Cardiopulmonary Bypass/Extracorporeal Membrane Oxygenation/Left Heart Bypass: Indications, Techniques, and Complications

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KEYWORDS
- Cardiopulmonary bypass
- Extracorporeal membrane oxygenation • Left heart bypass
- Complications • Coronary artery bypass grafting
- Valve surgery

Cardiopulmonary bypass (CPB) has revolutionized the ability to provide cardiorespiratory support and has advanced the field of cardiac surgery. This invention has given surgeons the ability to perform many procedures that were not possible previously. The concept and development of CPB has been pioneered by numerous legendary surgeons. Alexis Carrel and Charles Lindbergh developed a device that successfully perfused organs, including hearts, keeping them alive for several days.1 John Gibbon2 deserves credit for devising the concept of a heart-lung machine after caring for a young woman with a massive embolus in 1930. Over the next 20 years, Gibbon developed the heart-lung machine during his time at the Massachusetts General Hospital, the University of Pennsylvania, and Thomas Jefferson University. In the early 1950s, Lillehei and colleagues3,4 at the University of Minnesota developed a technique called controlled cross-circulation by using circulatory support from another person’s native circulation, usually the patient’s parent or relative. By 1955,
Lillehei abandoned cross-circulation and began using CPB; this approach was rapidly adopted by many surgical groups.

The safe use of CPB requires an understanding of the device by all members of the operative team. Specifically, the cardiac surgeon, the anesthesiologist, and the perfusionist all must be experienced and knowledgeable in their understanding of the physiology of CPB, its risks and limitations, and the potential injuries that may result from its misuse. Protocols for the use of CPB are developed collaboratively, and any deviation from a protocol should be based on the needs of the individual patient and agreed to by all team members. If the surgeon is to realize the full advantage of CPB, he or she must have knowledge of the perfusion circuit in use at their institution. This includes priming solutions, speed and ability to vary perfusate temperature, maximum and minimum flow rates, and available cannula sizes.

Before each procedure, the surgeon must develop a plan for conducting the operation, especially the use of CPB. The surgeon should review with the other team members the planned incisions, methods of cannulating the heart and great vessels, the systemic and myocardial temperatures desired, the possible need for low flow or circulatory arrest, and any anticipated pathologic or anatomic variations that may require alterations in the plan.

The surgeon should consider all potential complications during the planning of the operation—possible anatomic variants and catastrophic events. Examples of anatomic variants might include mitral regurgitation with a heavily calcified posterior mitral annulus requiring a longer and more complex operation with additional steps to protect the myocardium, a persistent left superior vena cava (SVC) accompanying an atrial septal defect, or a tetralogy of Fallot with a variant coronary artery crossing the right ventricular outflow tract. Potential catastrophic events should be reviewed frequently, since they occur suddenly, and all members of the surgical team must be prepared to deal with them rapidly and precisely. Catastrophic events during reoperative surgery include unexpected right ventriculotomy or aortotomy, or ventricular fibrillation before the sternum is open.

### INDICATIONS FOR CPB

The most common indication to use CPB is to provide cardiac and respiratory support during operations on the heart or great vessels. Coronary artery bypass grafting (CABG) still remains the most frequent use for CPB. Roughly 20% of CABG procedures in the United States are performed without the use of CPB (off-pump CABG) and use the patient’s own heart and lungs to maintain perfusion to the body. Other common procedures where CPB is used in adult and/or acquired diseases include valve operations and operations on the ascending aorta and aortic arch. In these cases, it is not uncommon to use CPB to cool the patient and allow the bypass circuit to be temporarily ceased. This allows for a bloodless field to perform critical parts of the operation while protecting the brain. CPB has revolutionized the approach to repair of congenital heart defects. Rarely, CPB is also used to provide hemodynamic support during major venous reconstruction. An additional benefit of the bypass in this instance is in cases of major venous injury or bleeding, shed blood can be collected and recirculated to maintain intravascular volume and perfusion. Occasionally, CPB is used in complex airway and pulmonary operations and reconstructions. CPB has also been used for isolated hyperthermic limb perfusion to deliver chemotherapy at supranormal temperatures to treat malignancy confined to one limb. The primary goals and purposes of CPB are listed in Box 1.
COMPONENTS OF CPB CIRCUIT

