Ventricular Ectopy

Isolated ventricular ectopy may be an indication of ongoing myocardial ischemia, particularly within the first 6 h postoperatively. Other causes of ventricular ectopy are hypokalemia, hypomagnesemia, hypoxia, preexisting ectopy, sympathomimetic drugs, and mechanical irritation from the Swan–Ganz catheter. There remains controversy as to the significance of isolated ventricular ectopy. It is not clear what the incidence of isolated premature ventricular contractions (PVCs) degenerating to malignant ventricular arrhythmias actually is. However, most agree that in the presence of active myocardial ischemia, pharmacologic suppression is indicated and this concept includes those patients in the first 24 h after surgery when the myocardium may be irritable. Unlike chronic pharmacologic treatment of isolated ventricular ectopy, treatment in the acute postoperative period is not usually associated with the risk of proarrhythmia. Treatment is particularly beneficial in patients with LV dysfunction and ejection fractions less than 40%. In the first 24 h after surgery, ventricular ectopy is treated if the ectopic beats occur at a rate greater than 6 beats/min or ventricular tachycardia of less than 1 min. The treatment of PVCs begins with the correction of any underlying correctable cause such as hypokalemia or hypomagnesemia. If atrial wires are present, overdrive atrial pacing at a rate greater than the current sinus rate can be tried. *Lidocaine* is the initial drug treatment for ventricular ectopy. The dosage is an initial loading dose of 1 mg/kg as an initial bolus followed by one or two additional doses of 0.5 mg/kg every 10 min. After the initial bolus, an infusion of 1–2 mg/min can be started. An alternative option is an initial bolus of 75 mg followed by a loading infusion of 150 mg over 20 min. The loading dose is followed

by a maintenance dose of 1.5–2.5 mg/min. If the ectopy is uncontrolled, an additional bolus of 25–50 mg can be given and the infusion rate increased. Lidocaine toxicity is a significant risk at infusion rates greater than 4 mg/min, especially in the elderly. If lidocaine does not suppress ectopy, it can be elected not to treat unless ventricular tachycardia occurs or with intravenous amiodarone.

Sustained ventricular tachycardia (VT) or ventricular fibrillation (VF) are usually associated with acute myocardial ischemia or infarction or an electrolyte imbalance, but can occur without the obvious presence of either.¹²⁸ These arrhythmias are most often seen in patients with previous infarcts and subsequent revascularization to the infarcted area, and occur with a frequency of 1–3% after cardiac surgery.¹²⁹ Reperfusion of areas of ischemia or infarction can precipitate VT or VF as the areas of ischemic myocardium are reperfused. The reperfusion arrhythmias occur in patients with unstable angina, recent infarction, and ejection fractions of less than 40%. In these circumstances, nonviable myofibrils embedded in the scar are triggered and this leads to an altered dispersion of repolarization and the development of reentry arrhythmias. The resultant ventricular arrhythmia is usually a sustained polymorphic VT with a normal QT interval as compared to the monomorphic VT noted in patients with a previous myocardial infarction and depressed LV function. This reentry arrhythmia rarely responds to lidocaine and usually requires amiodarone and possible β -blockade. The treatment of nonsustained VT in patients with preserved LV function is similar to the treatment of PVCs. In patients with ejection fractions less than 30% and nonsustained VT, the prognosis is poor without treatment, and an electrophysiologic evaluation is necessary as an implantable cardioverter-defibrillator may be indicated.¹³⁰ Sustained VT without hemodynamic instability can be managed with ventricular overdrive pacing. Cardioversion may be necessary if overdrive pacing is not successful or if the patient becomes unstable. An *amiodarone* bolus of 150 mg infused over 15 min followed by an infusion of 1 mg/min for 6 h, then 0.5 mg/min for 18 h should be prescribed. These patients will ultimately need an electrophysiologic evaluation. All patients with VT or AF with hemodynamic instability require immediate defibrillation as per ACLS protocol.¹³¹ If the patient is unresponsive to defibrillation or persistence of hemodynamic instability, the sternotomy must be reopened emergently at the bedside. *Torsades de pointes* is an uncommon but malignant arrhythmia not often related to the postoperative cardiac surgical patient. On the EKG monitor, the QRS complex appears to “twist” around the isoelectric baseline. Its onset is usually pause-dependent, initiated by a PVC occurring at the end of a T wave. It is usually associated with a prolonged QT interval. Treatment of torsades de pointes is immediate cardioversion. If the patient is not hyperkalemic, potassium chloride should be administered to shorten the QT interval. Magnesium and β -blockers may eliminate the trigger and prevent recurrence. Finally, ventricular pacing at 90–100 bpm or an isoproterenol infusion of 1–4 mcg/min will shorten the action potential and prevent early afterdepolarization.^{132,133} Be aware that a wide complex tachyarrhythmia does not necessarily indicate ventricular tachycardia because atrial fibrillation with a rapid ventricular response

can result in RBBB with aberrant conduction (so-called Ashman phenomenon) mimicking ventricular tachycardia.²⁰

Atrial Fibrillation

Atrial fibrillation (AF) is the most common arrhythmia after cardiac surgery. Despite the recent institution of prophylactic regimens for AF, the overall incidence remains 25–30%. It has an occurrence of 10–40% after coronary artery bypass graft (CABG) surgery and up to 65% of patients undergoing combined CABG valve procedures.^{134–136} After on-pump coronary artery bypass surgery, the incidence is 27–33%,^{127,135} after minimally invasive CABG it is 19%, and following valve surgery it is 30–70%.^{137,138} There is controversy as to whether off-pump CABG has a lower incidence of AF.¹³⁹ Patient's age appears to be the most powerful predictor of the occurrence of AF. The incidence is 3.7% in patients less than 40 years of age and 28% in those older than 70.^{127,135} Other predictors are a history of congestive heart failure, preoperative atrial fibrillation, and chronic obstructive pulmonary disease.^{140–142} Atrial fibrillation is most likely to occur 2–4 days after surgery. The episodes of these arrhythmias may recur or persist for up to 6 weeks before resolving spontaneously. Ten to 15% of patients are discharged in atrial fibrillation whereas 80% will return to sinus rhythm within 1–3 days with only digoxin or β -blockade therapy.^{138,143–145} It is a leading cause for readmission after early discharge.

The management of postoperative AF begins with an assessment of the patient. If the patient is unstable, immediate *cardioversion* is indicated. A synchronized shock of 50–100 J is applied. Rarely is this the only treatment necessary, as the patient often reverts back to AF, especially if this occurs in the early postoperative period. If the patient is hemodynamically stable, the initial treatment of postoperative AF is rate control and is indicated if it lasts longer than 15–30 min or is associated with severe symptoms.¹³⁸ The most important aspect of the treatment of postoperative AF is the control of the ventricular rate. In many protocols, the first-line agent for rate control is the calcium channel blocker *diltiazem*. Therapy is initiated with a bolus of 0.25 mg/kg over 2 min and followed by an infusion of 10–15 mg/h to titrate the heart rate to less than 120 bpm. Slowing of the ventricular rate is usually noted within 3 min and is more effective for atrial fibrillation than atrial flutter. The use of *diltiazem* is limited by hypotension, which occurs with an incidence of 5–20%.^{146,147} Pretreatment with 500 mg of calcium may lessen the hypotensive effect. *Diltiazem* has a mild negative inotropic effect and must be used with caution in patients with compromised left ventricular function. While *diltiazem* is extremely effective in slowing the ventricular rate, it converts fewer than 10% to sinus rhythm. *Verapamil* can be used in lieu of *diltiazem* for rate control in rapid atrial fibrillation. Begin with a bolus of 20–25 mg, then an infusion of 10–15 mg/h. If the blood pressure is tenuous, pretreat with 500–1,000 mg of calcium chloride. While calcium channel blockers are effective rate control agents, they

are not as effective as β -blockers in converting patients back to normal sinus rhythm (NSR). Beta-blockers are equally or more effective for rate control and also can effect conversion to NSR 50% of the time.^{148,149} They are not used as frequently for postoperative AF by some clinicians because of their negative inotropic properties. *Esmolol* is a short acting, selective β -blocker. It must be used in an ICU setting with appropriate monitoring because of its propensity to cause hypotension, particularly in patients with poor LV function. The loading dose is 0.25–0.5 mg/kg over 1 min followed by an infusion of 50–200 mcg/kg/min. *Metoprolol* has less of a tendency to cause hypotension and is more suited for use in a non-ICU area. It is a long-acting, selective β -blocker. It is dosed at 5 mg IV every 5 min to a total dose of 15 mg. *Digoxin* has only a modest response in the acute setting. There is only a 10–15% decrease in ventricular rate with digoxin alone.¹⁵⁰

