

Chapter 22

Cardiopulmonary Bypass and the Anesthesiologist

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GOALS AND MECHANICS OF CARDIOPULMONARY BYPASS

The cardiopulmonary bypass (CPB) circuit is designed to perform four major functions: (1) oxygenation and carbon dioxide elimination, (2) circulation of blood, (3) systemic cooling and rewarming, and (4) diversion of blood from the heart to provide a bloodless surgical field. Typically, venous blood is drained by gravity from the right side of the heart into a reservoir that serves as a large mixing chamber for all blood return, additional fluids, and drugs. Because (in most instances) negative pressure is not employed, the amount of venous drainage is determined by the central venous pressure, the column height between the patient and reservoir, and resistance to flow in the venous circuitry.

Venous return may be decreased deliberately (as is done when restoring the patient's blood volume before coming off bypass) by application of a venous clamp. From the reservoir, blood is pumped to an oxygenator and heat exchanger unit before passing through an arterial filter and returning to the patient. Additional components

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Figure 22-1 Components of the extracorporeal circuit: (1) integral cardiotomy reservoir; (2) membrane oxygenator bundle; (3) venous blood line; (4) arterial blood line; (5) arterial filter purge line; (6) arterial line filter; (7) venous blood pump (also called the arterial pump head; this pump forces venous blood through the membrane oxygenator and arterialized blood to the patient's aortic root); (8) cardiotomy suction pump; (9) ventricular vent pump; (10) cardioplegia pump; (11) crystalloid cardioplegia; (12) water inlet line; (13) water outlet line; and (14) gas inlet line. (From Davis RB, Kauffman JN, Cobbs TL, Mick SL: *Cardiopulmonary Bypass*. New York, Springer-Verlag, 1995, p 239.)

of the circuit generally include pumps and tubing for cardiotomy suction, venting, and cardioplegia delivery and recirculation, as well as in-line blood gas monitors, bubble detectors, pressure monitors, and blood sampling ports. A schematic representation of a typical bypass circuit is depicted in [Figure 22-1](#).

The cannulation sites and type of CPB circuit used are dependent on the type of operation planned. Most cardiac procedures use full CPB, in which the blood is drained from the right side of the heart and returned to the systemic circulation through the aorta. The CPB circuit performs the function of heart and lungs. Aortoatriocaval cannulation is the preferred method of cannulation for CPB, although femoral arterialvenous cannulation may be the technique of choice for emergency access, repeat sternotomy, and other clinical settings in which aortic or atrial cannulation is not feasible. Procedures involving the thoracic aorta are often performed using partial bypass in which a portion of oxygenated blood is removed from the left side of the heart and returned to the femoral artery. Perfusion of the head and upper extremity vessels is performed by the beating heart, and distal perfusion is provided below the level of the cross-clamp by retrograde flow by the femoral artery. All blood passes through the pulmonary circulation, eliminating the need for an oxygenator.

PHYSIOLOGIC PARAMETERS OF CARDIOPULMONARY BYPASS

The primary objective of CPB is maintenance of systemic perfusion and respiration. Controversy arises with the question of whether systemic oxygenation and perfusion should be “optimal or maximal.” Remarkably, after more than one-half century

BOX 22-1 Practice of Cardiopulmonary Bypass**Best Practices Are Still Developing in Regard to**

- Perfusion pressure
- Pump flow
- Temperature management
- Central nervous system monitoring
- Pulsatility

of CPB, there is continued disagreement regarding the fundamental management of extracorporeal circulation. Clinicians and investigators disagree on what are the best strategies for arterial blood pressure goals, pump flow, hematocrit, temperature, blood gas management, or mode of perfusion (pulsatile vs. nonpulsatile) (Box 22-1). Additional considerations of what is best relate to other goals of CPB: maintenance of homeostasis, facilitation of surgery, and avoidance of complications.¹

Perfusion Pressure during Cardiopulmonary Bypass

Selection of perfusion pressure during CPB is based on balancing the demands of surgical access (bloodless field) with patient outcome (adequate oxygen delivery). Lower flow and pressure during CPB may optimize visualization, whereas higher flow and pressure may minimize patient complications. Determining the optimum perfusion pressure has been extremely challenging because no single study can adequately address all the complexities of CPB. Because of the brain's poor tolerance of ischemia, neurologic outcome has been the most common outcome studied in relation to perfusion pressure. The complicated relationship between neurologic outcome and perfusion pressure is likely related to two causes of adverse neurologic outcomes: hypoperfusion and embolism.

Between mean arterial pressures (MAP) of 50 and 150 mmHg, cerebral autoregulation maintains a relatively constant blood flow and oxygen delivery. During hypothermic CPB, the lower limit of cerebral autoregulation may be as low as 20 to 30 mmHg,² affording some additional protection against hypoperfusion. Increasing perfusion pressure to alleviate the risk of hypoperfusion may lead to greater embolic load and worse outcomes. Ultimately, the selection of perfusion pressure during CPB will need to be based on clinical outcome studies.

Subgroups at increased risk for adverse outcomes that may benefit from higher perfusion pressure during CPB include patients with severe atheromatous disease (cerebrovascular or aortic arch), advanced age, systemic hypertension, and diabetes. Increased cerebral dysfunction in the elderly may be a result of slower vasodilatation of cerebral resistance vessels during periods of rewarming and subsequent transient episodes of metabolism-flow mismatch with resultant ischemia. It is unknown what the effect of elevating perfusion pressure during rewarming would be on neurologic outcome. Hypertensive patients are generally accepted to have intact pressure-flow autoregulation, with a rightward shift in the cerebral autoregulation curve such that pressure-dependent flow patterns develop at higher perfusion pressures than in the normal population. In hypertensive patients the use of higher perfusion pressure during CPB is common practice. Patients with type 1 diabetes mellitus appear to have impaired metabolism-flow coupling during CPB. They also have some loss of pressure-flow autoregulation.

Once the CPB team has selected target perfusion pressures during CPB, a few technical issues emerge. Throughout this discussion perfusion pressure and MAP have been used almost interchangeably. In general, cerebral perfusion pressure is what is of most concern. Cerebral perfusion pressure is determined by the difference between MAP and the higher of central venous pressure and intracranial pressure. The latter values are usually less than 5 mmHg during CPB. However, in the presence of compromised cerebral venous drainage (malpositioned cannula, patient positioning), MAP will not accurately reflect cerebral perfusion pressure.

Measurement artifacts also play a role in perfusion pressure management. MAP may vary by as much as 20 mmHg over 30 seconds while pump flow is constant. The mechanism of this oscillation and its relation to outcome are unclear. A more common artifact is discordance between radial arterial and central arterial pressures during rewarming. This difference may be as great as 30% and is believed to occur from opening of arteriovenous shunts in the arm.

After acknowledging the technical issues of pressure monitoring, the CPB team is left to maintain the selected perfusion pressure. To achieve these perfusion pressure goals the team has two general options: alterations of pump flow or administration of vasoactive agents. Increasing pump flow may be used as a temporizing measure for hypotension if surgical demands allow it; however, this may come at the cost of dangerously reducing reservoir volume. Alternatively, phenylephrine and norepinephrine may be used to support perfusion pressure. In the case of hypertension, pump flow may be reduced, although this increases the potential for inadequate oxygen delivery; more commonly, a vasodilator, such as sodium nitroprusside or nitroglycerin, is employed. Isoflurane or another volatile anesthetic may be administered through the pump oxygenator, with careful attention paid to its use during weaning from CPB.

Nonpulsatile versus Pulsatile Perfusion

It remains uncertain whether pulsatile CPB improves outcome compared with standard, nonpulsatile CPB. Claims of advantages to pulsatile flow are effectively offset by conflicting studies of similar design.

The comparatively small size of the arterial inflow cannula can effectively filter out a large component of the pulsatile kinetic energy. Consequently, as achieved clinically, pulsatile flow may actually be quite similar energetically to nonpulsatile flow. This potentially unrecognized lack of difference in types of flow may partly explain the failure of pulsatile perfusion to alter hormone levels and clinical outcome.

Pump Flow during Bypass

Like perfusion pressure, pump flow during CPB represents a careful balance between the conflicting demands of surgical visualization and adequate oxygen delivery. Two theoretical approaches exist. The first is to maintain oxygen delivery during bypass at normal levels for a given core temperature. Although this may limit hypoperfusion, it does increase the delivered embolic load. The second approach is to use the lowest flows that do not result in end-organ injury. This approach offers the potential advantage of less embolic delivery as well as potential improved myocardial protection and surgical visualization.

During CPB, pump flow and pressure are related through overall arterial impedance, a product of hemodilution, temperature, and arterial cross-sectional area. This is important because the first two factors, hemodilution and temperature, are critical

determinants of pump flow requirements. Pump flows of 1.2 L/min/m² perfuse most of the microcirculation when the hematocrit is near 22% and hypothermic CPB is being employed. However, at lower hematocrits or periods of higher oxygen consumption these flows become inadequate.

Most perfusion teams also monitor mixed venous saturation, targeting levels of 70% or greater. Unfortunately, this level does not guarantee adequate perfusion of all tissue beds, because some (muscle, subcutaneous fat) may be functionally removed from circulation during CPB. Hypothermic venous saturation may overestimate end-organ reserves. Regional perfusion of various end-organs (brain, kidney, small intestine, pancreas, and muscle) has been quantified with a fluorescent microsphere technique.³ Cerebral blood flow was unchanged at higher pump flows. Renal perfusion was maintained at flows of 1.9 and 1.6 L/min/m². Perfusion to the pancreas was constant at all flows, and small bowel perfusion varied linearly with pump flow. Muscle bed flows were decreased at all flows.

During CPB, most of the outcomes studied in relation to pump flow are those related to the organs at high risk for ischemic injury (i.e., kidney and brain). Much work has been applied to examining the relationship between renal dysfunction and pump flow. Preexisting renal disease is a consistent predictor of postoperative renal dysfunction, the incidence of which ranges between 3% and 5%. Renal function appears unaltered when pump flows greater than 1.6 L/min/m² are employed, but whether this management will affect outcomes in patients with preexisting renal dysfunction is less clear.

Bypass Temperature Management Strategy

Although hypothermic temperatures have been employed since the advent of extracorporeal circulation, the importance of reduced temperatures during bypass was challenged in the early 1990s.

Effects on Central Nervous System

The brain is arguably the organ most vulnerable to ischemic damage during CPB. Cerebral hypoperfusion and embolic phenomena are likely to occur in every patient undergoing bypass, resulting in ischemic events. It is believed that hypothermia provides protection from ischemic phenomena and resultant infarction by decreasing cerebral oxygen demands, maintaining energy (ATP, phosphocreatine) stores. Although the effect of reduced temperatures on metabolism is of importance, there is increasing evidence that the most important salutary effects of hypothermia on cerebral ischemia are not related to the reduction in metabolism but rather to the attenuation of the excitotoxic cascade.