The components of the CPB circuit include venous cannula(e) typically in the right atrium or vena cavae, a venous reservoir, a membrane oxygenator, a heat exchanger, a pump, a microfilter in the arterial line, and an arterial cannula(s) (Fig. 1). Cannulae can be placed in the right side of the heart, into the right atrium, or into the SVC and inferior vena cava (IVC) and secured in place with 3-0 or 4-0 polypropylene (Prolene) pursestring sutures. These can be placed directly by opening the pericardium or percutaneously through the internal jugular vein and femoral vein. These latter approaches are used during minimally invasive cardiac operations. They remove lines from the operative field and allow for smaller incisions. Venous drainage can be obtained with gravity, whereby the venous reservoir is placed 40 to 70 cm below the level of the heart, or with vacuum suction. Venous cannula size is determined by the patient size, size of the right atrium and/or vena cava, and amount of flow desired.

<table>
<thead>
<tr>
<th>Box 1</th>
<th>Purposes and goals for CPB</th>
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<tr>
<td>1) Maintain perfusion to brain and other vital organs</td>
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<tr>
<td>2) Provide a bloodless field (heart, great vessels, or other) to allow the surgeon to visualize and perform the operation</td>
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<tr>
<td>3) Maintain thermoregulation for protection of organs (cooling and warming)</td>
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<tr>
<td>4) Provide cardiac assistance/protection</td>
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<tr>
<td>5) Provide pulmonary assistance/protection</td>
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Fig. 1. CPB circuit, including the venous reservoir, pump, heat exchanger, membrane oxygenator, and arterial filter.
Venous reservoirs provide a low pressure chamber that serves as a storage chamber for venous and shed blood. The reservoir can hold an additional 2 to 3 L of blood volume to allow for uninterrupted arterial blood flow if venous return is occluded. Rigid canister reservoirs facilitate removal of venous air and are easier to prime, whereas soft plastic bags maintain a closed system and lower the risk of embolization.7,8

Blood in the circuit then goes through a membrane oxygenator which distributes a thin layer of blood over a large surface area with high differential gas pressures across a thin microporous (0.3–0.8 \(\mu\)m pores) hollow-fiber membrane layer to facilitate oxygenation. Since carbon dioxide is highly diffusible in the plasma, it is removed easily through the membrane oxygenator. Partial pressure of oxygen in arterial blood (PaO₂) is controlled by the fraction of inspired oxygen delivered to the oxygenator, whereas partial pressure of carbon dioxide in arterial blood (PaCO₂) is controlled by the sweep speed of gas flow. Traditional bubble oxygenators were cheap, but they had a high risk for gas embolization and are no longer manufactured.

A heat exchanger is commonly used and allows for active cooling and rewarming of blood going into the patient. The temperature differential between the patient and blood is limited to a difference of 10°C to prevent bubble emboli. Moreover, blood should not be warmed over 42°C to minimize protein denaturation and emboli.7,8 A separate heat exchanger is used for cardioplegia and is often kept at temperatures of 4°C to 15°C.

The most recognized component of the CPB circuit is the pump (Fig. 2). Two options for pumps include roller pumps and centrifugal pumps. Roller pumps are independent of afterload, requiring low prime volumes, and they are cheap; however, they have a potential for air embolism, and they can cause significant positive and negative pressure, resulting in tubing rupture. Centrifugal pumps are afterload sensitive, adapt to venous return, and are superior for left heart bypass (LHB) and for long-term bypass, at the expense of large priming volumes, higher cost, and potential for passive backward flow.

The risk of embolism has been greatly decreased by the introduction of filters. Numerous sources of gaseous microemboli smaller than 500 \(\mu\)m are present, including loose pursestrings around venous cannulae, stopcocks in the circuit used for injection of medications, priming solutions, oxygenators, and rapid warming of

Fig. 2. Centrifugal pump used in CPB, ECMO, and LHB.
cold blood. Blood itself is the primary source for particulate emboli, including thrombin, fibrin, platelet clots, hemolyzed blood cells, and fat particles as well as shed muscle, bone, and marrow that gets aspirated into the cardiotomy reservoir.