At least half of the patients remain in AF after the rate has been slowed. An effort should be made to cardiovert the patient back to sinus rhythm. If the patient is hemodynamically unstable, electrical cardioversion is an option. There is a high incidence of recurrent atrial arrhythmia unless an antiarrhythmic regimen is instituted.

Currently in many institutions the antiarrhythmic of choice is *amiodarone*. Amiodarone has properties of class III antiarrhythmics and β -blockade. It is becoming the drug of choice for postoperative AF because it is safe and effective. It is associated with only modest hypotension and has no proarrhythmic effects. It does slow the ventricular rate as effectively as β -blockers or calcium channel blockers, which are often used as adjuncts to amiodarone.¹⁵¹ It does have a higher rate of cardioversion than either calcium channel blockers or β -blockers. Amiodarone has the same frequency of cardioversion as type IC antiarrhythmics, but takes longer.¹⁵² Amiodarone has fewer adverse side effects than those antiarrhythmics. It can be given intravenously, but is just as effective orally for non-life-threatening arrhythmias. The half-life of the drug is long, up to 120 days, and its long-term use is associated with visual disturbances, tremors and other neurologic sequelae, hepatitis, pulmonary fibrosis, photosensitivity, skin discoloration, thyroid abnormalities, and cardiac conduction disturbances. These side effects, however, are rarely a factor when used to treat postoperative atrial fibrillation because amiodarone is administered only for 6 weeks. If given intravenously, the initial loading dose is 150 mg over 15 min, followed by an infusion of 1 mg/min for 6 h, then 0.5 mg/min for 18 h. An oral taper dose is then prescribed of 400 mg bid for 1 week, 400 mg daily for 1 week, then 200 mg daily for 2 weeks. If the patient has no further episodes of AF, it can be discontinued at that time.

Procainamide is a type 1A antiarrhythmic that once was a first-line antiarrhythmic for the postoperative cardioversion of AF in most centers. It restores NSR in 87% of patients within 40 min.¹⁵³ Procainamide is proarrhythmic and has a mild negative inotropic effect. It is associated with more short-term side effects than amiodarone. It has vasolytic properties and as such should not be used until the ventricular rate has been slowed to

less than 120 bpm. The loading dose is an intravenous bolus of 17 mg/kg (dose not to exceed 1 g total) at a rate not exceeding 30 mg/min. This can be followed by an infusion of 2 mg/min or converted to an oral procainamide derivative in 24 h. Up to one-third of patients cannot tolerate procainamide because of gastrointestinal, hematological, or immunologic side effects. This drug is cleared by the kidneys and blood levels of procainamide and its active metabolite, *N*-acetyl procainamide (NAPA), should be monitored, particularly, in patients with renal and hepatic dysfunction.¹⁵⁴

Ibutilide is a rather new agent for the treatment of postoperative atrial fibrillation. The incidence of torsades de pointes is about 1–2%, which is considerably higher than with either procainamide or amiodarone.¹⁵⁴ *Ibutilide* is useful in patients with poor left ventricular function or chronic lung disease, but its use is limited by its proarrhythmic effect. Conversion to sinus rhythm occurs at a rate of 30–50% for atrial fibrillation and 50–70% for atrial flutter.¹⁵⁵ The dose begins with a bolus of 1 mg over 10 min with a second infusion 10 min later. No further dosing is indicated. The drug must be stopped if QT prolongation occurs as it may contribute to torsades, but sustained polymorphic ventricular tachycardia may occur even in the absence of QT interval prolongation.

There are several strictly oral agents that can be used for pharmacologic conversion back to sinus rhythm. *Sotalol* is useful as a single-agent therapy for atrial fibrillation cardioversion. It is a class III antiarrhythmic with beta-blocking activity. It can cause prolongation of the QT interval and initiation of therapy must be done while monitoring the patient. The drug is limited mainly by its beta-blocking effects such as reactive airway disease, depression, and negative inotropy. The dose is 80–160 mg twice daily. *Quinidine* is still used by some clinicians for the conversion of atrial fibrillation to sinus rhythm. It may be slightly more effective than amiodarone, but it is being used with decreasing frequency.^{156,157} Though quinidine is cost-effective and has very little negative inotropy, it is associated with a high incidence of side effects, particularly gastrointestinal, neurological, and hematological. Also, the proarrhythmic and frequent dosing make other agents a better choice. *Flecainide* can also be used for the management of atrial fibrillation. *Flecainide* was found to be associated with an increased mortality when given after a myocardial infarction, and created much concern when given with ischemic heart disease. It is not recommended for patients with structural heart disease.¹⁵⁸

Postoperative atrial fibrillation is associated with increased morbidity and cost; therefore, there is great interest in the prophylaxis of postoperative atrial fibrillation. Multiple trials and multiple protocols have been investigated searching for an effective prophylactic regimen. The most effective and practical regimens all include preoperative β -blockade therapy started 12–24 h preoperatively.^{159–162} Beta-blockade therapy given preoperatively and through the postoperative period is superior to their use only postoperatively. When given preoperatively and postoperatively, the incidence of AF is 17%.^{163–165}

Magnesium sulfate has been used as prevention for postoperative AF. Hypomagnesemia is common after cardiac surgery and is associated with atrial arrhythmias. There is a debate as to whether routine magnesium administration lowers the incidence of postoperative AF.¹⁶⁶ It may be effective when used with β -blockers and when the serum magnesium is low.^{167,168} Since it is relatively benign and may be potentially effective, some recommend its routine administration through the first postoperative day.

Sotalol is a β -blocker with class III antiarrhythmic properties. It reduces the incidence of postoperative AF by as much as 65% when given preoperatively and postoperatively.¹⁶⁹ Because it has β -blocker action, it must be used with caution in patients with LV dysfunction and those with marginal systemic blood pressure. It is excreted by the kidneys and is not recommended in patients with renal insufficiency. *Sotalol* can also cause QT interval prolongation and has been associated with torsades de pointes. It is not well tolerated in 20% of patients and must be withdrawn. The dose of *sotalol* is 80 mg twice daily.

Amiodarone is a class III antiarrhythmic with some properties of class I, II, and IV drugs. It is as effective as *sotalol* in preventing postoperative AF and can be used alone or in conjunction with β -blockers.^{170–173} *Amiodarone* is particularly useful in patients with intolerance to β -blockers. It is rarely associated with pulmonary toxicity when used as a short-term therapy, but the rare incidence of *amiodarone* toxicity can cause hypoxemia.¹⁷⁴ As prophylaxis, *amiodarone* is started in the operating room as a 150 mg bolus over 15 min followed by an infusion of 1 mg/min for 6 h then 0.5 mg/min for 18 h. The oral dose of 400 mg twice daily is continued for 1 week. If the patient should develop AF, a 6-week regimen is recommended. In the event the patient should develop AF with either the *sotalol* or *amiodarone* prophylactic regimen, the ventricular response rate is usually slow and easier to manage. The efficacy of both *sotalol* and *amiodarone* as prophylaxis is better if started several days preoperatively.