Several groups of investigators have assessed the effect of normothermic temperatures during bypass on perioperative central nervous system events in cardiac surgery patients.⁴ Mild hypothermia provides some magnitude of cerebral protection during CPB, whereas mildly hyperthermic temperatures (>37°C) exacerbate and amplify the ischemic injury associated with CPB.

Temperature Monitoring

Because the brain is vulnerable to hyperthermic temperatures, it is important to use the temperature-monitoring site most likely to reflect cerebral temperature. The most commonly used sites in cardiac surgery patients include esophageal, nasopharyngeal, tympanic, pulmonary arterial, rectal, urinary bladder, subcutaneous (or muscle), and cutaneous sites. Unfortunately, none of these monitoring locations

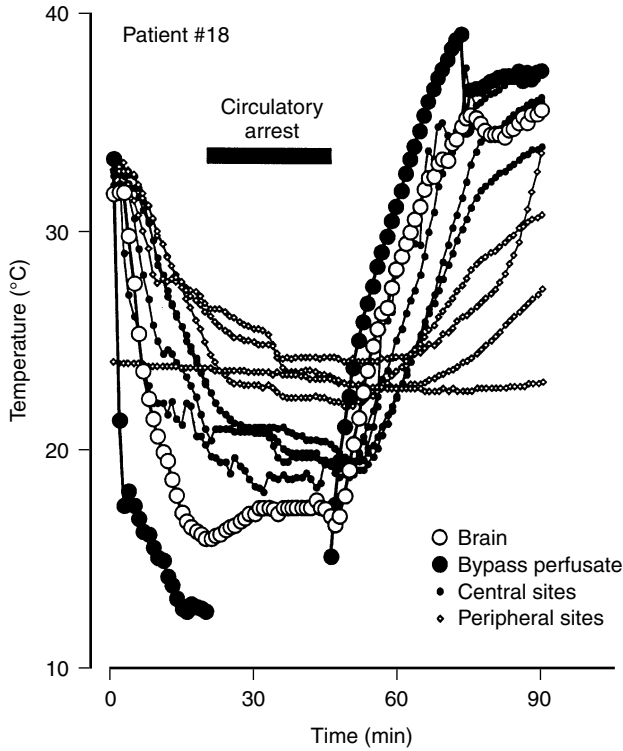


Figure 22-2 Graphic depiction of temperature-time relationship during cardiopulmonary bypass and deep hypothermic circulatory arrest. Temperatures are plotted every minute. Central sites are the nasopharynx, tympanic membrane, esophagus, and pulmonary artery. Peripheral sites are the bladder, rectum, axilla, and sole of the foot. The two slowest cooling central sites were tympanic membrane and esophagus. (From Stone JG, Young WL, Smith CR, et al: Do standard monitoring sites reflect true brain temperature when profound hypothermia is rapidly induced and reversed? *Anesthesiology* 82:344, 1995.)

has been demonstrated to reflect cerebral temperature reliably. With exposure of the brain, investigators have placed a thermocouple directly in the cerebral cortex. Brain temperature was compared with values obtained from sensors in eight locations.⁵ Investigators found a poor concordance between cerebral temperature and values obtained at the other monitoring sites. Locations hypothesized to best reflect core temperature—tympanic membrane, esophagus, nasopharynx, pulmonary artery—sometimes overestimated cerebral temperature or underestimated brain temperature. Because of the substantial variability noted in central temperature readings (Fig. 22-2) and lack of the concordance of central temperature measures in every patient, the investigators recommended the use of at least three measures of central or core temperature.

Acid-Base Strategy

The management of acid-base status during hypothermic CPB has been a long-standing source of debate. Understanding of the physiologic responses to hypothermia, and the influences of P_{CO_2} have led to shifts in clinical practice over the past decades. Two strategies exist for managing acid-base balance during

periods of hypothermia: α -stat and pH-stat. The term α -stat was first proposed to describe the theory that acid-base regulation in vertebrate animals functioned during temperature fluctuation to maintain a constant ratio (α) of dissociated to undissociated forms of the imidazole ring on histidine. It is this protein charge state that is important in regulating pH-dependent cellular processes. Hypothermia increases the solubility of oxygen and carbon dioxide in the blood, leading to a decrease in P_{CO_2} and an increase in pH at lower temperatures. With α -stat blood gas management, the uncorrected (37°) pH is kept at 7.40 with the P_{CO_2} at 40 mmHg, creating a relative alkalosis at the patient's actual body temperature. This strategy is considered to be physiologic because the ionization state of histidine is unchanged over all temperature ranges and protein structure and function are preserved.

The pH-stat approach to acid-base balance maintains a pH of 7.40 and P_{CO_2} of 40 mmHg when corrected for body temperature, typically requiring the addition of CO_2 during hypothermic CPB. This method of blood gas management was generally favored until the mid 1980s because it was believed that the potent vasodilatory effects of CO_2 would provide increased cerebral blood flow and thereby minimize the risk of cerebral ischemia during CPB. It is now recognized that pH-stat management during hypothermia produces passive cerebral vasodilation, impairs autoregulatory responses to blood pressure changes and metabolic demands in the brain, and does not improve overall oxygen balance. In contrast, α -stat management preserves autoregulation and the relationship between cerebral blood flow and metabolism. Neither blood gas strategy has any significant effect on hypothermic cerebral metabolism. The increased CBF seen with pH-stat may also increase the risk of cerebral embolization or produce a steal phenomenon.⁶

Fluid Management

The choice of fluid for priming the extracorporeal circuit in CPB remains controversial. The idea of using nonblood prime was first introduced in 1959. This technique of hemodilution was found to be safe when combined with hypothermia to reduce oxygen consumption and demand. The use of nonblood primes and moderate hemodilution for CPB has become routine in most centers. A reduction in hematocrit from 40% to 20% allows cooling to $22^\circ C$ without an increase in blood viscosity or required driving pressure. Hematocrit reduction may be achieved before bypass by means of acute normovolemic hemodilution in the hope of reinfusing the patient's own heparin-free blood, rather than allogeneic red blood cells, after CPB.

Several studies have investigated the differences between colloid and crystalloid priming solutions. In general, crystalloid solutions lead to decreased colloid osmotic pressure with a resultant increase in extracellular water retention, irrespective of the osmolarity of the pump prime. Albumin, unlike a pure crystalloid prime, can decrease the interaction of blood components with the bypass circuit by coating the fluid pathway surfaces. In their meta-analysis of 21 controlled trials enrolling 1346 patients, Russell and associates showed a notably smaller drop in on-bypass platelet counts in patients treated with albumin in the pump prime.⁷

Ultrafiltration during bypass can be used as a means of reducing excess water accumulation. Modified ultrafiltration describes the process of hemofiltration immediately after the cessation of bypass. This process results in a more consistent reduction in total body water with significant increases in hematocrit, myocardial contractility, cardiac index, and improved pulmonary compliance.

END-ORGAN EFFECTS OF CARDIOPULMONARY BYPASS

Myocardial Injury

Most coronary revascularization procedures are completed with the assistance of CPB. Although the completion of coronary anastomoses is facilitated by CPB (i.e., the surgeon can operate on a quiet, nonbeating heart), the heart is subjected to a series of events leading to ischemic myocardium during extracorporeal circulation. The operation, which is designed to preserve and improve myocardial function, is sometimes associated with myocardial damage (Box 22-2). The extent and incidence of this injury are dependent on the sensitivity and specificity of the diagnostic methods being used. However, most patients who undergo cardiac operations sustain some degree of myocardial injury. Although patients with normal ventricular function may tolerate these minor amounts of injury without detectable sequelae, those with impaired ventricular function preoperatively may not be able to tolerate the slightest injury. As the patient population for CPB continues to become older and have greater degrees of concomitant illness, understanding the physiology of and developing effective preventive strategies for myocardial injury during CPB are increasingly important. Because myocardial damage influences early and long-term results, the identification and control of factors associated with myocardial injury are critical to ensuring good outcomes. Although injury may be linked to anesthetic and surgical management, myocardial injury usually is thought to occur from inadequate myocardial protection during CPB.

Mechanisms

The underlying mechanism for most types of myocardial injuries during CPB is ischemia. Ischemia develops when oxygen demand outstrips its supply in the heart. This process involves a complex cascade of events that compromise high-energy phosphate and calcium homeostasis. Many reports confirm the role of high-energy phosphate depletion and intracellular calcium accumulation in the pathogenesis of myocardial damage during ischemia and subsequent reperfusion. Oxidative phosphorylation ceases when the tissue Po_2 falls below 5 to 10 mmHg. Then creatine phosphate (CP) and anaerobic production become the main sources of high-energy phosphate. These mechanisms are unfortunately limited. Creatine kinase (CK)-mediated transfer of high-energy phosphate from CP to adenosine diphosphate (ADP) provides an immediate source of energy; the amount of adenosine triphosphate (ATP) produced by transfer is limited initially by substrate availability and subsequently by lactate inhibition. Anaerobic production is inefficient and self-limiting because of accumulation of metabolites (i.e., lactate, pyruvate, and hydrogen ions) with inhibition of enzyme systems. As high-energy phosphate stores

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BOX 22-2 End Organs That Can Be Adversely Affected by Cardiopulmonary Bypass

- Heart
- Brain
- Kidneys
- Gastrointestinal tract
- Endocrine system

become depleted, the cardiac cells are no longer able to maintain normal transport of calcium out of the cell. Energy-dependent mechanisms that lower intracellular ionized calcium concentration and terminate the contractile process fail because of a lack of high-energy phosphate. The cytosolic concentration of ionized calcium remains high, and energy use persists with the formation of rigor bonds between the contractile proteins. Continued energy use with calcium and proton-activated release of destructive lipoprotein lipase eventually leads to loss of cell integrity and function.

Certain specific events during CPB are associated with myocardial ischemia and injury (Table 22-1). These events lead to ischemia by increasing oxygen demands, decreasing oxygen supply, or a combination of both. When these factors are present together they potentiate myocardial damage. For example, the distended, fibrillating ventricle with a low perfusion pressure is particularly susceptible to damage.