Methods to minimize emboli to the arterial system include the use of membrane oxygenators, centrifugal pumps, and filters in the cardiotomy venous reservoir and in the arterial line. In our practice, we use two sequential arterial filters to decrease the number of microemboli in the arterial system. The temperature differential between the blood in the circuit and the body is maintained at less than 10°C to minimize emboli formation.

**TECHNIQUES/CONDUCT OF CPB**

Although the surgeon takes primary responsibility for the patient during the hospital course, a team of experts is required to administer anesthesia, maintain perfusion, and relay changes in the patient status during the operation. The surgeon will determine the plan of the operation, including methods of cannulation, cardioplegia, and cooling. The anesthesiologist is responsible for induction of anesthesia, endotracheal intubation, and the placement or insertion of most monitoring devices. In patients who are hemodynamically unstable, direct arterial pressure measurement should be established and a pulmonary artery catheter inserted before the induction of anesthesia. Often, the anesthesiologist provides assistance with transesophageal echocardiography (TEE) during the operation. The perfusionist helps to select the optimal cannula size, provides circulatory support and cardiac protection, and maintains anticoagulation during the operation. Further, the perfusionist is responsible for maintaining a written perfusion record and performing a series of safety checks. The surgeon, anesthesiologist, and perfusionist must have free and open communication.

**Patient Positioning**

Once all monitoring lines have been placed, the patient is positioned and pressure points are padded to prevent pressure necrosis. All monitoring cables and lines are secured to prevent displacement or disconnection during the operation. The traditional approach is through a median sternotomy. In this case, a padded roll is placed beneath the patient’s shoulders and arms placed at the sides to avoid brachial plexus injury. Minimally invasive approaches to the mitral and tricuspid valve are often performed through a right mini-thoracotomy. In this setting, a small bump is placed under the right chest and arms are secured at the patient’s sides.

Sterile preparation of the skin and draping is performed to ensure access to all aspects of the operative field. This typically includes the chest, abdomen, and both groins, as well as both lower extremities if saphenous vein is needed for CABG. In cases where the saphenous vein may be of poor quality and additional conduit for CABG is required, the nondominant arm is prepped in the field to harvest the radial artery.

The pump and cell-saving equipment are brought into position and the pump lines are passed to the field. The pump lines are located such that the operative field and surgeons are unhampered; with the pump lines in full view of the perfusionist, allowing immediate access to the lines should an event occur. The lines should be secured in a standard manner so that even excessive force cannot displace them. Inexperienced members of the team are instructed not to touch or compress the lines.

**Incisions**

The selection of the incision site for exposure and cannulation of the heart is based on considerations of safety, exposure, and cosmesis. Anatomic and pathologic
variations, such as a large ascending aortic aneurysm pressing against the sternum or severe pectus excavatum in which the entire heart is displaced to the left chest, may require careful planning to avoid catastrophe. Obviously, variations in the incision to achieve cosmesis must not compromise safety or adequate exposure.

The pericardium is opened in the midline from its reflection on the aorta down to the diaphragm. The pericardium is released from the diaphragm with a transverse incision, with care being taken to avoid entering the pleural space or injuring the phrenic nerve. At this point, consideration is given to the specific exposure that will be required for the operation. Heavy silk sutures are placed in the cut edges of the pericardium and tied to the presternal fascia on the ipsilateral side of the incision to elevate and stabilize the appropriate cardiovascular structures.

**Cannulation**

Once the pericardium is opened, the aortic cannulation site is chosen. Commonly the distal ascending aorta, just proximal to the innominate artery, is used. There are many methods to cannulate and secure the arterial cannula. The authors’ preference is to use two opposing diamond pursestring sutures with pledgeted 3-0 polypropylene approximately 30% larger than the size of the arterial cannula. The sutures are kept on opposing tourniquets. Venous cannulation sutures are placed using nonpledgeted 3-0 polypropylene pursestring. One or two venous cannulae are used depending on the operation. Heavy silk sutures are placed in the cut edges of the pericardium and tied to the presternal fascia on the ipsilateral side of the incision to elevate and stabilize the appropriate cardiovascular structures.