Postoperative stroke as a consequence of atrial fibrillation is well documented. The incidence of stroke is between 3 and 7% in patients with postoperative atrial fibrillation as compared to 1–1.5% in patients without atrial fibrillation.^{141,175} The risk of embolic stroke is substantial after 48 h or more of atrial fibrillation.¹⁷⁶ All patients with postoperative atrial fibrillation should be anticoagulated unless there is a contraindication. Anticoagulation should be started within 24–36 h of the onset AF.

Bradycardia

Bradycardia requiring pacing occurs in approximately 10% of postoperative patients. The most common defect is right bundle branch block (RBBB). About 5% of the patients will have permanent conduction abnormalities. The associated bradycardia is treated with temporary epicardial pacing. The most commonly used mode is ventricular pacing. In all the open-heart patients, temporary epicardial ventricular pacing wires are fixed to the right ventricle and, in many, right atrial wires are also placed.

Bradycardia from any etiology is an indication for ventricular pacing. If the patient is hemodynamically unstable with simple ventricular pacing, physiologic pacing may be required if atrial electrodes are available. If an atrial electrode was not fixed to the heart, a temporary transvenous atrial pacing electrode can be inserted. Simple ventricular pacing is accomplished by connecting the temporary electrodes to an external pacemaker. These pacemaker units are bipolar and require the ventricular lead electrode be connected to the negative pole and an indifferent electrode, often a skin wire, connected to the positive pole of the pacemaker. The output is set initially at 10 mA and the threshold adjusted to assure a safe margin of capture. A decision is then made as to the mode of pacing; i.e., synchronous (demand) or asynchronous (fixed). The synchronous mode is chosen to avoid pacer stimulation on the T wave and the resulting ventricular fibrillation. The asynchronous mode is used only in unusual situations, such as the use of electrocautery, when other electrical activity interfere with the sensing in the synchronous mode. The rate must be set depending on the needs of the patient. Physiologic pacing requires choosing the desired mode, atrial thresholds, atrioventricular intervals, as well as the ventricular settings. Failure to pace may be the result of faulty electrical connections, dislodgment of the epicardial electrodes from the heart, a faulty pacemaker, the development of electrically silent areas of the myocardium in the region of the electrodes, or the development of a rhythm incompatible with pacing such as atrial or ventricular fibrillation.

Hemorrhagic Complications of Open-Heart Surgery

Postoperative bleeding is always present to some extent. It is related to mechanical factors and coagulopathy. Mechanical factors are considered surgically correctable. Less than 3% of postoperative bleeding is from surgically correctable causes. It is usually indicated by bleeding greater than 200 mL/h with normal or near-normal coagulation studies. Mechanical bleeding is characterized by clots in the drainage tubes.¹⁷⁷

Etiology of Coagulopathy

Coagulopathy is present to some extent in all patients after cardiopulmonary bypass. With the current aggressive use of percutaneous catheter intervention for the treatment of various acute coronary syndromes (ACS), drug-induced coagulopathy is frequently seen. Following deployment of stents for ACS, patients are placed on platelet inhibitors such as glycoprotein IIb/IIIa inhibitors (eptifibatide, tirofiban, or abciximab) or the ADP binding inhibitor clopidogrel. In some instances, acute myocardial infarctions are treated with thrombolytic therapy and this results in a profound coagulopathy.^{178,179}

Fibrinolysis results from the activation of the fibrinolytic system either intrinsically from cardiopulmonary bypass or therapeutically from preoperative thrombolytic therapy.^{180,181} This appears to be the primary cause in coagulopathy following

cardiopulmonary bypass (CPB). A progressive fibrinolytic state occurs and its intensity is directly related to the duration of cardiopulmonary bypass.¹⁸² It is associated with the degradation of clotting factors as well as platelet dysfunction.

Platelet defects are also an important cause of postoperative bleeding. The platelet-related bleeding diathesis is a result of a decrease in the absolute platelet number, and more importantly, secondary to impaired platelet function.^{183,184} The decrease in the platelet number, or quantitative defect, results from hemodilution, preoperative thrombocytopenia from medications, and the consumption of platelets by the cardiopulmonary bypass circuit. The CPB circuit itself can reduce the platelet count by 30–50% and worsens as the duration of bypass lengthens. The diminished platelet function, or qualitative defect, may be directly related to the duration of CPB. Passage of platelets through the cardiopulmonary bypass circuit results in decreased platelet membrane receptors for fibrinogen and glycoprotein Ib and glycoprotein IIb/IIIa complex.¹⁸⁵ Thrombocytopenia may also be caused by *heparin-induced thrombocytopenia*. This usually occurs in patients with a previous exposure to heparin within 3 months. It is the result of heparin antibodies causing platelet aggregation. There is often a history of heparin resistance during CPB.¹⁸⁶ The qualitative defect in platelets may also be related to preoperative medications such as aspirin, heparin, and the glycoprotein IIb/IIIa inhibitors.^{187,188} *Residual heparin effect* can account for a postoperative bleeding diathesis. Heparin effect is usually reversed by the time the patient gets to the intensive care unit. It should always be considered as a possibility in the bleeding patient. *Heparin rebound* is the recurrence of measurable heparin activity after complete protamine neutralization. It is associated with larger heparin doses given intraoperatively, after long CPB runs, and obese patients.¹⁸⁹ It is thought to be the result of elution of heparin from plasma proteins.¹⁹⁰ *Hypothermia* is a significant cause for postoperative coagulopathy. The coagulation cascade is mediated by enzymatic reactions. These reactions are temperature-sensitive and occur most efficiently at normothermia. Hypothermia retards the normal coagulation cascade as a result of this altered enzymatic activity. *Hemodilution* of CPB is another source of coagulopathy and affects all blood elements including coagulation factors. Most factors are reduced by 50% and factor V by 80%.¹⁹¹ This phenomenon affects patients with small blood volumes more profoundly. Also, coagulation factors are lost with cell saving.

Diagnosis of Coagulopathy

An attempt should be made to specifically diagnose the coagulopathy. The specific abnormalities can usually be diagnosed if appropriate studies are ordered. *Platelet defects* are both quantitative and qualitative. The diagnosis of quantitative defects, thrombocytopenia, can be made early in the postoperative period with a simple platelet count. If thrombocytopenia occurs later in the course, consider HIT and obtain a heparin-platelet aggregation test to confirm the presence of heparin

antibodies. Qualitative platelet defects, thrombasthenia, can be present with a normal platelet count but platelet function will be abnormal and the clot formation inadequate. The bleeding time is prolonged and indicates abnormal platelet aggregation and adhesiveness. *Residual heparin effect* is diagnosed by a prolonged partial thromboplastin time (PTT) and/or activated clotting time (ACT). Either a PTT or an ACT should be measured on admission to the intensive care unit because inadequate heparin reversal with protamine is usually seen early in the postoperative period. Generally, other laboratory values will be normal. A heparin–protamine titration test can be performed if the Hepcon system (Medtronic Inc., Minneapolis, Minnesota) is available. This test directly quantifies the amount of heparin circulating. It will detect any residual heparin and also allow for a calculation of the appropriate dose of protamine needed to neutralize the residual heparin. If the PTT or ACT are elevated 5 h after the last heparin dose, it is unlikely secondary to heparin as the half-life of heparin is 1 h; if heparin effect is suspected at this time, obtain heparin levels to confirm the diagnosis.¹⁹¹