Aortic Cross-Clamping

Aortic cross-clamping, potentially a major cause of myocardial injury during CPB, was a product of evolution. Initially, continuous aortic or direct coronary artery perfusion of the empty, beating heart was used to “protect” the myocardium during cardiac repairs. Ventricular fibrillation was frequently induced and maintained to “quiet” the heart and thereby improve exposure and prevent air embolism. Despite continuous perfusion, myocardial damage commonly occurred. Although myocardial protection improved with the addition of moderate cardiac hypothermia (28° to 32°C), operating conditions did not. Most surgeons found it difficult to perform precise repairs on the firm, bleeding, beating, or fibrillating heart. To improve exposure and minimize the complications associated with direct coronary cannulation for aortic valve replacement (AVR), myocardial ischemia was induced by aortic cross-clamping. However, the technique of normothermic or moderate hypothermic ischemic arrest is not without problems. First, the heart continues to beat for some time after application of the aortic cross-clamp, thereby compromising the anticipated improvement in operating conditions. Persistent electrical and mechanical activity during much of the ischemic period needlessly depletes high-energy phosphate and compromises post-repair ventricular performance. Second, few surgeons can complete a complex repair quickly enough to prevent significant myocardial damage in the unprotected heart. Third, the use of intermittent cross-clamping with periods of reperfusion does little to improve operating conditions or prevent necrosis. Reactive hyperemia after release of the aortic clamp continues to obscure the

Table 22-1 Factors Associated with Myocardial Injury during Cardiopulmonary Bypass

- Abnormal perfusate composition
- Persistent ventricular fibrillation
- Inadequate myocardial perfusion
- Ventricular distention
- Ventricular collapse
- Coronary embolism
- Catecholamines
- Aortic cross-clamping
- Reperfusion

operative field. Multiple short periods of reperfusion, particularly in the presence of VF, may potentiate rather than prevent ischemic damage. Defibrillation to improve reperfusion reintroduces the problem of systemic air embolism during open repairs.

Rapid cessation of electrical and mechanical activity immediately after aortic cross-clamping is desirable to potentiate surgical exposure and myocardial preservation. The extent of necrosis in unprotected myocardium is directly related to the duration of aortic cross-clamping. The ischemic time should be minimized. Variability among patients in terms of myocardial vulnerability makes it difficult to accurately predict safe periods of interval ischemia. Prolonged surgical time demands direct interventions to protect the myocardium. These focus along the lines of maximizing high-energy phosphate production while minimizing high-energy phosphate use and intracellular calcium accumulation during the ischemic period. Specific interventions include hypothermia, cardioplegia, β -adrenergic and calcium channel blockade, and adenosine-regulating compounds. Uninterrupted periods of ischemia provide the best operating conditions while minimizing the risk of reperfusion injury and air embolism.

Myocardial Protection

Myocardial protection strategies can be summarized with four basic concepts:

1. Myocardial protection begins with preparation of the heart before arrest.
2. Metabolic requirements should be reduced during the arrest interval.
3. A favorable metabolic milieu during arrest helps provide a margin of safety with reduced metabolism.
4. Reperfusion modification after an ischemic insult can minimize structural and functional damage to the myocardium.

The first concept includes phenomena under the direct control of the anesthesiologist. In the pre-bypass period, the heart should be prepared for ischemic arrest by optimizing myocardial metabolism and providing hemodynamic conditions that optimize myocardial oxygen supply-demand ratios.

Patients coming to cardiac surgery (especially in this era of same-day admissions) are frequently dehydrated and hypoglycemic. The anesthesiologist should rehydrate the patient and administer sufficient glucose to improve the heart's ability to tolerate ischemic arrest. Because the initiation of bypass is frequently accompanied by hypotension, the anesthesiologist should be prepared to administer vasoconstrictive drugs (e.g., phenylephrine) to maintain coronary perfusion pressure. Similarly, ventricular distention must be avoided (especially before fibrillatory arrest) because increases in left ventricular end-diastolic pressure decrease coronary perfusion pressures and greatly compromise subendocardial oxygen delivery. The anesthesiologist should monitor intraventricular volume with a transesophageal echocardiography (TEE) probe after the initiation of bypass. The surgeon can prevent ventricular distention by placing a hole in the left atrium, left ventricle, or pulmonary artery or by placing a vent in the left ventricle. Although negative pressure venting enhances the risk of intracavitary air entrapment, many surgeons prefer active venting to passive methods. Several pharmacologic interventions administered to patients or added to the cardioplegic solution may enhance myocardial protection. β -Receptor antagonists (e.g., propranolol, esmolol) provide myocardial protection by decreasing heart rate and myocardial metabolism. The heart rate should be maintained at less than 80 beats per minute in patients with ischemic heart disease in the pre-bypass period.

Brain Injury

The brain is highly susceptible to injury during CPB. Many clinicians believe that cerebral injuries after cardiac surgery are the most devastating adverse outcomes associated with CPB. A study of 2400 patients undergoing elective coronary artery bypass grafting (CABG) from 24 U.S. centers reported that 6.1% of patients suffer adverse postoperative gross neurologic or psychiatric central nervous system events. These patients remain in the intensive care unit and hospital for greater periods of time, and 1 in every 3 surviving patients does not return home but requires continued long-term care and rehabilitation.⁸ (see chapter 23).

Renal Dysfunction

The effects of CPB on the renal system have significant health and economic impacts; however, despite intensive investigation into the pathogenesis and prevention of renal failure, there remains limited progress in the development of effective protective strategies in recent decades.⁹ Because intravascular volume depletion and hypoperfusion can lead to exacerbation of renal ischemia and accentuate the risk for postoperative acute renal failure, avoidance of nephrotoxic agents and close attention to intravascular volume, blood pressure, and cardiac output (CO) are central in the effort to reduce the occurrence of acute renal failure after cardiac surgery.

Gastrointestinal Effects

The effects of CPB on the gastrointestinal system are complex and not fully elucidated. Although most patients undergoing cardiac surgery do not suffer adverse changes in gastrointestinal function, subclinical perturbations including transient elevations in hepatocellular enzymes and hyperamylasemia have been observed after CPB. Although the incidence of gastrointestinal complications after CPB is low (range, 0.3% to 3.7%), they are associated with significant morbidity and remarkably high mortality (range, 11% to 67%) compared with cardiac surgery patients without postoperative gastrointestinal compromise. The frequently reported adverse gastrointestinal outcomes include gastroesophagitis, upper and lower gastrointestinal hemorrhage, hyperbilirubinemia, hepatic and splenic ischemia, colitis, pancreatitis, cholecystitis, diverticulitis, mesenteric ischemia, as well as intestinal obstruction, infarction, and perforation.¹⁰

Although the pathophysiology of gastrointestinal complications after cardiac surgery is likely multifactorial, a unifying mechanism is splanchnic hypoperfusion. The gastrointestinal system is particularly vulnerable for ischemia due to the lack of autoregulation and to the preferential shunting of blood away from the gastrointestinal circulation during periods of hypotension. Hypothermia and nonpulsatile flow during CPB may be detrimental to mucosal perfusion. However, hypothermia has little effect on hepatic arterial blood flow and may actually increase portal flow. There is no significant difference in hepatic blood flow between pulsatile and nonpulsatile perfusion at high flow rates (2.4 L/min/m²) during hypothermia. Perhaps more important to the development of inadequate gastrointestinal perfusion is the significant increase in total body oxygen consumption in the immediate hours after CPB. Visceral hypotension is the most significant factor in the development of gastrointestinal complications after cardiac surgery. Gut ischemia of sufficient duration impairs gastrointestinal tract barrier function. Studies evaluating gut permeability have shown that CPB is associated with an increase in mucosal permeability and systemic endotoxin concentration.

Endocrine and Inflammatory Responses

Endocrine Response

Cardiopulmonary bypass provokes a marked stress response, which has been quantified by measurements of hormones and vasoactive substances in plasma. Hypothermia, hemodilution, and nonpulsatile flow produce insulin, prostaglandin, and renin release during CPB and are potent stimuli for catecholamine release. Epinephrine levels increase throughout CPB with a ninefold increase that peaks during rewarming, after aortic cross-clamp release. Although striking, the magnitude of the catecholamine responses is comparable to that after syncope, myocardial infarction, strenuous exercise, or caffeine ingestion. It is likely that increased plasma catecholamine concentrations are in part due to decreased clearance. The heart and lungs, which serve as primary clearance organs for these substances, are partially or completely excluded from the circulation during much of CPB. Hypothermia slows all enzymatic processes responsible for metabolism.

Many other hormones increase during CPB. Vasopressin increases up to 20 times baseline levels during CPB. Some investigators suggest that vasopressin and angiotensin II are responsible for the elevations in SVR observed during CPB, and this may explain why vasopressin can be a useful drug to increase SVR on CPB in patients who are extremely vasodilated.¹¹

Data from clinical and laboratory investigators now conclusively demonstrate the untoward affects of hyperglycemia in cardiac surgery. Aggressive control of perioperative glucose values represents the standard of care in cardiac surgery. Glucose values should be maintained at levels less than 200 mg/dL. Lower values (blood glucose 80 to 120 mg/dL) are likely superior to values of glucose more than 120 mg/dL. A protocol for management of glucose in cardiac surgery patients is outlined in [Table 22-2](#).¹²

Immunologic Inflammatory Response

The physiologic insult of CPB results in a myriad of exaggerated, complex, and mostly pathologic immunologic events. The passage of blood through the extracorporeal circuit causes activation of complement, platelets, neutrophils, and proinflammatory kinins. At the conclusion of bypass, blood perturbed by the process of extracorporeal circulation reperfuses ischemic organs, exacerbating the local inflammatory responses in end organs, including the brain, kidney, heart, and lung. These phenomena result in whole-body inflammatory response and represent the collective effect of activation of the complement, fibrinolytic, kallikrein, and coagulation systems.

The complement system is formed by two interconnected cascades: the classical and the alternative pathways. The elements of the classical pathway are C1, C4, and C2, with subunits and fragments of these elements developing as the cascade progresses. The classical pathway is thought to be normally triggered by antigen-antibody complexes. The alternative pathway, bypassing C1, C4, and C2 to activate C3, is triggered by complex polysaccharides, lipopolysaccharides, IgA and IgD and by exposure of blood to foreign surfaces. The two pathways converge at C3 and lead to activation of the terminal components, C5 to C9. The fragments C3a and C5a are known anaphylatoxins.

With initiation of CPB, complement is thought to be activated through the alternative pathway. Exposure of blood to the CPB circuit initiates activation of the coagulation cascade by means of the Hageman factor (XII). Although the coagulation cascade is initiated, it is not completed because of the presence of heparin. Activated factor XII (XIIa) results in plasmin generation. Plasmin activates complement by

Table 22-2 Stanford University Adult Cardiac Anesthesia Continuous Insulin Infusion Protocol

Bolus and start infusion as follows:		
Blood Glucose (mg/dL)	Insulin Bolus Units	Units/hr
<125	0	0
125 to 175	5	1
175 to 225	10	2
>225	15	3
Measure blood glucose values every 30 minutes intraoperatively!		
Insulin Titration		
Blood Glucose	Treatment	
<75	Stop insulin; D5W and recheck in 30 min; when > 150, restart at 50% of previous rate.	
75-100	Stop insulin; recheck in 30 min; restart at 50% of previous rate (unless < 0.25 U/hr).	
101-125	If < 10% lower than last value, decrease by 0.5 U/hr. If > 10% lower than last value, decrease by 50%.	
126-175	If neither, continue current rate.	
176-225	Continue current rate. If lower than last value, continue current rate. If higher than last value, increase by 0.5 U/hr.	
>225	If > 10% lower than last value, continue current rate. If < 10% lower or greater than last value increase by 1 U/hr. If > 225 and not decreased after three adjustments, double current rate.	