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After ensuring systemic heparinization (200–300 units/kg, confirmed by activated clotting time [ACT] >400 sec), the aorta is cannulated by creating an aortotomy with a #15 blade and inserting the cannula. It is important to ensure that the aortotomy is large enough to admit the cannula without difficulty to avoid injuring the aorta. In addition, care must be taken to avoid cutting the cannulation sutures. After the cannula is secured to the aorta with the tourniquets, it is attached to the arterial line and deaired. The arterial line is tested to ensure that flow into the arterial system is unobstructed and line pressure on the arterial cannula is not high.

Venous cannulation is performed by creating an atriotomy with scissors or a #11 blade. The atriotomy must be made large enough to admit the cannula easily. Deairing of the venous cannula and line is only necessary if using gravity drainage and an airlock needs to be avoided.

Additional cannulae are placed depending on the plan of the operation, including cannulas for cardioplegia and venting of the heart. Typically, a small cannula for cardioplegia is placed into the ascending aorta with 4-0 pledgeted polypropylene and a retrograde cardioplegia cannula placed through the right atrium into the coronary sinus secured with 4-0 polypropylene. These will be used to administer cardioplegia to arrest the heart and protect the myocardium. The left ventricle can be vented by using a cannula placed into the right superior pulmonary vein and advanced through the left atrium and mitral valve into the left ventricle. This will allow for a bloodless field when operating on the left ventricle or aorta.

Venous return can be achieved by a passive or assisted approach. Passive venous return is more traditional, and is dependent on gravity, the height of the operating table above the venous reservoir, and large-bore tubing. Assisted venous return is achieved with the aid of vacuum being applied to the venous line or reservoir and does not require gravity drainage. Assisted venous return provides some advantages over the traditional venous drainage, such as permitting smaller venous cannula, tubing,
incisions, and lowering the priming volume. It can increase the risk for gaseous microemboli if the vacuum is too great and the reservoir volume is too low to allow proper dissociation. Because of these concerns, the maximum amount of vacuum is limited to less than 80 mm Hg and maintains a venous reservoir volume that permits at least 10 second reaction time or no less than 1000 mL.

**Blood Strategy During CPB**

The pump is typically primed with 1.5 to 2 L of crystalloid. It is important to prime the pump before use in a patient to eliminate microemboli through the filter. The addition of this volume results in significant hemodilution. The usual hematocrit when on CPB is 20 to 25 mg/dL. The degree of hemodilution may be calculated before bypass is initiated, and if the expected priming volume would cause an unacceptable anemia, packed red blood cells may be added to the extracorporeal circuit.

Hemodilution provides an advantageous effect for perfusion by decreasing viscosity and by augmenting blood flow. Blood flow reflects the interaction of many influences; hemodilution aids in negating those inherent effects by diminishing blood’s viscosity and resistance to flow and promotes increased microcirculatory flow and tissue perfusion. However, hemodilution can be deleterious by reducing oncotic pressure, resulting in tissue edema and decreasing oxygen delivery during bypass. Hypothermia also influences blood rheology and vascular geometry. A decrease in temperature provokes direct vasoconstriction and increases viscosity, creating sludging and stasis at the capillary level, and a reduced blood flow. These effects are counteracted by hemodilution.

The acceptable degree of hemodilution is highly contested. It is common to see hematocrit of 18% to 21% during CPB. Hematocrit less than 15% can also be tolerated in cases of circulatory arrest and in patients who will not accept blood transfusion. The authors use a blood conservation strategy that has established transfusion indicators during CPB, depicted in Box 2. A general rule of thumb is that the hematocrit in percent should not exceed the desired level of hypothermia in °C.

**Initiating CPB**

CPB is begun at the instruction of the surgeon. Visual inspection of the field, monitors, and bypass lines as the perfusionist initiates CPB will provide an immediate assessment of the conversion. The perfusionist initiates CPB by releasing the arterial line clamp and slowly transfusing the patient with the volume. The arterial blood flow of the extracorporeal circuit should be free-flowing and exhibit a reasonable

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**Box 2**

**Strategy for blood transfusion during CPB**

1. During moderate hypothermic CPB, a hematocrit less than 18% is the trigger threshold for blood transfusion unless the patient exhibits a history of cerebrovascular accident and disease, carotid stenosis, or diabetes mellitus, in which case a hematocrit of 21% becomes the trigger.