Fibrinolysis is associated with an elevated PT and PTT; decreased levels of factors I, V, and VIII; rapid euglobulin clot lysis; and the presence of D-dimers. D-dimers indicate the presence of fibrin monomers, and their presence is diagnostic for fibrinolysis if accompanied by decreased fibrinogen levels. An elevated D-dimer alone is not uncommon, particularly if shed blood is being reinfused and in itself is not diagnostic of fibrinolysis.¹⁹² *Disseminated intravascular coagulation* (DIC) is the severest form of coagulopathy. From a laboratory standpoint, it is manifested by an elevated PT and PTT, decreased fibrinogen levels, thrombocytopenia, and an elevated fibrin-split products (greater than 40 mcg/mL) and D-dimer.¹⁹³ DIC is rarely seen in the early postoperative period and usually is associated with other complications.¹⁹⁴

Thromboelastography¹⁹⁵ and Sonoclot¹⁹⁶ analysis are two studies available in some institutions that have been shown to specifically identify the source of the bleeding diathesis. These studies are not commonly available. *Coagulation factor deficiencies* either from hemodilution or true deficiencies can be diagnosed by measuring the specific factors, but in the acute setting this may not be practical as obtaining these results is time-consuming. Increased PTT and PT (prothrombin time) usually manifest factor deficiencies. Specific studies can be ordered, but it is usually reasonable to proceed with the empiric treatment before results are available. There must be a high degree of suspicion for factor deficiencies in the patient with a previous or family history of abnormal bleeding, liver disease, prior warfarin therapy, hemodilution, or clinical evidence of disseminated intravascular coagulation.

Treatment of Coagulopathy

The treatment of a postoperative coagulopathy must be prompt and aggressive. The bleeding cycle must be interrupted as “bleeding begets bleeding.”¹⁹⁵ The specific treatment consists

of blood component therapy based on an accurate diagnosis. Initial therapy begins by sending coagulation studies to include a PT, PTT, platelet count, and fibrinogen level. Then, notify the blood bank that component therapy will be needed and an adequate supply of cross-matched packed red blood cells, fresh frozen plasma (contains all coagulation factors except platelets), cryoprecipitate (factor VIII and fibrinogen), and platelet concentrates should be readily available. Next, hypothermia should be corrected. Within the first 2 h and even before the coagulation studies are available, consider the empiric use of protamine sulfate in the event residual heparin or heparin rebound is the cause. If the bleeding continues after the hypothermia is corrected and the empiric protamine is given, an algorithmic approach can be used.¹⁹⁴ This algorithm begins by sending coagulation studies. Then, transfuse platelets, 1 unit/10 kg body weight, and draw post-transfusion platelet count. If the bleeding continues and the posttransfusion platelet count is less than 100,000, repeat the platelet transfusion of 1 unit/10 kg body weight. If the posttransfusion platelet count is greater than 100,000, *but* the fibrinogen is less than 100 mg/100 mL, give 1 unit of cryoprecipitate/4 kg body weight. If the posttransfusion platelet count is greater than 100,000, *but* fibrinogen is greater than 100 mg/100 mL, *and* the PT or PTT is less than 1.5 times control value, recheck for surgical bleeding and do a bleeding time; and if it is greater than 9 min, give desmopressin 0.3 mcg/kg IV. If the posttransfusion platelet count is greater than 100,000, *but* the fibrinogen is greater than 100 mg/100 mL, *and* the PT or PTT is greater than 1.5 times control value, give fresh frozen plasma 15 mL/kg. If bleeding persists at the completion of the algorithm, consult a hematologist.

In addition to blood component therapy, there are drugs available for the treatment of postoperative coagulopathy. *Protamine* is the specific drug for the reversal of heparin. The dosage is 25–50 mg increments given IV over 10 min. Be aware there are three types of adverse reactions to protamine administration. Type I reaction is systemic hypotension from rapid administration that usually occurs if the entire neutralizing dose is given in less than 3 min. It is a histamine release reaction that causes a reduction in the SVR and PVR. It can be avoided by giving the dose over 10–15 min. Type II reaction is an anaphylactic or anaphylactoid reaction resulting in hypotension, bronchospasm, flushing, and edema. It is further divided into Type IIA that is an idiosyncratic reaction mediated by IgE or IgG and is caused by the release of histamine or leukotrienes producing a capillary leak syndrome with hypotension and edema. It usually occurs within the first 10 min of administration. Type IIB is an immediate reaction and is not related to immunoglobulins. Type IIC is a delayed reaction occurring after 20 min or longer, and seems to be related to complement activation and leukotriene release producing bronchospasm and a capillary leak syndrome that leads to hypovolemia and noncardiac pulmonary edema. Type III reaction is catastrophic pulmonary vasoconstriction with acute pulmonary hypertension, right ventricular failure, and severe peripheral

vasodilatation with hypotension and myocardial depression. It occurs 10–20 min after the protamine is given and is thought to be secondary to the heparin–protamine complex. This complex incites leukocyte aggregation and the release of liposomal enzymes that damage pulmonary tissue. Type III reactions are highly lethal unless cardiopulmonary bypass can be reinstated to support the patient. Treatment is initially calcium chloride and α -agonists to support the SVR. It may also be beneficial to add β -agonists to reduce the PVR. Specific drugs to lower the PVR (such as prostaglandin E) may be helpful, but usually it is necessary to readminister heparin and reinstate cardiopulmonary bypass.

Desmopressin (DDAPV) has not been shown to be of benefit in the uncomplicated patient, but is of value in patients with platelet dysfunction secondary to uremia, liver dysfunction, and antiplatelet medications.^{196–198} It is specific therapy for patients with an acquired defect in platelet plug formation as a result of a deficiency in von Willebrand's factor. The dosage is 0.3–0.4 mcg/kg IV over 20 min. *Epsilon-aminocaproic acid* (EACA) is an antifibrinolytic agent that inhibits conversion of plasminogen to plasmin. It may act to preserve platelet function. EACA is best used when given before cardiopulmonary bypass prophylactically, but it can also be used as a rescue agent for severe bleeding, especially if fibrinolysis is present.¹⁹⁹ It should be used with caution or not at all with aprotinin as the combination appears to cause a prothrombotic state with associated graft closure, renal dysfunction, and stroke. The rescue dose for postoperative bleeding is usually 5–10 g IV bolus.

Aprotinin is a serine protease inhibitor that preserves adhesive platelet receptors (GPIb) during the early phase of cardiopulmonary bypass. It also has antifibrinolytic properties by inhibiting plasmin. Aprotinin has been demonstrated to reduce blood loss when given before and during cardiopulmonary bypass in patients at high risk for postoperative bleeding, such as thrombocytopenia, uremia, hepatic dysfunction, and long complex procedures, particularly reoperations.²⁰⁰ It does have a role as a rescue agent for postoperative bleeding, but must be used with caution as it may be prothrombotic in the nonheparinized patient.²⁰¹ The rescue dose is two million KIU. Aprotinin therapy has been associated with an increased morbidity and mortality in some studies and its use is controversial.

Blood Component Therapy

Blood component therapy includes packed red blood cells (RBCs), fresh frozen plasma (FFP), cryoprecipitate (factor VIII and von Willebrand's factor), and platelets. RBC transfusion should be managed by protocol and determined by the clinical status of the patient. RBCs are indicated in the anemic patient with normal LV function when the hematocrit is 22–24%.^{29,202} If the patient is actively bleeding, the hematocrit should be maintained at 26% to afford a margin of safety.²² If the patient is elderly or has LV dysfunction and cannot increase the cardiac output in response to anemia, the hematocrit should be maintained at a higher level. Platelet transfusions are indicated for a platelet count under 70,000 if the patient is bleeding excessively.