C1 (classical pathway), cleaves C3 (alternative pathway), and cleaves factor XII, which activates the kallikrein-kinin systems. Complement activation can also occur through the classical pathway by heparin-protamine complexes. Complement activation leads to direct membrane injury by complement subunits, neutrophil activation, enhancement of phagocytosis due to interaction of complement components and phagocytic cells, and release of lysosomal enzymes. The complement fragments are stimulants that induce changes in neutrophil behavior, causing neutrophil activation and migration and the promotion of adhesive and secretory events. These phenomena contribute to the reperfusion injury observed in cardiac surgery patients. Activated neutrophils attach to the endothelium, causing translocation of P-selectin from intracellular vesicles to the cell membrane and platelet-activating factor (PAF) synthesis. Endothelial membrane-bound PAF leads to increased neutrophil adhesion and activation and neutrophil adhesion protein (CD11/CD18) expression. Ultimately, increases in adhesion molecule emission in the endothelium and other tissue cell types (e.g., myocytes, alveolar cells, glomerular or renal tubular epithelium) result in transmigration of neutrophils into the interstitial space and release of large amounts of free radicals. These phenomena are schematically presented in [Figure 22-3](#).

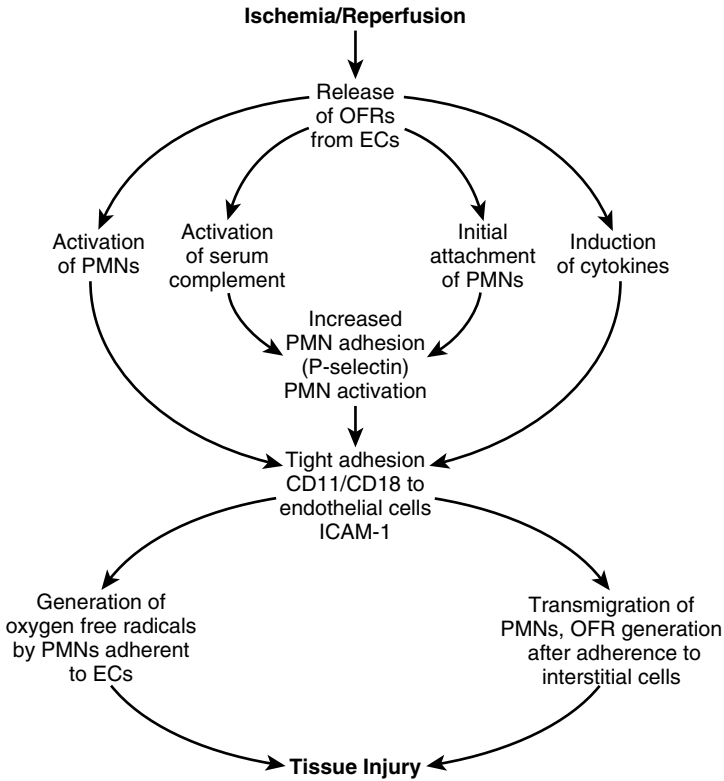


Figure 22-3 A schematic representation of the interactive components of the immune response that likely occurs during the posts ischemic inflammatory state after cardiopulmonary bypass. EC = endothelial cells; ICAM = intercellular adhesion molecules; OFR = oxygen free radicals; PMNs = polymorphonuclear leukocytes. (From Herskowitz A, Mangano DT: Inflammatory cascade: A final common pathway for perioperative injury? *Anesthesiology* 85:957, 1996.)

Although complement has been recognized as a significant factor in the development of the physiologic disturbances seen after cardiac surgery, endotoxins released into the bloodstream during CPB are also believed to play a significant role in the inflammatory cascade. Endotoxin binds to lipopolysaccharide-binding protein normally present in serum. This complex binds to specific receptors on macrophages with subsequent production of cytokines. The collective result of these cellular and humoral responses may be manifest by cardiovascular instability, pulmonary dysfunction, renal insufficiency, alterations in hemostasis, fever, and excess extravascular fluid retention.

Interventions aimed at reducing morbidity associated with the systemic inflammatory response seen after CPB may be directed at preventing or minimizing the activation of the various systems contributing to the response or at blocking the physiologic effects once activation occurs. Studies evaluating membrane versus bubble oxygenators have reported conflicting data regarding the degree of complement activation or clinical outcome.

Corticosteroids may play an important role in minimizing the inflammatory response by reducing complement activation, decreasing production of cytokines, and interfering with neutrophil adherence and migration. Most clinical trials have reported a beneficial effect on markers of inflammation (e.g., cytokine and

BOX 22-3 Management before Cardiopulmonary Bypass

- Anticoagulation
- Cannulation of the heart
- Careful monitoring
- Protection of the heart
- Preparation for cardiopulmonary bypass

complement levels, histamine release, leukocyte counts, endothelial activation). The use of aprotinin or other protease inhibitors has been shown to produce a dose-dependent reduction in complement activation, cytokine release, and neutrophil activation during cardiac surgery.

MANAGEMENT BEFORE BYPASS

An important objective of this phase is to prepare the patient for CPB (Box 22-3).¹³ This phase invariably involves two key steps: anticoagulation and vascular cannulation. Heparin is still the anticoagulant clinically used for CPB. Dose, method of administration, and opinions as to what constitutes adequate anticoagulation vary. Heparin must be administered before cannulation for CPB, even if cannulation must be done emergently. Failure to do so is to risk thrombosis in the patient and extracorporeal circuit. After heparin has been administered, a period of 3 to 5 minutes is customarily allowed for systemic circulation and onset of effect. Various confirmatory tests of actual achievement of anticoagulation are performed if time permits.

Vascular Cannulation

The next major step in the pre-bypass phase is vascular cannulation. The goal of vascular cannulation is to provide access whereby the CPB pump may divert all systemic venous blood to the pump oxygenator at the lowest possible venous pressures and deliver oxygenated blood to the arterial circulation at pressure and flow sufficient to maintain systemic homeostasis.

Arterial Cannulation

Arterial cannulation is generally established before venous cannulation to allow volume resuscitation of the patient, should it be necessary. The ascending aorta is the preferred site for aortic cannulation because it is easily accessible, does not require an additional incision, accommodates a larger cannula to provide greater flow at a reduced pressure, and carries a lower risk of aortic dissection compared with other arterial cannulation sites (femoral or iliac arteries). Because hypertension increases the risk of aortic dissection during cannulation, the aortic pressure may be temporarily lowered (MAP < 80 mmHg during aortotomy and cannula insertion). Several potential complications are associated with aortic cannulation, including embolization of air or atheromatous debris, inadvertent cannulation of aortic arch vessels, aortic dissection, and other vessel wall injury.

Reviews and clinical reports emphasize the importance of embolization as the major mechanism of focal cerebral injury in cardiac surgery patients.¹⁴ Intraoperative use of two-dimensional ultrasound to image the ascending aorta as a guide to selection of cross-clamping and cannulation sites is increasing. A femoral artery, rather than the ascending aorta, can be cannulated for systemic perfusion. Femoral

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Figure 22-4 Aortic (Ao) and single, double-staged, right atrial (RA) cannulation. Notice the drainage holes of venous cannula in right atrium and inferior vena cava. (From Connolly MW: *Cardiopulmonary Bypass*. New York, Springer-Verlag, 1995, p 59.)

cannulation is used when ascending aortic cannulation is considered relatively contraindicated, as in severe aortic atherosclerosis, aortic aneurysm or dissection, or known cystic medical necrosis. The anesthesiologist should seek evidence of cannula malposition by looking for unilateral blanching of the face, gently palpating carotid pulses, and checking for new unilateral diminution and by measuring blood pressure in both arms and checking for new asymmetries.

Venous Cannulation

Venous cannulation can be achieved using a single atrial cannula that is inserted into the right atrium and directed inferiorly (Fig. 22-4). Drainage holes are located in the inferior vena cava (IVC) and right atrium to drain blood returning from the lower extremities and the superior vena cava (SVC) and coronary sinus, respectively. This technique has the advantage of being simpler, faster and requiring only one incision; however, the quality of drainage can be easily compromised when the heart is lifted for surgical exposure. The bicaval cannulation technique, required in cases in which right atrial (RA) access is needed, involves cannulating the SVC and IVC (Fig. 22-5). Loops placed around the vessels can be tightened to divert all caval blood flow away from the heart. Blood returning to the right atrium from the coronary sinus will not be drained using this technique, so an additional vent or atriotomy is necessary.

During CPB, blood will continue to return to the left ventricle from a variety of sources, including the bronchial and thebesian veins, as well as blood that traverses the pulmonary circulation. Abnormal sources of venous blood include a persistent left SVC, systemic-to-pulmonary shunts, and aortic regurgitation. It is important to avoid left ventricular (LV) filling and distention during CPB to prevent myocardial rewarming and to minimize LV wall tension and limit myocardial oxygen demand. This can be accomplished with the use of a vent placed in the pulmonary artery, aortic root, or left ventricle, depending on the likely source of LV blood return.

Venous cannulas, using a two-stage or bicaval cannula, are large and can impair venous return from the IVC or SVC. Superior vena caval obstruction is detected by

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Figure 22-5 Position of two-vessel cannulation of right atrium (RA) with placement of drainage holes into superior vena cava (SVC) and inferior vena cava (IVC). The aortic cannula is not shown. (From Connolly MW: *Cardiopulmonary Bypass*. New York, Springer-Verlag, 1995, p 59.)

venous engorgement of the head and neck, conjunctival edema, and elevated SVC pressure. Inferior vena caval obstruction is far more insidious, presenting only as decreased filling pressures because of lowered venous return.

Femoral venous cannulation is sometimes used to permit partial CPB without, or before, sternotomy or RA cannulation (e.g., repeat sternotomy, ascending aortic aneurysms). Because of their comparatively small size and placement in the distal IVC, femoral venous cannulas do not permit complete drainage of systemic venous blood and only partial CPB may be achieved. A long cannula with multiple fenestrations can be inserted through the femoral vein and passed to the level of the IVC-RA junction to enhance venous return.

Other Preparations

Once anticoagulation and cannulation are complete, CPB can be instituted. Because there is redundant pulmonary artery (PA) catheter length in the right ventricle, and the heart is manipulated during CPB, there is a tendency for distal migration of the PA catheter into pulmonary artery branches. This distal migration of the catheter increases the risks of “autowedging” and pulmonary artery perforation. During the pre-bypass phase it is advisable to withdraw the PA catheter 3 to 5 cm to decrease the likelihood of these untoward events. It is also advisable to check the integrity of all vascular access and monitoring devices. A PAC placed through an external jugular or subclavian vein can become kinked or occluded on full opening of the sternal retractor. If TEE is being used, the probe should be placed in the “freeze” mode and the tip of the scope placed in the neutral and unlocked position. Leaving the electronic scanning emitter on during hypothermic CPB adds heat to the posterior wall of the ventricle.