2. The patient’s clinical condition also determines the need for blood transfusion: age, severity of illness, cardiac function, end-organ ischemia, massive or active blood loss, mixed venous oxygen saturation (SvO2), and so on. In this environment, a hematocrit of 21% to 24% becomes the authors’ trigger.

3. Routine use of the cell saver except for patients with infection and malignancy

4. Low-prime and mini-extracorporeal bypass circuits
extracorporeal line pressure. A sudden spike in the extracorporeal line pressure may indicate an occluded arterial line, a malpositioned aortic cannula, or an aortic dissection. Should this occur, CPB should be terminated immediately and the cause identified and corrected.

As soon as it is obvious that arterial flow is unobstructed, the venous clamp is released, diverting the patient’s venous blood into the CPB circuit. The right heart should be decompressed, and the central venous pressure should be less than 5 mm Hg. A high central venous pressure and poor venous drainage at the initiation of CPB may indicate a malpositioned venous cannula, a kinked venous line, an “air-lock,” venous cannulas that are too large or too small, an inappropriate height between the operating table and the venous reservoir, an inappropriate amount of vacuum, or a vacuum leak.

During this transition period of 1 to 2 minutes, the perfusionist gradually increases the rate of arterial flow, the ventricles receive less blood, and the pulsatile arterial waveform diminishes and becomes “flat-lined.” Once total bypass is achieved, a continued pulsatile arterial waveform signifies the left ventricle is receiving unwanted blood from aortic insufficiency, excessive bronchial venous return, or incomplete drainage of the systemic venous return.

Because of acute vasoactive substance release on initiating CPB, an acute, transient state of systemic arterial hypotension is common and can be treated with vasopressor agents if needed. Acceptable mean arterial pressure when on CPB ranges from 50 to 90 mm Hg. In the presence of cerebrovascular or renovascular disease, a perfusion pressure of 70 to 90 mm Hg is preferred. The adequacy of a mean arterial pressure in a patient is confirmed by a normal systemic vascular resistance index and mixed venous blood gas.

In patients with severe aortic regurgitation, the surgeon should be ready to cross-clamp the ascending aorta if ventricular fibrillation occurs. A distended, fibrillating left ventricle is subject to additional ischemia and injury to the myocardium. Once on full CPB support, the patient can be cooled to the desired temperature. The primary advantage of systemic hypothermia during CPB is the reduced metabolic rate and oxygen consumption of approximately 5% to 7% per °C. In addition, hypothermia sustains intracellular reservoirs of high-energy phosphates (essential for cellular integrity) and preserves high intracellular pH and electrochemical neutrality (a constant OH⁻/H⁺ ratio). As a result of these associated interactions, hypothermic patients can survive periods of circulatory arrest of up to 1 hour without suffering from the effects of anoxia.

In addition to core cooling with cold blood through the circuit, hypothermia may be augmented by surface cooling using cooling blankets and ice packs applied directly to the patient. Because tissues and organs have varying amounts of perfusion, systemic cooling is not a uniform process. To minimize this, the flows on the circuit are maintained at high rates (2.2 to 2.5 L/min/m²), and the rate of the cooling is limited to less than 1°C per minute until the desired temperature is reached. Bladder and nasopharyngeal temperatures are monitored to ensure uniform temperatures.

In most cases, the beating heart will be arrested to cease motion and allow a bloodless field on the heart. This is achieved by administering cardioplegia antegrade through the coronary arteries or retrograde through the coronary sinus. Since there are no valves in the coronary sinus, cardioplegia is able to run retrograde into the coronary arteries and out the ostium.

In certain cases, a state of circulatory arrest may be desired where the blood flow to the patient is drained and the circuit is stopped to allow for a bloodless field. This state of “no blood flow” to the patient is achieved with extreme systemic cooling at 16°C to
22°C. Safe periods of circulatory arrest can be achieved based on the patient’s core temperature (Table 1). Beyond these times there are risks for cerebral and other end-organ injury. The negative effects of circulatory arrest include additional time required to cool and rewarm the patient and systemic coagulopathy that often requires blood component replacement.