FFP is recommended in the excessively bleeding patient for an INR (International Normalized Ratio) of greater than 1.5–1.7. Specific treatment with cryoprecipitate and other components is indicated in the presence of a consumptive coagulopathy as reflected by a diminished fibrinogen level, positive D-dimer assay, or the presence of fibrin degradation products.⁹¹

Blood Conservation

Blood conservation is an important part of managing the postoperative patient both with and without significant bleeding. There are preoperative measures, intraoperative measures, and postoperative measures. The preoperative measures include autologous blood donation for elective cardiac procedures. This must be done with care, particularly in the patient with ischemic heart disease or congestive heart failure secondary to valvular heart disease. Therefore, it is not a measure widely practiced. Another preoperative measure is the modification of the preoperative antiplatelet regimen within limits of therapeutic prudence. And, finally, preoperative erythropoietin can be used in the anemic patient to improve hemoglobin levels sufficiently to avoid perioperative transfusions.²⁰³ Intraoperatively, the crystalloid prime of cardiopulmonary bypass circuit with resultant hemodilution to hematocrit of 20–30% minimizes the loss of red cells. Also, blood salvage with reinfusion of washed, centrifuged red cells, both from the field and from the circuit after separation from cardiopulmonary bypass, conserves blood. Careful operative hemostasis is a must for blood conservation. Postoperative autotransfusion and cell saving also conserve blood and reduce the complications of transfusions. The “cell saver” in most institutions has supplanted traditional autotransfusion techniques. The cell saver is a system that combines washing and centrifuging shed blood before reinfusing, as opposed to directly reinfusing shed blood after passing it through a filter. Shed blood does not require an anticoagulant because it has undergone fibrinolysis, unless the hemorrhage was extremely rapid. Shed, traditional autotransfused blood has low levels of factors VIII and fibrinogen as well as platelets, but the platelets present are dysfunctional. Autotransfused blood does contain fibrin-split products. Conversely, cell saver blood is devoid of clotting factors and platelets as well as fibrin-split products.²⁰⁴ Transfusion of less than one liter of either autotransfusion blood or cell saver blood is without significant risk of exacerbating a coagulopathy. Transfusion of greater amounts can potentially worsen the coagulopathy by infusing fibrin monomers, in the case of autotransfusion, and from platelet and factor depletion with both.^{205,206} Autotransfusion of greater than 1,500 mL of shed blood should be avoided and blood component therapy should be used to augment reinfusion of cell saver blood to avoid depletion of platelets and clotting factors.

Mediastinal Bleeding

Multiple factors contribute to postoperative bleeding.^{207,208} Despite deficiencies in the coagulation cascade and multiple potential sites of surgical bleeding, mediastinal drainage slows

over the first few hours in the majority of patients. Aggressive management of the bleeding patient is generally successful, such that only about 1–3% of patients require reoperation for persistent bleeding. Normally, when the patient returns from the operating room, mediastinal drainage is in the order of 100–300 mL/h for the first 2–3 h and 50 mL/h thereafter.

The initial steps in managing the bleeding patient after open-heart surgery are aggressive treatment of hypothermia and hypertension, order coagulation studies, notify the blood bank to have blood products available, and consider an empiric dose of protamine. If coagulation studies indicate a coagulopathy, proceed with the algorithm for management. In any patient with excessive mediastinal drainage, cardiac tamponade must be considered. Be alert for the following signs of tamponade: equalization of filling pressures, low cardiac output, hypotension, wide respiratory variation of systolic blood pressure with positive pressure ventilation, and a narrowed pulse pressure. At times, the classic findings of tamponade may be absent, but the following points may signal tamponade: the sudden cessation of chest tube drainage, progressive low cardiac output in a patient with a previously normal cardiac output, an unexplained left or right heart failure, severe peripheral vasoconstriction with cyanosis of the ears and digits, progressive fall in the urine output, an unexplained tachycardia, mediastinal widening on chest X-ray, pleural effusion, and diminished ECG voltage.

There are caveats regarding cardiac tamponade in the immediate postoperative setting. First, a pulsus paradoxus is not an applicable sign of tamponade in the patient on positive pressure ventilation. Positive pressure ventilation reverses blood pressure response to respiration. On the ventilator, during early inspiration, the positive airway pressure causes a compression of the pulmonary veins augmenting left heart filling and thus blood pressure, whereas, later in the inspiratory cycle, left heart filling is diminished and the blood pressure falls. This early rise in the blood pressure is opposite of the fall in blood pressure seen during spontaneous inspiration and makes pulsus paradoxus an unreliable sign of tamponade during positive pressure ventilation. Also, it is not unusual for a clot to accumulate next to the right or left atrium and cause unequal elevations of the RA or LA pressures. Most important, the diagnosis will be made only if a high degree of suspicion is maintained. The diagnostic modality of choice for cardiac tamponade in the postoperative period is transesophageal echocardiography.

The definition of excessive mediastinal bleeding is 500 mL/h for 1 h, 400 mL/h for 2 h, and 300 mL/h for 3 h. If mediastinal bleeding persists despite correction of the coagulopathy or if the patient demonstrates evidence of hemodynamic compromise, mediastinal reexploration in the operating room is indicated. An aggressive approach to mediastinal reexploration is in the best interest of the patient. Reexploration is associated with increased mortality and morbidity usually because of a delay in proceeding.²⁰⁹ Early reexploration reduces these complications.²¹⁰ An emergency reexploration in the intensive care unit is indicated for exsanguinating hemorrhage or impending arrest from any cause.

The technique for emergency reexploration begins with a call for the necessary assistance. Intubate the patient if necessary and hand ventilate the patient with inspired oxygen of 100%. Remove the dressing and pour antiseptic over the sternotomy incision and block drape the site with sterile towels. Reopen the incision with a scalpel and cut or untwist the wires. The sternum is opened with a sternal spreader. Then, evacuate the hematoma and attempt to identify the source of bleeding. If a bleeding site is identified, tamponade it with digital pressure. Proceed to complete the resuscitation of the patient. Ideally, the site of hemorrhage should be repaired in the operating room, but if this is not practical or feasible, repair it in the ICU.

If internal cardiac massage is needed, do so with two hands by placing the left hand beneath the heart and compressing the anterior aspect of the heart with the right hand using the palm and flattened fingers and take care not to injure the grafts. If the patient has a prosthetic mitral valve in place, take care not to injure the posterior left ventricle with the struts during internal massage. Once some semblance of hemodynamic stability has returned, return the patient to the operating room for repair of the bleeding site, irrigation of the mediastinum, and closure. If the reason for emergency re-sternotomy was hemodynamic collapse not related to bleeding or tamponade, placement of an IABP is highly recommended.

Noncardiac Complications of Open-Heart Surgery

Pulmonary Complications

After the heart, the lungs are the organs most likely to be dysfunctional after CPB. During CPB, neutrophils are sequestered in the pulmonary vasculature and oxygen free radicals cause peroxidation of membrane lipids. These changes produce pulmonary vasoconstriction and are thought to increase the permeability of the alveolar–capillary barrier and consequently produce interstitial edema within the lungs. Leukocytes are also activated and cause an inflammatory response of the pulmonary vasculature.²¹¹ During CPB and diminished pulmonary arterial flow, plasma thromboxane B₂ increases, further contributing to the pulmonary vascular inflammation.²¹² The cumulative effect of these responses is a more permeable alveolar–capillary membrane and a predisposition to interstitial pulmonary edema.²¹³ Atelectasis also contributes to pulmonary dysfunction. This appears in some way to be linked to a decrease in pulmonary surfactant, and may partially explain the left lower atelectasis seen almost universally after cardiac surgery.²¹⁴ Thermal injury to the phrenic nerve and/or diaphragmatic dysfunction as well as effusions, pain, and chest tubes are other contributing factors to altered pulmonary function postoperatively. Lung and chest wall compliance decrease significantly following cardiac surgery, with the maximum decrease occurring at 3 days and lasting as long as 6 days.