Before initiating CPB, the anesthesiologist should assess the depth of anesthesia and muscle relaxation. It is important to maintain paralysis to prevent patient movement that could result in dislodgment of bypass-circuit cannulae and prevent shivering

Table 22-3 Preparation for Bypass: Pre-bypass Checklist

1. Anticoagulation
 - a. Heparin administered
 - b. Desired level of anticoagulation achieved
2. Arterial cannulation
 - a. Absence of bubbles in arterial line
 - b. Evidence of dissection or malposition?
3. Venous cannulation
 - a. Evidence of superior vena cava obstruction?
 - b. Evidence of inferior vena cava obstruction?
4. Pulmonary artery catheter (if used) pulled back
5. Are all monitoring/access catheters functional?
6. Transesophageal echocardiograph (if used)
 - a. In “freeze” mode
 - b. Scope in neutral/unlocked position
7. Supplemental medications
 - a. Neuromuscular blockers
 - b. Anesthetics, analgesics, amnestics
8. Inspection of head and neck
 - a. Color
 - b. Symmetry
 - c. Venous drainage
 - d. Pupils

as hypothermia is induced (with the attendant increases in oxygen consumption). It is difficult to determine the depth of anesthesia during the various stages of CPB. Because blood pressure, heart rate, pupil diameter, and the autonomic nervous system are profoundly affected by extracorporeal circulation (e.g., the heart is asystolic; blood pressure is greatly influenced by circuit blood flow; sweating occurs with rewarming), these variables do not reliably reflect the anesthetic state. Although hypothermia decreases anesthetic requirements, it is necessary to provide analgesia, unconsciousness, and muscle relaxation during CPB. With the initiation of bypass and hemodilution, blood levels of anesthetics and muscle relaxants will acutely decrease. However, plasma protein concentrations also decrease, which increases the free-fraction and active drug concentrations. Every drug has a specific kinetic profile during CPB, and kinetics and pharmacodynamics during CPB will vary greatly among patients. Many clinicians administer additional muscle relaxants and opioids at the initiation of CPB. A vaporizer for potent inhalation drugs may be included in the bypass circuit. A final inspection of the head and neck for color, symmetry, adequacy of venous drainage (neck vein and conjunctiva engorgement), and pupil equality is reasonable to serve as a baseline for the anesthetic state. A summary of preparatory steps to be accomplished during the pre-bypass phase is given in [Table 22-3](#).

INITIATION AND DISCONTINUATION OF BYPASS SUPPORT: AN OVERVIEW

Initiation of Cardiopulmonary Bypass

Uncomplicated Initiation

Once all preparatory steps have been taken, the perfusionist progressively increases delivery of oxygenated blood to the patient’s arterial system, as systemic venous blood is diverted from the patient’s right side of the heart, maintaining the pump’s venous

Table 22-4 Checklist for Bypass Procedure

1. Assess arterial inflow
 - a. Is arterial perfusate oxygenated?
 - b. Is direction of arterial inflow appropriate?
 - c. Evidence of arterial dissection?
 - Patient's arterial pressure persistently low?
 - Inflow line pressure high?
 - Pump/oxygenator reservoir level falling?
 - Evidence of atrial cannula malposition?
 - Patient's arterial pressure persistently high or low?
 - Unilateral facial swelling, discoloration?
2. Assess venous outflow
 - a. Is blood draining to the pump/oxygenator's venous reservoir?
 - Evidence of SVC obstruction?
 - Facial venous engorgement or congestion, CVP elevated?
3. Is bypass complete?
 - a. High CVP/low PA pressure?
 - b. Impaired venous drainage?
 - c. Low CVP/high PA pressure?
 - d. Large bronchial venous blood flow?
 - e. Aortic insufficiency?
 - f. Arterial and PA pressure nonpulsatile?
 - g. Desired pump flow established?
4. Discontinue drug and fluid administration
5. Discontinue ventilation and inhalation drugs to patient's lungs

CVP = central venous pressure; PA = pulmonary artery; SVC = superior vena cava.

reservoir volume. After full flow is achieved, all systemic venous blood is (ideally) draining from the patient to the pump reservoir. The central venous pressure (CVP) and pulmonary arterial pressure (PAP) should decrease to near zero (2 to 5 mmHg), whereas systemic flow, arterial pressure, and oxygenation are maintained at desired values. Table 22-4 outlines tasks to be completed within 5 minutes of initiating CPB.

Hypotension with Onset of Bypass

Systemic arterial hypotension (MAP = 30 to 40 mmHg) is relatively common on initiation of CPB. Much of this can be explained by the acute reduction of blood viscosity that results from hemodilution with nonblood priming solutions. MAP increases with initiation of hypothermia-induced vasoconstriction, along with levels of endogenous catecholamines and angiotensin. Treatment with α -agonists is usually not necessary. Of concern is the potential for myocardial and cerebral ischemia because hypothermia has not yet been achieved.

Until the aortic cross-clamp is applied, the coronary arteries are perfused with hemodiluted, nonpulsatile blood. If placement of the aortic cross-clamp is delayed, MAP should be maintained in the range of 60 to 80 mmHg to support myocardial perfusion, especially in the presence of known coronary stenosis or ventricular hypertrophy. This arterial pressure is likely adequate to maintain cerebral blood flow until hypothermia is induced.

Preparation for Separation

Before discontinuation of CPB, conditions that optimize cardiac and pulmonary function must be restored. To a great extent this is achieved by reversing the processes and techniques used to initiate and maintain CPB (Table 22-5).

Table 22-5 Preparation for Separation-from-Bypass Checklist

1. Air clearance maneuvers completed
2. Rewarming completed
 - a. Nasopharyngeal temperature 36-37°C
 - b. Rectal/bladder temperature $\geq 35^{\circ}\text{C}$, but $\leq 37^{\circ}\text{C}$
3. Address issue of adequacy of anesthesia and muscle relaxation
4. Obtain stable cardiac rate and rhythm (use pacing if necessary)
5. Pump flow and systemic arterial pressure
 - a. Pump flow to maintain mixed venous saturation $\geq 70\%$
 - b. Systemic pressure restored to normothermic levels
6. Metabolic parameters
 - a. Arterial pH, Po_2 , Pco_2 within normal limits
 - b. Hct: 20%-25%
 - c. K^+ : 4.0-5.0 mEq/L
 - d. Normal ionized calcium
7. Are all monitoring/access catheters functional?
 - a. Transducers re-zeroed
 - b. TEE (if used) out of freeze mode
8. Respiratory management
 - a. Atelectasis cleared/lungs reexpanded
 - b. Evidence of pneumothorax?
 - c. Residual fluid in thoracic cavities drained
 - d. Ventilation reinstated
9. Intravenous fluids restarted
10. Inotropes/vasopressors/vasodilators prepared

Hct = hematocrit; TEE = transesophageal echocardiography.

Potential for Patient Awareness

It is not uncommon for patients to sweat during rewarming. This is almost certainly caused by perfusion of the hypothalamus (i.e., the thermoregulatory site) with blood that is warmer than the latter organ's set point (37°C). The brain is a high-flow organ and can be assumed to equilibrate fairly quickly (15 to 20 minutes) with cerebral perfusate temperature (i.e., nasopharyngeal temperature). A less likely but more disturbing possibility is that restoration of brain normothermia with decreased anesthetic concentration may result in inadequate depth of anesthesia and the potential for awareness. It is estimated that awareness occurs during cardiac surgery in 1% of patients.

Patient movement before discontinuation of CPB is extremely disruptive and may be genuinely life-threatening if it results in cannula dislodgment or disruption of the procedure. Additional muscle relaxant should be administered. If awareness is suspected, supplemental amnestics or anesthetics should be administered during rewarming. Because sweating stops almost immediately on discontinuation of bypass, continued sweating after emergence from CPB may be a sign of awareness. Neurologic monitors such as the Bispectral Index are being used by some clinicians to help judge the depth of anesthesia during and after weaning from CPB.¹⁵

Rewarming

When systemic hypothermia is used, body temperature is restored to normothermia by gradually increasing perfusate temperature with the heat exchanger. Time required for rewarming (i.e., heat transfer) varies with arterial perfusate temperature, patient temperature, and systemic flow. Excessive perfusate heating is not advisable for at least three key reasons: possible denaturation of plasma proteins, possible

cerebral hyperthermia, and the fact that dissolved gas can condense into bubbles if the temperature gradient is too great. Because small increases (0.5°C) in cerebral temperature exacerbate ischemic injury in the brain, it is critical to perfuse the patient with blood temperatures at or below 37°C. Although this will increase the duration of rewarming, the risk of hyperthermic brain injury is greatly increased with hyperthermic blood temperatures. Many centers employ mild hypothermia (i.e., systemic temperature = 31° to 34°C) instead of moderate hypothermia (26° to 28°C), reducing the amount of heat transfer to achieve normothermia.

Rewarming may be enhanced by increasing pump flow, which thereby increases heat input. At levels of hypothermia routinely used (25° to 30°C), the patient behaves as if vasoconstricted (calculated SVR is relatively high). Increasing pump flow in this setting may result in unacceptable hypertension. There are two approaches to this problem: wait out the vasoconstriction or pharmacologically induce patient vasodilation. When rectal or bladder temperature approaches 30° to 32°C, patients appear to rapidly vasodilate. This is probably the result of decreasing blood viscosity or relaxation of cold-induced vasoconstriction with warming. Increasing pump flow at this point serves several purposes: increased heat transfer, support of systemic arterial pressure, and increased oxygen delivery in the presence of increasing oxygen consumption. Often, waiting for the patient to spontaneously “vasodilate” is sufficient; and with subsequent increased pump flows, rewarming will be adequate at separation from bypass support. Circumstances in which more aggressive rewarming may be needed include profound hypothermia with a large hypoperfused “heat sink” and late initiation of warming by accident or design.

Skeletal muscle and subcutaneous fat are relatively hypoperfused during CPB. These tissues cool slowly and are also slow to warm. Temperatures at high-flow regions (e.g., esophagus, nasopharynx) do not reflect the temperature of these tissues. Pharmacologic vasodilation allows an earlier increase in pump flow and delivery of warmed arterial blood to low-flow beds, making the rewarming process more uniform. Arteriolar vasodilators (e.g., sodium nitroprusside, hydralazine) are much more likely to be effective in this process than venodilators (e.g., nitroglycerin). Other aids to warming during or after CPB are heating blankets, warmed fluids, heated humidified gases, and increased room temperature. Sterile forced-air rewarming devices and servoregulated systems are also available.

Restoration of Systemic Arterial Pressure to Normothermic Value

After aortic cross-clamp release, the heart is again perfused through the native coronary arteries. Until the proximal anastomoses are made, myocardial perfusion may be compromised in the presence of a low MAP. Consequently, it is advisable to gradually increase MAP during rewarming to levels of 70 to 80 mmHg.