Systemic rewarming is instituted by gradually increasing the perfusate temperature. Rewarming is slower than cooling because of the maximum 10°C permissible temperature gradient between perfusate and nasopharyngeal temperatures, the maximum allowable blood temperature of 42°C, and the reduced thermal exchange as the temperature gradient between the patient and perfusate narrows. During this part of the procedure, warming blankets are set to 40°C, the perfusion flow rates are increased to 2.5 to 3.0 L/min/m², and, pressure permitting, pharmacologic vasodilation is used. When the bladder temperature reaches 32°C, the patient begins to vasodilate spontaneously and the pharmacologic vasodilator may be terminated.

**Weaning Off of CPB**

The heart is deaired before the cross-clamp is removed. The patient is placed in a 30° head-down (Trendelenberg) position, and the heart is filled with blood by manually restricting venous return to the pump. The right heart begins to fill, and the anesthesiologist ventilates the lungs. The heart is gently massaged. Vents in the left ventricle or in the aortic root cardioplegic cannula are used to remove air from within the heart. Once all air appears to have been evacuated, pump flow is reduced to half flow, arterial pressure is reduced to 50 mm Hg, and the aortic cross-clamp is removed while suction is maintained on the antegrade cardioplegic cannula. TEE is often used to determine if there is residual air within the heart. Maneuvers to remove any residual air include filling the heart, giving Valsalva breaths, and rocking the table from side to side when the aortic root vent is on. When echocardiography confirms that the left heart is free of air, the operating table is restored to a level position and the aortic cardioplegic/vent cannula and the retrograde cardioplegic cannula are removed.

Temporary pacing wires are sutured to the right atrium and ventricle if needed. Rewarming is continued until the patient’s temperature reaches 36°C. Termination of CPB is performed gradually, with constant communication between surgeon, perfusionist, and anesthesiologist. The ventilator is turned on. The perfusionist progressively occludes the venous return line, translocating blood volume from the venous reservoir into the patient’s vascular system. The patient is now on “partial” CPB, with blood flowing through the heart and pulmonary circulation. When the blood volume in the heart reaches an adequate level, the aortic valve begins to open with each heart beat, and a measurable cardiac output will be observed. The translocation of volume is continued until the arterial systolic pressure reaches 100 mm Hg. Simultaneously, the flow through the circuit is reduced. The surgeon checks for surgical

<table>
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<th>Hypothermia Level</th>
<th>Patient Temperature (°C)</th>
<th>Circulatory Arrest Times (min)</th>
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<tr>
<td>Mild</td>
<td>37–32</td>
<td>5–10</td>
</tr>
<tr>
<td>Moderate</td>
<td>32–28</td>
<td>10–15</td>
</tr>
<tr>
<td>Deep</td>
<td>28–18</td>
<td>15–60</td>
</tr>
<tr>
<td>Profound</td>
<td>&lt;18</td>
<td>60–90</td>
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bleeding and assesses heart function, as well as checking heart and valve function by TEE. On the surgeon’s approval, the perfusionist then terminates CPB by completely occluding the venous and arterial lines. Thereafter, the perfusionist transfuses volume to the patient to maintain a systolic blood pressure of 100 mm Hg unless the heart becomes distended.

If the heart does not function effectively when CPB is terminated, bypass is reinstituted to prevent overdistention or hypoxia. If heart functions appropriately with hemodynamic stability, decannulation can begin. The venous cannulae are removed but the tourniquets are still present should the need arise for rapid return to bypass. The heparin is reversed with protamine. When half of the protamine is administered, the aortic cannula should be removed to prevent arterial embolism from the cannula. Additional volume should be given to the patient as needed to fill the heart adequately though the aortic cannula before removing it. The protamine is then completed and arterial and venous cannulation sites are tied and secured. Shed blood should not be returned to the extracorporeal circuit once protamine is introduced into the patient’s circulation. Thereafter, final hemostasis and surgical closure of the wound are performed.

COMPLICATIONS

Complications associated with CPB can be divided into those related to malfunction of the circuit, those related to problems with cannulation, and those related to the physiology of CPB on the body.