The respiratory management of the postoperative cardiac surgical patient is not unlike any other postoperative patient, but there are several factors that are unique to these patients. The unique factors include: incision pain, the interference of chest tubes with the respiratory function, an element of diaphragmatic dysfunction, elevated left heart filling pressures with alveolar edema and diminished compliance, and capillary permeability.^{20,31,215} Atelectasis is the most common pulmonary complication occurring in 70% of these patients.²¹⁶ After cardiac surgery, atelectasis occurs most commonly in the left lower lobe. The exact etiology of this phenomenon remains unclear. It is associated with left phrenic nerve paralysis only in 11% of patients.²¹⁷ Alterations of the chest wall result in a decrease in the FEV₁ and FRC and persist for 6 weeks. These alterations lead to an increased respiratory rate, decrease tidal volume, decreased respiratory efficiency, and increased oxygen utilization. Pulmonary infiltrates are the result of pneumonia, pulmonary embolism, and adult respiratory distress syndrome (ARDS) – although with ARDS, there is typically more of a diffuse process and is associated with more severe hypoxemia. The basic treatment of pneumonia and ARDS includes blood and sputum cultures, hemodynamic maintenance, euvoletic fluid management with a consideration of fluid restriction and the use of colloid for ARDS, and the maintenance of an arterial saturation greater than 50 mmHg with minimum inspired oxygen content.^{218–220} Bronchospasm can occur immediately after CPB and may interfere with hemodynamic stability. The probable cause is activation of C5a anaphylatoxin by CPB. Other causes include pulmonary edema, exacerbation of pre-existing reactive airway disease, the use of β -blockers, and a reaction to protamine.²¹⁶ The treatment for bronchospasm includes the exclusion of heart failure, inhaled β_2 -agonists, the addition of cholinergic agents, a short course of systemic steroids for refractory bronchospasm, and intravenous aminophylline. Aminophylline is reserved for refractory situations because of its arrhythmogenicity in the postoperative period.

Renal Complications

During CPB, renal blood flow and glomerular filtration rate are reduced 25–75%, with partial but not complete recovery in the first day after CPB.^{221,222} This is thought to be secondary to renal artery vasoconstriction, hypothermia, and loss of pulsatile flow. The nonpulsatile blood flow of CPB promotes renal artery vasoconstriction and diminishes renal blood flow to the cortex. In addition, angiotensin II levels are elevated by nonpulsatile flow.^{223,224} There appears to be a relationship between length of CPB and renal insufficiency, but not pressure or flow rates while on pump.²²⁵ Other factors associated with renal failure include preexisting renal dysfunction (creatinine greater than 1.5 mg/dL), older age, poor left ventricular function and congestive heart failure, emergency surgery, the use of deep hypothermic circulatory arrest, moderate hypothermia, a preoperative history of hypertension, diabetes, and peripheral vascular disease, isolated valve operations, and the

use of radiocontrast dye agents immediately preoperatively. Postoperative factors contributing to renal insufficiency include: low cardiac output; hypotension; vasoconstriction; atheroembolism from the IABP; sepsis; RV failure with systemic venous hypertension; respiratory insufficiency with hypoxemia; and medications such as cephalosporins, aminoglycosides, and ACE-inhibitors.^{22,226–232} The incidence of renal complications following open-heart surgery has been reported as high as 35%. The frequency of oliguric renal failure requiring dialysis is 2–3% with a mortality of 50%.^{230–233}

The most common form of renal failure after CPB, is non-oliguric renal failure. Nonoliguric renal failure has a better prognosis with a mortality rate of 10–17%.^{231,234} The management goal of nonoliguric renal failure is the maintenance of an appropriate glomerular filtration rate by maintaining an adequate cardiac output and an adequate systemic blood pressure. The use of loop diuretics is controversial. They are unlikely to prevent the progression of nonoliguric to oliguric renal failure. Dopamine at a “renal dose” of 1–2.5 mcg/kg/min is commonly used to preserve renal function. There are no studies demonstrating a renoprotective effect. Dopamine may increase urine output, but it has been shown to be associated with renal tubular necrosis equal to or worse than controls.^{41,235} In patients with a serum creatinine of >1.4 mg/dL, infusion of fenoldopam of 0.03–0.1 mcg/kg/min has been shown to preserve renal function.²³⁶

The best management of oliguric renal failure is prevention by early identification and treatment of deteriorating renal function. This prevention begins by avoiding hypotension and low cardiac output states, optimizing volume status, considering the early use of inotropic agents and pressors, and the early use of IABP. Once oliguric renal failure occurs, a nephrology consultation is in order. Strict euvolemia must be maintained, as well as careful monitoring of metabolic status and electrolyte balance and the daily review of medications looking for drugs excreted by kidneys. If renal failure occurs several days following surgery, it is most likely not related to CPB but more likely as a result of sepsis, nephrotoxic drugs, low cardiac output, and obstruction of the urinary tract.

Gastrointestinal Complications

The perfusion of intra-abdominal viscera is also adversely effected by CPB. The blood flow to the liver is reduced by 19% during CPB and there is concomitant relative hypoperfusion of splanchnic and gastric flow. The decrease in gastric flow results in gradual decreasing of gastric pH and is associated with the appearance of endotoxin in the circulation, suggesting that the intestinal barrier is compromised and translocation is a possibility.^{237,238} Gastrointestinal complications are generally not a common source of significant morbidity after open-heart surgery. They occur at a rate of approximately 1–2%. These complications are the result of a low cardiac output state with its associated sympathetic vasoconstriction and hypoperfusion of the abdominal organs. The most common serious complication after CPB

is gastrointestinal hemorrhage from gastritis or gastroduodenal ulcer disease.²³⁹ The pathology is usually hemorrhagic gastritis or duodenitis.^{240,241} Occasionally, the hemorrhage is from previous duodenal ulcer disease and rarely from the colon.²⁴²

Gastrointestinal hemorrhage occurs in only about 1% of cases and the risks are higher in patients with COPD, hypotension, excessive postoperative bleeding, reoperation, and a prior history of peptic ulcer disease.²³⁴ It is recommended that these high-risk patients have prophylactic ulcer therapy.²⁴³ An appropriate prophylactic regimen would include sucralfate 1 g q6h orally or down a nasogastric tube. Another option is omeprazole 20 mg daily. Ranitidine appears to be the best option with a lower rate of gastrointestinal hemorrhage and an equivalent incidence of pneumonia.²⁴⁴

Hepatic dysfunction is marked by transient elevation of liver function tests in 20% of patients. Less than 1% of the patients will develop significant hepatocellular damage resulting in either chronic hepatitis or liver failure.^{245,246} The risk factors for these complications are prolonged CPB, multiple transfusions, and multiple valve replacements. Elevated LFTs in association with hyperbilirubinemia occurring within the first 1–10 days is a result of low cardiac output and “shock liver.” Shock liver may cause hemodynamic instability with low systemic vascular resistance. Hyperbilirubinemia without elevated LFTs, if it occurs early, may be the result of cholestasis from red blood cell trauma and destruction, as well as from right heart failure with passive congestion of the liver, although the alkaline phosphatase may be elevated in this instance. Bilirubin usually normalizes in 1–14 days with observation only. If isolated hyperbilirubinemia occurs late, it is caused by infection from transfused blood products. The risk of infection after transfusion depends on the number of units transfused and types of products transfused. The most common infections are non-A, non-B hepatitis (seen more often after clotting factor transfusions), cytomegalovirus, Epstein–Barr virus, and acute cholecystitis.²⁴⁷ Acute cholecystitis is seen more often in the elderly after prolonged CPB, suggesting hypoperfusion may be a factor. Transient hyperamylasemia can be found in as many as 35% of patients after CPB, yet is associated with pancreatitis in only 1–3% of the patients.²⁴⁸ The risk factors include long CPB time and multiple transfusions. It is a must to exclude postoperative pancreatitis as this is a serious problem with a high mortality rate.²⁴⁹ Ischemic bowel syndrome as a result of mesenteric ischemia is a catastrophic complication. It is often associated with the hypoperfusion of low cardiac output, particularly the elderly patient requiring inotropic or IABP support.