With discontinuation of CPB, a marked discrepancy often exists between blood pressure readings measured from the radial artery and the central aorta. Radial arterial catheters may underestimate central aortic systolic pressures by 10 to 40 mmHg. Discrepancies in MAP tend to be of a lesser magnitude (5 to 15 mmHg). Such a discrepancy is not present before CPB, nor is it present after CPB in all patients. Mechanisms are undefined, but evidence supports vasodilatory and arteriovenous shunting phenomena in the forearm and hand.

Removal of Intracardiac Air

At the end of the procedure, intracardiac air is present in virtually all cases that require opening the heart (i.e., valve repair or replacement, aneurysmectomy, septal defect repair, repair of congenital lesions). In such cases, it is important to remove as much air as possible before resumption of ejection. Surgical techniques differ. With

the aortic cross-clamp still applied, the surgeon or perfusionist can partially limit venous return and LV vent flow, causing the left atrium and left ventricle to fill with blood. Through a transventricular approach, the left ventricle then can be aspirated. The left atrium and left ventricle are ballotted to dislodge bubbles, and the cycle is repeated. The operating table can be rotated from side to side and the lungs ventilated to promote clearance of air from the pulmonary veins. Rather than transventricular aspiration, some surgeons vent air through the cardioplegia cannula or a needle vent in the ascending aorta. Before removal of the aortic cross-clamp, the patient is placed head down, so that bubbles will float away from the dependent carotid arteries. Some surgeons favor temporary manual carotid occlusion before cross-clamp removal, but safety and efficacy of this potentially dangerous maneuver are undocumented. A venting cannula is often left in the aorta at a location that should allow air pickup after resumption of ejection. The aortic cross-clamp can be temporarily reapplied for additional air-clearing maneuvers.

TEE has shown that routine air clearance techniques are not completely effective. Transcranial Doppler studies document a high incidence of intracranial gas emboli on release of the aortic cross-clamp or resumption of ejection. Three essential elements of air removal are mobilization of air by positive chamber filling, stretching of the atrial wall, and repeated chamber ballottement; removal of mobilized air by continuous ascending aortic venting; and proof of elimination by TEE.

Intracardiac air may be present in 10% to 30% of closed cardiac cases as well (e.g., CABG). During aortic cross-clamping, air may enter the aorta and left ventricle retrograde through native coronary arteries opened in the course of CABG surgery, particularly when suction is applied to vent the left side of the heart or aortic root. Efforts to expel air from the left ventricle and aortic root should be routine before unclamping the aorta. It is unclear to what extent gas emboli originating from the heart and aorta contribute to neurologic injury. However, microembolic load correlates with magnitude of cognitive dysfunction. Air ejected from the left ventricle can also travel to the coronary arteries, resulting in sudden and sometimes extreme myocardial ischemia and failure after separation from bypass.

Defibrillation

Before discontinuation of CPB, the heart must have an organized rhythm that is spontaneous or pacer induced. Ventricular fibrillation (VF), common after cross-clamp release and warming, will often spontaneously convert to some other rhythm. Prolonged VF is undesirable during rewarming for at least three reasons: (1) subendocardial perfusion is compromised in the presence of normothermic VF; (2) myocardial oxygen consumption is greater with VF compared with a beating heart at normothermia; and (3) if the left ventricle receives a large amount of blood (aortic insufficiency or bronchial return) in the absence of mechanical contraction, the left ventricle may distend. LV distention increases wall tension and further compromises subendocardial perfusion. On the other hand, early resumption of mechanical contraction may make some surgical procedures difficult (e.g., modification of distal anastomoses).

Defibrillation, when necessary, is accomplished with internal paddles at much lower energies than would be used for external cardioversion. In the adult, starting energies of 5 to 10 J are routine. Defibrillation is less effective when the heart has not fully rewarmed, and it is rarely successful if myocardial (perfusate) temperature is less than 30°C. Repeated attempts at defibrillation, particularly with escalating energy levels, can lead to myocardial injury. If defibrillation is not successful after two to four attempts, options include further warming, correction of blood gas and electrolyte abnormalities if present (high P_{O_2} and high normal serum potassium $[K^+]$ seem favorable), increased MAP, and antiarrhythmic therapy. Bolus administration of 100 mg

of lidocaine before the release of the cross-clamp significantly lowers the incidence of reperfusion ventricular fibrillation. Increasing coronary perfusion by increased MAP is believed to result in myocardial reperfusion and recovery of the energy state.

Restoration of Ventilation

Before discontinuation of CPB, the lungs must be reinflated. Positive pressure (20 to 40 cmH₂O) is repeatedly applied until all areas of atelectasis are visually reinflated. Attention is specifically directed at the left lower lobe, which seems more difficult to reexpand. Fluid that has collected in the thoracic cavities during CPB is removed by the surgeon; and if the pleural cavity has not been opened, evidence of pneumothorax is also sought. The tidal volume or ventilatory rate is increased 10% to 20% above pre-bypass values to compensate for increased Vd/Vt if present. Ventilation is resumed with 100% oxygen and subsequent adjustments in Fio₂ are made based on arterial blood gas analysis and pulse oximetry.

Correction of Metabolic Abnormalities and Arterial Oxygen Saturation

When rewarming is nearly complete and separation from CPB is anticipated to occur in 10 to 20 minutes, an arterial blood sample is taken and analyzed for acid-base status, Po₂, Pco₂, hemoglobin or hematocrit, potassium, glucose, and ionized calcium.

OXYGEN-CARRYING CAPACITY

Generally, a hematocrit of at least 20% to 25% is sought before discontinuation of bypass. The primary compensatory mechanism to ensure adequate systemic oxygen delivery in the presence of normovolemic anemia is increased CO. Increased CO results in an increased myocardial oxygen need, which is met by increased coronary oxygen delivery by coronary vasodilation. The lower limit of the hematocrit, below which increased CO can no longer support systemic oxygen needs, is reported to be 17% to 20% in dogs with *completely healthy hearts*. With increases in systemic Vo₂, such as occur with exercise, fever, or shivering, higher values of the hematocrit are required. Patients with good ventricular function and good coronary reserve (or good revascularization) might be expected to tolerate hematocrit values in the 20s. When ventricular function is impaired or revascularization is incomplete, hematocrit above 25% may aid in support of the systemic circulation and concomitantly lower myocardial oxygen requirements on discontinuation of bypass.

ARTERIAL PH

Considerable debate has centered on the extent to which acidemia affects myocardial performance and whether correction of arterial pH with sodium bicarbonate is advantageous or deleterious to the heart. Most clinical studies have found metabolic acidosis impairs contractility and alters responses to exogenous catecholamines. Hemodynamic deterioration is usually mild above pH 7.2 because of compensatory increases in sympathetic nervous system activity. Attenuation of sympathetic nervous system responses by β -blockade or ganglionic blockade increases the detrimental effect of acidosis. The ischemic or hypoxic myocardium has been found to be particularly vulnerable to detrimental effects of acidosis. Patients with poor contractile function or reduction of myocardial sympathetic responsiveness (e.g., chronic left ventricular failure), those treated with β -blockers, or those with myocardial ischemia are especially susceptible to the adverse effects of acidosis. For these reasons arterial pH is corrected to near-normal levels before discontinuation of CPB, using sodium bicarbonate. Concerns regarding carbon dioxide generation and acidification of the intracellular space can be obviated by slow administration and appropriate adjustment of ventilation, both of which are easily achieved during CPB.

ELECTROLYTES

Electrolytes most commonly of concern before discontinuation of CPB are potassium and calcium. Serum potassium concentration may be acutely low because of hemodilution with non-potassium-containing priming solutions or large-volume diuresis during CPB. More commonly, potassium concentration is elevated as a result of systemic uptake of potassium-containing cardioplegic solution; values exceeding 6 mEq/L are not uncommon. Other potential causes of hyperkalemia that must be considered are hemolysis, tissue ischemia or necrosis, and acidemia. Hypokalemia can be rapidly corrected during CPB with *relative* safety because the heart and systemic circulation are supported. Increments of 5 to 10 mEq of KCl over 1- to 2-minute intervals can be given directly into the oxygenator by the perfusionist, and potassium subsequently is rechecked. Depending on severity and urgency of correction, elevated potassium can be treated or reduced by any of several standard means: alkali therapy, diuresis, calcium administration, or insulin and glucose. Alternatively, hemofiltration can be used to lower serum potassium. While still on CPB, potassium-containing extracellular fluid is removed from the patient and replaced with fluid not containing potassium.

Ionized calcium is involved in the maintenance of normal excitation-contraction coupling and therefore in maintaining cardiac contractility and peripheral vascular tone. Low concentrations of ionized calcium lead to impaired cardiac contractility and lowered vascular tone. Concerns have been raised about the contribution of calcium administration to myocardial reperfusion injury and to the action of various inotropes. Some investigators argue in favor of measuring ionized calcium before discontinuation of CPB and to administer calcium in patients with low concentrations to optimize cardiac performance. Although they routinely measure ionized calcium before discontinuation of bypass, calcium salts are not routinely administered. When confronted with poor myocardial or peripheral vascular responsiveness to inotropes or vasopressors after bypass *in the presence of a low level of ionized calcium*, calcium salts should be administered to restore ionized calcium to normal (not elevated) levels in the hope of restoring responsiveness. The same strategy can be used for measuring and administering magnesium.

Other Final Preparations

Before separating from CPB, all monitoring and access catheters should be checked and calibrated. The zero-pressure calibration points of the pressure transducers are routinely checked. Not uncommonly, finger pulse oximeter probes do not have a good signal after CPB. In those cases, a nasal or ear probe is placed to obtain reliable oximetry. Intravenous infusions are restarted before separation from CPB, and their flow characteristics are assessed for evidence of obstruction or disconnection.

During warming and preparation for separation, an assessment should be made of the functional status of the heart and peripheral vasculature based on visual inspection, hemodynamic indices, and metabolic parameters. Based on this assessment, inotropes, vasodilators, and vasopressors thought likely to be necessary for successful separation from bypass should be prepared and readied for administration.

Separation from Bypass

After all preparatory steps are taken, CPB can be discontinued. Venous outflow to the pump or oxygenator is impeded by slowly clamping the venous line, and the patient's intravascular volume and ventricular loading conditions are restored by transfusion of perfusate through the aortic inflow line. When loading conditions are optimal, the aortic inflow line is clamped and the patient is separated from CPB.

BOX 22-4 Perfusion Emergencies

- Arterial cannula malposition
- Aortic dissection
- Massive air embolism
- Venous air lock
- Reversed cannulation

At this juncture it must be determined whether oxygenation, ventilation, and more commonly myocardial performance (systemic perfusion) are adequate. A discussion of these issues no longer involves CPB per se but, rather, applied cardiopulmonary physiology. Should separation fail for any reason, CPB can simply be reinstated by unclamping the venous outflow and arterial inflow lines and restoring pump flow. This allows for support of systemic oxygenation and perfusion while steps are taken to diagnose and treat those problems that precluded successful separation.

PERFUSION EMERGENCIES

Accidents or mishaps occurring during CPB can quickly evolve into life-threatening emergencies (Box 22-4). Many of the necessary conditions of bypass (cardiac arrest, hypothermia, volume depletion) preclude the ability to resume normal cardiorespiratory function if an accident threatens the integrity of the extracorporeal circuit. Fortunately, major perfusion accidents occur infrequently and are rarely associated with permanent injury or death (Table 22-6). However, all members of the cardiac surgery team must be able to respond to perfusion emergencies to limit the likelihood of perfusion-related disasters.

Arterial Cannula Malposition

Ascending aortic cannulas can be malpositioned such that the outflow jet is directed primarily into the innominate artery, the left common carotid artery (rare), or the left subclavian artery (rare). In the first two circumstances, unilateral cerebral *hyperperfusion*, usually with systemic hypoperfusion, occurs, whereas flow directed to the subclavian artery results in global cerebral *hypoperfusion*. Despite the fact that not all combinations of arterial pressure monitoring site and cannula malposition produce systemic hypotension, it is commonly regarded as a cardinal sign of cannula malposition. For example, right arm blood pressure monitor and innominate artery cannulation, or left arm monitor and left subclavian artery cannulation may result in *high* arterial pressure on initiation of bypass. With other positioning and monitoring combinations, investigators report persistently low systemic arterial pressure (MAP = 25 to 35 mmHg), which is poorly responsive to increasing pump flow or vasoconstrictors. Over time (minutes), signs of systemic hypoperfusion (e.g., acidemia, oliguria) develop. Because a variable period of systemic hypotension with CPB initiation is nearly always seen with hemodilution, hypotension alone is not significant evidence to establish a diagnosis of arterial cannula malposition. On initiation of CPB and periodically thereafter, it is advisable to inspect the face for color change and edema, rhinorrhea, or otorrhea and to palpate the neck with onset of cooling for temperature asymmetry. EEG monitoring has been advocated as a method of detecting cannula malposition.

Table 22-6 Comparison of the Five Most Common Accidents from the Three Perfusion Surveys

Complication*	Stoney 1972-1977		Wheeldon 1974-1979		Kurusz 1982-1985	
	Incidents	PI/D	Incidents	PI/D	Incidents	PI/D
Air embolism	(2) 1.14	0.41	(2) 0.79	0.18	(6) 0.80	0.12
Coagulopathy	(1) 1.26	0.51	(6) 0.26	0.09	(8) 0.21	0.05
Electrical failure	(3) 0.67	0.01	(1) 1.00	0.06	(4) 0.84	0.003
Mechanical failure	(4) 0.38	0.02	(5) 0.27	0	(7) 0.30	0.007
Inadequate oxygenation	(5) 0.33	0.02	(3) 0.59	0	(3) 0.88	0.07
Hypoperfusion	—	—	(4) 0.30	0.18	(2) 0.96	0.15
Protamine reaction	—	—	—	—	(1) 2.80	0.22
Drug error	—	—	—	—	(5) 0.82	0.08

*The five most common complications for each study are listed as incidence per 1000 perfusions and the number of permanent injuries and mortalities as incidence per 1000 perfusions. The numbers in parentheses are the rank of each complication from most to least.

PI/D = permanent injury or death.

Data from Stoney WS, Alford WC Jr, Burrus GR, et al: Air embolism and other accidents using pump oxygenators. *Ann Thorac Surg* 29:336, 1980; Wheeldon DR: Can cardiopulmonary bypass be a safe procedure? In Longmore DB (ed): *Towards Safer Cardiac Surgery*. Lancaster, London, MTP, 1981, pp 427-446; and Kurusz M, Conti VR, Arens JF, et al: Perfusion accident survey. *Proc Am Acad Cardiovasc Perf* 7:57, 1986.

Two other arterial cannula malpositions are possible: abutment of the cannula tip against the aortic intima, which results in high line pressure, poor perfusion, or even acute dissection when bypass is initiated, and the cannula tip directed caudally toward the aortic valve. This may result in acute aortic insufficiency, with sudden left ventricular distention and systemic hypoperfusion on bypass. If the aortic inflow cannula is soft, aortic cross-clamping will occlude the arterial perfusion line, which can rupture the aortic inflow line. Suspicion of any cannula malposition must immediately be brought to the attention of the surgeon.

Aortic or Arterial Dissection

Signs of arterial dissection, often similar to those of cannula malposition, must also be sought continuously, especially on initiation of CPB. Dissection may originate at the cannulation site, aortic cross-clamp site, proximal vein graft anastomotic site, or partial occlusion (side-biting) clamp site. Dissections are due to intimal disruption, or more distally to fracture of atherosclerotic plaque. In either case, some systemic arterial blood flow becomes extraluminal, being forced into the arterial wall. The dissection propagates mostly in the direction of the systemic flow but not exclusively. Extraluminal blood compresses the luminal origins (take-offs) of major arterial branches such that vital organs (e.g., heart, brain, kidney, intestinal tract, spinal cord) may become ischemic. Because systemic perfusion may be low, and origins of the innominate and subclavian arteries may be compressed, probably the best sign of arterial dissection is persistently low systemic arterial pressure. Venous drainage to the pump decreases (blood is sequestered), and arterial inflow “line pressure” is usually inappropriately high. The surgeon may see the dissection if it involves the anterior or lateral ascending

aorta (bluish discoloration), or both. It is possible the surgeon may *not* see any sign of dissection, because the dissection is out of view (e.g., posterior ascending aorta, aortic arch, descending aorta). Dissection can occur at any time before, during, or after CPB. As with cannula malposition, a suspicion of arterial dissection must be brought to the attention of the surgeon. The anesthesiologist must not assume that something is suddenly wrong with the arterial pressure transducer but should “think dissection.”

After a dissection of the ascending aorta is diagnosed, immediate steps to minimize propagation must be taken. If it has occurred before CPB, the anesthesiologist should take steps to reduce MAP and the rate of rise of aortic pressure (dp/dt). If it occurs during CPB, pump flow and MAP are reduced to the lowest acceptable levels. Arterial perfusate is frequently cooled to profound levels (14° to 19°C) as rapidly as possible to decrease metabolic demand and protect vital organs. A different arterial cannulation site is prepared (e.g., the femoral artery is cannulated or the true aortic lumen is cannulated at a site more distal on the aortic arch). Arterial inflow is shifted to that new site in hopes that perfusing the true aortic lumen will reperfuse vital organs. The ascending aorta is cross-clamped just below the innominate artery, and cardioplegia is administered (into the coronary ostia or coronary sinus). The aorta is opened to expose the site of disruption, which is then resected and replaced. Reimplantation of the coronary arteries or aortic valve replacement, or both, may be necessary. The false lumina at both ends of the aorta are obliterated with Teflon buttresses, and the graft is inserted by end-to-end suture. With small dissections it is sometimes possible to avoid open repair by application of a partial occlusion clamp with plication of the dissection and exclusion of the intimal disruption. In some cases of arterial dissection during CPB, TEE has been found useful. Although provisional diagnoses were made on the basis of traditional signs, TEE allowed assessment of the origin and extent of dissection.¹⁶ Diagnosis of arterial dissection has also been assisted by presence of EEG asymmetry.

Arterial dissections originating from femoral cannulation also necessitate reductions in arterial pressure, systemic flow, and temperature. If the operation is near completion, the heart may be transfused and CPB discontinued; otherwise, the aortic arch must be cannulated and adequate systemic perfusion restored to allow completion of the operation.

Massive Arterial Gas Embolus

Macroscopic gas embolus is a rare but disastrous CPB complication. Studies in 1980 reported incidences of recognized massive arterial gas embolism of 0.1% to 0.2%. The current incidence is probably lower because of the widespread use of reservoir level alarms and bubble detection devices. Between 20% and 30% of affected patients died immediately, with another 30% having transient or non-debilitating neurologic deficits, or both. Circumstances that most commonly contributed to these events were inattention to oxygenator blood level, reversal of left ventricular vent flow, or unexpected resumption of cardiac ejection in a previously opened heart.

The pathophysiology of cerebral gas embolism (macroscopic and microscopic) is not well understood. Tissue damage after gas embolization is initiated from simple mechanical blockage of blood vessels by bubbles. Although gas emboli may be absorbed or pass through the circulation within 1 to 5 minutes, the local reaction of platelets and proteins to the blood gas interface or endothelial damage is thought to potentiate microvascular stasis, prolonging cerebral ischemia to the point of infarction. Areas of marginal perfusion, such as arterial boundary zones, do not clear gas

emboli as rapidly as well-perfused zones, producing patterns of ischemia or infarction difficult to distinguish from those due to hypotension or particulate emboli.

Recommended treatment for massive arterial gas embolism includes immediate cessation of CPB with aspiration of as much gas as possible from the aorta and heart, assumption of steep Trendelenburg position, and clearance of air from the arterial perfusion line. After resumption of CPB, treatment continues with implementation or deepening of hypothermia (18° to 27°C) during completion of the operation, clearance of gas from the coronary circulation before emergence from CPB, and administration of glucocorticoids in an attempt to minimize cerebral edema. In many reports of patients suffering massive arterial gas embolus, seizures occurred postoperatively and were treated with anticonvulsants. Because seizures after ischemic insults are associated with poor outcomes, owing perhaps to hypermetabolic effects, prophylactic phenytoin seems reasonable. Hypotension has been shown to lengthen the residence time of cerebral air emboli and worsen the severity of resulting ischemia. Maintenance of moderate hypertension therefore is reasonable and clinically attainable to hasten clearance of emboli from the circulation and, hopefully, improve neurologic outcome.

Many clinicians have reported dramatic neurologic recovery when hyperbaric therapy is used for arterial gas embolism, even if delayed up to 26 hours after the event. Spontaneous recovery from air emboli has also been reported, and no prospective study of hyperbaric therapy in the cardiac surgery setting has been performed. Few institutions that do cardiac surgery have an appropriately equipped and staffed compression chamber to allow expeditious and safe initiation of hyperbaric therapy. Nonetheless, immediate transfer by air is often possible and should seriously be considered. It seems reasonable to expect that institutions that do cardiac surgery should have policies regarding catastrophic air embolism.

In 1980, Mills and Ochsner¹⁷ suggested venoarterial perfusion as an alternative to hyperbaric therapy. Retrograde perfusion through the SVC cannula at 1.2 L/min at 20°C for 1 to 2 minutes was used in five of their eight patients with massive gas embolism. The goal was to flush air from the cerebral arterial circulation. None of the patients so treated had evidence of neurologic injury. Other reports using this technique have followed.

Venous Air Lock

Air entering the venous outflow line can result in complete cessation of flow to the venous reservoir, and this is called *air lock*. Loss of venous outflow necessitates immediate slowing, even cessation of pump flow, to prevent emptying the reservoir and subsequent delivery of air to the patient's arterial circulation. After an air lock is recognized, a search for the source of venous outflow line air must be undertaken (e.g., loose atrial purse string, atrial tear, open intravenous access) and repaired before reestablishing full bypass.