Metabolic Complications

Electrolyte imbalances are common after cardiopulmonary bypass. Potassium alterations are the result of rapid shifts that occur during cardiac surgery and CPB. The factors related to *potassium* fluxes are hyperkalemic cardioplegia, renal dysfunction while on CPB, low cardiac output and associated

oliguria and acidosis, hemolysis of red cells, diuresis, and diminished potassium uptake in the face of diabetes mellitus.²⁰ Certain medications also impair potassium excretion and cause hyperkalemia. This list of medications include ACE inhibitors, potassium-sparing diuretics, non-steroidal anti-inflammatory drugs, angiotensin receptor blockers, and β -blockers.²² The principal adverse effect of potassium alterations is on the electrical activity of the heart and can be life-threatening. Hyperkalemia manifests itself predominantly electrocardiographically. Asystolic arrest can occur when potassium rises rapidly to a level exceeding 6.5 mEq/L. The EKG findings are more related to the rate of rise of potassium level than to an absolute level. They are peaked T waves, ST depression, prolonged PR interval, loss of P wave, QRS widening, bradycardia, and asystole. Hyperkalemia may result in failure of the heart to respond to the pacemaker stimulus and this may be a factor during resuscitation. Treatment includes optimizing cardiac function and shifting potassium into the cells and increasing its excretion. The cardiac function is optimized with calcium gluconate. If there is evidence of cardiac toxicity, 0.5–1 g of calcium gluconate is given intravenously over 15 min. Potassium is shifted into the cells by giving 50 mEq of NaHCO_3 to correct acidosis and giving 10 units of regular insulin and 25 g of 50% dextrose. Potassium excretion is enhanced with furosemide 10–200 mg IV, Kayexalate enema 50 g in water enema or 50 g PO with sorbitol or dialysis. Hypokalemia is usually a result of diuresis without adequate replacement of potassium. Diuresis is usually profound after CPB owing to hemodilution. Diuretics, insulin administration, or alkalosis may exacerbate this diuresis. Hypokalemia promotes atrial, junctional, and ventricular ectopy.²² It can cause life-threatening ventricular tachycardia, but usually does not become clinically evident until serum concentration is less than 2.5 mEq/L. Hypokalemia can also be the cause of metabolic alkalosis as hydrogen ions replace potassium within the cells. The treatment is potassium chloride (KCl) administration through a central line at 10–20 mEq/h. Serum potassium raises approximately 0.1 mEq/L for each 2 mEq of KCl given. A slower rate is recommended in the presence of renal insufficiency.

Calcium plays a complex role in myocardial reperfusion damage and energetics. Ionized calcium should be measured during and after CPB because hemodilution, hypothermia, pH shifts, and use of citrated blood will affect protein binding of calcium. Hypocalcemia is the most frequently seen calcium abnormality in the perioperative period. The treatment of hypocalcemia is a calcium chloride bolus of 0.5–1 g. Calcium gluconate 10 mL of 10% solution will have fewer cardiovascular effects than calcium chloride.

Hypomagnesemia is not uncommon after CPB. The incidence is 70%.²⁵⁰ The most common etiology for hypomagnesemia is the diuresis and hemodilution associated with CPB. The effects of hypomagnesemia are mainly cardiac effects and similar to those of potassium on the electrical activity of the heart. Manifestations of hypomagnesemia include atrial

and ventricular dysrhythmias, potentiation of digoxin-related dysrhythmias, and a predilection to coronary spasm. Since magnesium is also related to energy metabolism, prolonged ventilator support has also been related to low serum magnesium levels. Treatment is an infusion of 2 g magnesium sulfate in 100 mL of solution to raise the serum level to 2 mEq/L. Note that magnesium has been shown to inhibit the vasoconstrictive effect of epinephrine but not its cardiotoxic effect.²⁵¹

Hyperglycemia routinely occurs during CPB. Modest elevations are present during hypothermia, but more marked elevations of blood glucose happen during rewarming. Hyperglycemia is caused by increased glucose mobilization related to increases in cortisol, catecholamines, and growth hormone levels during CPB. There also appears to be a blunted insulin response and impaired insulin production as well as a peripheral insulin resistance during CPB.²⁰ The impaired insulin secretory response may last 24 h. These changes are exaggerated in the diabetic patient, and insulin requirement may be seven times greater than preoperative requirements in the first 4 h after surgery.²⁵² Hyperglycemia postoperatively is associated with osmotic diuresis, impaired wound healing, increased risk of infection, and impaired blood pressure regulation.²²

Hyperosmolar, hyperglycemic, non-ketotic coma is unusual following open-heart surgery. It usually occurs in type II diabetics 4–7 days after surgery.²⁵³ Diabetic ketoacidosis is rarely encountered in the postoperative period. The most efficient method of managing the postoperative patient is with an insulin infusion. The usual dose is 0.1 unit/kg/h of regular insulin in a saline mix. Blood glucose levels must be monitored every 4 h to maintain serum glucose of 70–200 mg/dL. Type II diabetics should be restarted on their oral regimen as soon as they are taking PO.

Hematologic Complications

The most common and most frequent hematologic complication of open-heart surgery is thrombocytopenia and platelet dysfunction.^{207,254} Platelet counts decrease rapidly by 50% soon after the institution of CPB but usually remain above 100K. Platelet counts less than 150,000/mm³ occur in approximately 62% of patients on postoperative day one.²⁰ Platelet counts begin to increase by the third postoperative day. Bleeding from thrombocytopenia is usually not a problem until the platelet count falls below 60,000/mm³. Of greater clinical significance is the progressive deterioration of platelet function during CPB. Within minutes of CPB, platelet aggregation is impaired and continues to worsen throughout CPB. This platelet dysfunction is precipitated by contact of the platelets with synthetic surfaces of the CPB circuit as well as by hypothermia. Also, the mechanical stresses of CPB cause fragmentation of the platelets and a temporary depletion in the membrane antigen for glycoproteins IB, IIb, and IIIa.²⁵⁵ Hypothermia impairs platelet thromboxane A₂ synthesis resulting in reversible platelet dysfunction. Bleeding time returns to normal in about 2–4 h and the platelet count

is restored in several days.^{208,256,257} Platelet dysfunction occurs less commonly with the use of antifibrinolytic drugs, such as ε-aminocaproic acid, because these agents act in part by reducing platelet activation during CPB.

Indications for platelet transfusion are as follows: a platelet count less than 20–30,000/mm³, ongoing bleeding with a platelet count less than 100,000/mm³, and a platelet count less than 60,000/mm³ if a surgical procedure is planned.²² CPB also effects the plasma concentration of *coagulation factors* II, V, VII, IX, X, and XIII. The plasma concentration of these factors decline during CPB secondary to hemodilution but remain at levels adequate for hemostasis, and, with the exception of fibrinogen, return to normal by 12 h.^{208,256} Fibrinogen and plasminogen decrease during CPB from dilution and not consumption, and usually return to normal by 24 h.