Reversed Cannulation

In this case, the venous outflow limb of the CPB circuit is incorrectly connected to the arterial inflow cannula and the arterial perfusion limb of the circuit is attached to the venous cannula. On initiation of CPB, blood is removed from the arterial circulation and returned to the venous circulation at high pressure. Arterial pressure is found to be extremely low by palpation and arterial pressure monitoring. Very low arterial pressures can also (more commonly) be due to dissection in the arterial tree. In the latter case, the perfusionist will rapidly lose volume, whereas with reversed cannulation, the perfusionist will have an immediate gross excess of volume. If high

pump flow is established, venous or atrial rupture may occur. The CVP will be dramatically elevated, with evidence of facial venous engorgement.

Line pressure is the pressure in the arterial limb of the CPB circuit. Because arterial cannulas are much smaller than the aorta, there is always a pressure drop across the aortic cannula. Arterial inflow line pressure will always be considerably higher than systemic (patient) arterial pressure. The magnitude of the pressure drop depends on cannula size and systemic flow; small cannulas and higher flows result in greater gradients. The CPB pump must generate a pressure that overcomes this gradient to provide adequate systemic arterial pressure. For a typical adult (i.e., MAP of about 60 mmHg, systemic flow of about 2.4 L/min/m², and a 24-Fr aortic cannula), line pressure in an uncomplicated case usually ranges from 150 to 250 mmHg. The fittings on the arterial inflow line are plastic; the fittings and the line itself can rupture. Perfusionists typically do not want a line pressure in excess of 300 mmHg.

CPB must be discontinued and the cannula disconnected and inspected for air. If air is found in the arterial circulation, an air embolus protocol is initiated. Once arterial air is cleared, the circuit is correctly reconnected and CPB restarted. In adults, the venous outflow limb of the CPB circuit is a larger-diameter tubing than the arterial inflow tubing, precisely to eliminate reversed cannulation. This is why reversed cannulation is rare in adults, but it has happened. In pediatric cases, the arterial inflow and venous outflow limbs of the CPB circuit are close or equal in size.

SPECIAL PATIENT POPULATIONS

Care of the Gravid Patient during Bypass

Studies assessing the effects of cardiac surgery and CPB on obstetric physiology and fetal well-being are lacking. However, several reviews and many case reports describe individual experience in caring for the gravid patient and fetus during cardiac surgery and extracorporeal circulation. These surveys and anecdotal reports, along with an understanding of the well-documented physiology of pregnancy and the effects of cardiac therapeutics on fetal physiology, can serve as a basis for a rational approach to care for the pregnant patient and fetus during cardiac surgery.¹⁸

Maternal and Fetal Monitor Information

The pregnant patient undergoing cardiac surgery requires the usual monitors employed during cardiac surgery, as well as monitors that can assess fetal well-being. Monitors that help assess the adequacy of maternal cardiovascular performance and oxygen delivery to the fetus are of paramount importance. Little is known about the effects of cardiovascular drugs and other therapeutic measures on the pregnant cardiac patient undergoing CPB. Appropriate monitors permit the assessment of an individual therapy on maternal and fetal oxygen delivery.

Uterine activity should be monitored with a tocodynamometer applied to the maternal abdomen. This monitor transduces the tightening of the abdomen during uterine contractions. As is the case with other types of major surgeries, the tocodynamometer should not interfere with the conduct of cardiac surgery; if necessary, the monitor may be intermittently displaced by the operating surgeon. The use of an intra-amniotic catheter to monitor uterine activity and pressure may be inadvisable in a patient who will be fully heparinized. Intraoperative uterine contractions may have a deleterious effect on fetal oxygen delivery (by causing an increase in uterine venous pressure and decrease in uterine blood flow) and signal the onset of preterm labor. Use of the tocodynamometer is imperative, because it will provide

important information about the state of the uterus and allow intervention if necessary. Various reports have documented the common occurrence of uterine contractions during cardiac surgery and CPB. Uterine contractions may appear at any time during the perioperative period but occur most frequently immediately after the discontinuation of CPB and in the early ICU period. It is therefore important to leave the tocodynamometer in place after the completion of surgery. Although uterine contractions occur frequently in the perioperative course, they usually are effectively treated with magnesium sulfate, ritodrine, or ethanol infusions, and they do not result in preterm labor and fetal demise.

Fetal heart rate (FHR) monitors should be employed in all gravid patients after 16 weeks' gestation, because one of the primary perioperative goals is to avoid fetal loss. Use of an FHR monitor permits recognition of fetal distress and allows the clinician to institute measures to improve fetal oxygen delivery. The FHR monitor recognizes and records the FHR, FHR variability, and uterine contractions. A spinal electrode placed in the fetal scalp gives the most reliable fetal ECG and therefore the best FHR information. However, this method may be undesirable in the presence of maternal anticoagulation. External FHR monitoring, using ultrasound, phonocardiography, or external abdominal ECG, is less exact but preferable in this clinical setting.

The cardiac surgeon and perfusionist may not be familiar with uterine and FHR monitors; the anesthesiologist is accustomed to caring for these patients during labor and delivery and can assess uterine and FHR tracings. However, in some clinical circumstances, such as preoperative fetal distress, or anticipated need for emergency cesarean section during cardiac surgery, having a perinatologist or an obstetrician present during cardiac surgery may be desirable.

FHR is usually normal in the pre-bypass period but decreases precipitously with the initiation of CPB and remains below normal for the entire bypass period. There are many potential causes of this observed decrease in FHR. Persistent fetal bradycardia is a classic sign of acute fetal hypoxia. However, in the CPB setting, especially when hypothermia is employed, it is difficult to ascribe fetal bradycardia to hypoxia or to decreased fetal oxygen demand. Fetal tachycardia typically occurs after the discontinuation of bypass support. This tachycardia may represent a compensatory mechanism for the oxygen debt incurred during CPB. The FHR usually returns to normal by the end of the operative period.

Interventions optimizing maternal blood oxygen content, correcting any acid-base imbalance, and replenishing fetal glycogen stores may alleviate signs of fetal hypoxia. Some clinicians recommend an increase in CPB pump flow to improve fetal oxygen delivery.

Conducting the Bypass Procedure

The conditions of extracorporeal circulation—nonpulsatile blood flow, hypothermia, anemia, and requisite anticoagulation—will likely have a negative impact on fetal well-being during CPB. There are no studies that recommend a CPB management strategy in gravid patients. Recommendations are summarized (Table 22-7) for the management of bypass in pregnant patients.

BLOOD FLOW

Optimal CPB blood flow in the gravid patient is unknown. However, the increase in CO associated with pregnancy is well defined, and it might be argued that high blood flows during CPB are more physiologic in the gravid patient. It has been suggested that flow during CPB in the pregnant patient be maintained at a minimum of 3.0 L/min/m². A few reports demonstrate that increasing CPB circuit blood flow improves FHR, suggesting improvement in fetal oxygen delivery.

Table 22-7 Recommendations for the Conduct of Extracorporeal Circulation in the Gravid Patient

Variable	Recommended Value/ Characteristic	Rationale
Blood flow	3.0 L/min/m ²	Cardiac index normally is increased during pregnancy.
Blood pressure (MAP)	60-70 mmHg	Uterine blood flow depends on maternal MAP.
Temperature	32-34°C	Mild hypothermia decreases fetal oxygen requirements and is less likely to cause fetal arrhythmia.
Oxygenator type	Membrane	Membrane oxygenators are associated with fewer embolic phenomena than bubblex.
Hematocrit	25%-27%	The quantity of oxygen carried in maternal blood (and therefore the oxygen available to the fetus) greatly depends on hemoglobin concentration.
Duration of perfusion	Minimized (?)	The duration of bypass is dictated by the complexity of the operative procedure.
Cardioplegia	?	
Pulsatile perfusion	?	

MAP = mean arterial pressure.

BLOOD PRESSURE

Under normal conditions, uterine blood flow is determined solely by maternal blood pressure, because the placental vasculature is maximally dilated. However, it is not known what factors determine uterine blood flow during the very abnormal condition of CPB. For example, catecholamine levels increase by several times during CPB; therefore, uterine vascular resistance may increase during extracorporeal circulation in response to increased levels of norepinephrine and epinephrine. However, regardless of the state of uterine vascular resistance during CPB, maternal blood pressure will be an important determinant of uterine blood flow and fetal oxygen delivery. Moderately high pressure (mean arterial pressure \geq 65 mmHg) should be employed during perfusion in the gravid patient.

TEMPERATURE

There are theoretical advantages and disadvantages for normothermic and hypothermic CPB in the gravid patient. Hypothermia can cause fetal bradycardia and may lead to fetal ventricular arrhythmias resulting in fetal wastage. Rewarming after hypothermic bypass may precipitate uterine contractions and preterm labor. However, others reported the onset of uterine contractions at the time of discontinuation of bypass support in spite of normothermic perfusion. Uterine

contractions also occur at various times in the post-bypass and postoperative periods. The association of uterine contractions with rewarming after hypothermic bypass is unclear.

Hypothermia may be protective to the fetus during extracorporeal circulation by decreasing fetal oxygen requirements. Perfusion temperatures of 25° to 37°C have been used in gravid patients undergoing CPB. There are no data that suggest hypothermia is harmful to the mother or fetus undergoing bypass. Normothermic CPB may increase the likelihood of untoward neurologic sequelae in the mother, an event that would be catastrophic in a woman with young children.

SUMMARY

- Cardiopulmonary bypass (CPB) provides extracorporeal maintenance of respiration and circulation at hypothermic and normothermic temperatures. CPB permits the surgeon to operate on a quiet, or nonbeating, heart at hypothermic temperatures, thus facilitating surgery in an ischemic environment.
- CPB is associated with a number of profound physiologic perturbations. The central nervous system, kidneys, gut, and heart are especially vulnerable to ischemic events associated with extracorporeal circulation.
- Controversy regarding the optimal management of blood flow, pressure, and temperature during CPB remains. Perfusion should be adequate to support ongoing oxygen requirements; mean arterial pressures of more than 70 mmHg may benefit patients with cerebral and/or diffuse atherosclerosis. Arterial blood temperatures should never exceed 37.5°C.
- The initiation and termination of CPB are key phases of a cardiac surgery procedure, but the anesthesiologist must remain vigilant throughout the entire bypass.
- CPB is a complex system that is vulnerable to accidents. Careful and constant communication among the anesthesiologist, surgeon, perfusionist, and nurse is critical for patient safety.
- Minimally invasive cardiac surgery can be performed with port-access bypass circuits. This approach adds considerable complexity to the procedure and is not as popular as off-pump techniques for coronary artery bypass grafting.
- Bloodless cardiac surgery is possible, and numerous approaches including autotransfusion and hemodilution facilitate this goal.
- Total CPB can be tailored to produce deep hypothermic, circulatory arrest, or partial bypass. The special techniques require sophisticated monitoring and care.

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