Heparin-induced thrombocytopenia (HIT) is an infrequent but serious complication with a high mortality rate if the fulminant course progresses to heparin-induced thrombotic thrombocytopenia (HITT).¹⁸⁶ HIT is caused by the formation of IgG platelet membrane antibodies, which, in the presence of heparin, produce platelet aggregates and heparin resistance. The range of intensity of HIT and HITT spans from only moderate thrombocytopenia to a syndrome of arterial or venous thrombosis caused by platelet aggregation and bleeding from profound thrombocytopenia.^{258,259} If the diagnosis of HIT is suspected, all heparin must be discontinued including therapeutic infusions, line flushes, heparin-coated monitoring lines, and low-molecular-weight heparins. The laboratory confirmation by platelet aggregation testing is important, but may take at least 24 h to confirm; therapy should be instituted as soon as the diagnosis is suspected. Platelet counts must be monitored on a daily basis.

Infectious Complications

In-hospital, postoperative infections after open-heart surgery occur at a rate of 12–20%. The most common infections are the respiratory, urinary, and wound or surgical site infections.²⁶⁰ While all postoperative infections adversely affect outcomes, it is the sternal wound infection and mediastinitis that have the greatest adverse effects. The overall incidence of sternal wound infections is 0.8–1.4%.^{261,262} When sternal wound infections are associated with mediastinitis, the mortality varies from 6 to 70%.²⁶³ When recognized early and effectively treated, the mortality is 5–10%.²⁶⁴ The rate of mediastinitis is higher in valvular procedures and in combined procedures.²⁶⁵ The use of bilateral internal mammary arteries increases the risk of sternal wound complications to 5%.²⁶² *Staphylococcus aureus* and *Staphylococcus epidermidis* are the most common pathogens encountered accounting for 42% of infections.²⁶⁶

Preoperative predisposing factors include type and timing of skin preparation, cardiopulmonary failure, need for an IABP, diabetes mellitus, steroid use, a history of mediastinal radiation, osteoporosis, age, and COPD.^{264,267} Intraoperative factors are a CPB run greater than 3 h, excessive bleeding, the

use of bilateral internal mammary arteries, valve procedures, combined procedures, and inadequate sternal fixation.²⁶⁸ Postoperative bleeding will increase the risk for sternal wound complications, as will low-flow states, concurrent infections, tracheotomies, and prolonged ventilatory support.²⁶⁹

The most obvious sign of a wound infection is purulent drainage from the incision. There should be a heightened level of suspicion in a patient whose pain begins to increase toward the end of the first postoperative week rather than decrease.²⁶⁸ Also the wound is reddened and swollen and there is a localized area of skin necrosis associated with the drainage. The drainage is serous if the complication is minor, involving only the superficial soft tissue. However, if the complication is a major one with mediastinitis there is extensive purulent drainage with infection extending down to the sternum and mediastinum. These findings may not always be an indication of infection, but could be aseptic necrosis from internal mammary artery mobilization.

Fever, leukocytosis, or gram-positive bacteremia should raise the suspicion of a sternal wound infection. Any fever of undetermined etiology should raise the question of wound sepsis, particularly in diabetics where few other local or systemic signs may be present as a result of a poor inflammatory response. The evaluation begins with a culture of the purulent drainage. If there is no drainage, a likely area of the wound should be opened and careful cultures obtained. Radiographic workup is of limited value. Routine chest X-rays are of little help. A chest computed tomography (CT) scan may identify indolent, retrosternal infections, particularly if gas-forming organisms are present.²⁷⁰⁻²⁷²

Minor infections usually respond to treatment with antibiotics and local care, including wound packing. Major infections require mediastinal exploration and debridement of infected tissue, including the sternum. If the sternum is necrotic or grossly infected, removal of the sternum is necessary and requires closure with a muscle flap, either a pectoralis major or rectus abdominis flap. Omentum can also be used to provide a vascular bed for healing, but omental mobilization is associated with a higher morbidity than the creation of a muscle flap. Appropriate parenteral antibiotics are required for a 6-week period.

The incidence of leg wound infections is 1–10%. These complications may result from poor surgical technique with a creation of flaps, failure to eliminate dead space, or hematoma formation. The risk factors are obese women, use of thigh veins, diabetes, and severe peripheral vascular disease.²⁷³ The prevention of leg infections involves careful surgical technique and the use of suction drains to eliminate dead space in the leg. The treatment is appropriate antibiotic coverage, debridement, and a consideration for early plastic surgery involvement.

Prophylactic antibiotics should be administered for 48 h starting in the operating room just prior to the incision. First- or second-generation cephalosporins are used because of their effectiveness against gram-positive cocci. Vancomycin is used in patients with true anaphylactic allergy to penicillin or cephalosporins. If the patient does not have a documented history

of a severe anaphylactic reaction to penicillin or a cephalosporin, a cephalosporin should be used. Attempts must be made to limit the use of vancomycin for prophylaxis to lessen the likelihood of vancomycin-resistant *Enterobacter* infections.

Neurologic Complications

Neurologic complications following open-heart surgery are dreaded sequelae. The overall incidence of focal deficits is 1–3%.^{274,275} These usually occur intraoperatively and are noted in the first 24–48 h. Some 30% of the deficits may develop postoperatively as a result of hemodynamic instability or arrhythmia.²² Risk factors of stroke for the open-heart patient include increasing age (a risk up to 15% in patients older than 75 years), diabetes mellitus, preexisting cerebrovascular disease especially with a history of recent stroke, perioperative hypotension, atherosclerotic plaques and calcifications in the ascending aorta, left ventricular mural thrombus, opening a cardiac chamber, postoperative atrial fibrillation, long duration of CPB, and warm blood CPB.²⁷⁶⁻²⁷⁹

The presentation of neurologic complications depends on the site and extent of the insult. Transient ischemic attacks present with focal deficits of hemiparesis or hemiplegia, aphasia, dysarthria, hand incoordination, visual deficits (either retinal or central), and coma. If an interventional neurologist is available, an immediate consultation should be obtained. An evaluation begins with a careful neurologic examination, then a CT scan of the brain with contrast infusion, an echocardiogram (surface or transesophageal) to exclude a cardiac source, and noninvasive carotid studies. If there is no evidence of an intracranial hemorrhage on CT scan, heparin is started, and then warfarin if the stroke is thought to be embolic. If the deficit occurs during surgery, there is some debate as to the need for anticoagulation versus just antiplatelet therapy. Other therapy includes the standard measures to reduce intracranial pressure and even a carotid endarterectomy in patients with severe carotid stenosis and transient neurologic deficits. Physical therapy is started soon after the event is diagnosed. As regards prognosis, patients with focal deficits have an excellent prognosis. In patients with coma, the prognosis is poor with a mortality rate of 50% and a high percentage of survivors staying in the vegetative state.²²

Postoperative encephalopathy and delirium occur in approximately 30% after open-heart surgery.²⁸⁰ The risk factors include older age, recent alcoholism, preoperative organic brain syndrome, severe cardiac disease, multiple associated medical illnesses, and complex and prolonged surgical procedures on CPB. Common causes of delirium are medication toxicity, metabolic disturbances, alcohol withdrawal, low cardiac output syndromes, periods of marginal cerebral blood flow during CPB, hypoxia, sepsis, and a recent stroke. The evaluation of delirium begins with a review of the patient's current medications and drug levels, an identification of a possible history of recent alcoholism or substance abuse, neurologic examination, and ABGs, electrolytes, BUN, creatinine, CBC, magnesium,

and calcium determinations. The management of delirium begins by correcting any metabolic abnormalities, discontinuing inappropriate medications, and psychotropic medications for agitation such as haloperidol 2.5–5.0 mg PO/IM/IV q6h. The treatment of suspected alcohol withdrawal include benzodiazepines, thiamine, and folate.

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