Complications Related to Cannulation

Cannulation of the heart must be done carefully because this can result in major catastrophes. The risk for ascending aortic dissection is less than 1% with direct cannulation; however, when it does occur, it may require circulatory arrest and complete replacement of the ascending aorta. More common is bleeding from the aortic cannulation site as a result of misplaced sutures, too small a pursestring, bites of the aorta that are full thickness (and too deep), or poor quality tissue. Many of these errors can be avoided with careful planning of the location of cannulation and meticulous suture placement. Repair of a distal aortic injury can often be performed by covering the site with an autologous pericardial patch. At this point of the operation, the patient is typically off bypass and the aortic cannula has been removed. The assistant will need to control the bleeding with direct pressure on the aortic cannulation site. The surgeon can harvest a 2 to 3 cm circular piece of autologous pericardium. Using 5-0 polypropylene the surgeon secures the pericardium to the aorta around the cannulation site, making certain to get good bites of the aortic adventitia and media. The suture is run circumferentially and tied down. This will control the bleeding in most cases. Rarely, femoral cannulation is required to go back on pump and the patient may need to be cooled and circulation arrested to fix the cannulation injury as with an aortic dissection.

Venous cannulation injuries can occur as well and are typically related to quality of the atrial tissue and location of the pursestring suture. When cannulating the right atrial appendage and the IVC, the surgeon should ensure there is enough atrial tissue to allow closure of the atriotomy without tension. A tear in the atrioventricular groove or down the IVC can be very challenging to repair but can often be repaired primary or with a large bovine pericardial patch.

Peripheral arterial and venous cannulation can also lead to complications. Femoral arterial cannulation should only be performed with some knowledge of the femoral,
iliac, and aortic anatomy to avoid retrograde aortic dissection, malperfusion of the body during bypass, and aortic or iliac injury. In cases of severe peripheral vascular disease, calcification of the vessels, or the presence of an aortic or iliac aneurysm, alternative cannulation sites should be considered with a preoperative CT scan. Femoral venous cannulation can also lead to venous injury in the retroperitoneum or abdomen leading to hemorrhage and poor flows when on bypass. Cannulation of the axillary artery should be performed by sewing a Dacron graft in an end to side fashion. In this setting, the surgeon must ensure there is no obstruction or disease in the axillary or innominate arteries by CT angiogram.

Complications Related to the Effects of CPB on the Body

Although CPB has advanced heart surgery to allow us to perform complex reconstruction on the heart, it is clearly not a physiologic state with nonpulsatile flow, manipulation of core temperature, alterations in venous pressure, and increased interstitial fluid. In addition to a host of inflammatory cytokines that are released during bypass, CPB also causes dysfunction of clotting factors and platelet activation and lysis which ultimately lead to coagulopathy and bleeding. Meticulous hemostasis is the first key to minimize bleeding. Longer procedure times are associated with higher risk for bleeding and more coagulopathy. Additional topical hemostatic agents can be used to minimize nonsurgical bleeding. Blood component administration is the most common method of treating coagulopathy following CPB. Antifibrinolytic agents including aminocaproic acid are commonly used during and after CPB in long or complex cases to prevent fibrinolysis.

In addition to effects on coagulation, there are multiple effects of CPB that can lead to organ damage. It can be difficult to determine the source of postoperative cardiac injury and attribute it to CPB or to cardiac arrest/cross-clamping. Ischemic reperfusion causes myocardial edema. Lung injury has been attributed to ischemic reperfusion injury as well as changes in pulmonary capillary permeability. Renal dysfunction is thought to be because of alterations in blood flow when on CPB as well as tissue edema. Neurologic dysfunction has been the focus of many studies and is thought to be a result of nonpulsatile cerebral blood flow, microemboli to the brain, and loss of cerebral autoregulation. Neurologic sequelae include frank strokes as well as mild cognitive dysfunction often termed “pump head.” Careful planning of arterial cannulation, maintenance of adequate perfusion pressure when on CPB, and avoidance of microemboli with the use of arterial filters can minimize the risk for neurologic injury.

Complications Related to Pump Malfunction

Pump malfunctions are rare events but can have devastating consequences. Massive air embolism can occur with break in the integrity of the circuit, on depletion of the venous reservoir, during opening of the left atrium or ventricle without a cross-clamp (as can occur during insertion of a left ventricular vent), or from an inadvertent bolus of air into the arterial line. Systemic air embolism is treated by stopping the CPB and placing the patient in steep Trendelenberg. The circuit is reprimed to remove the air. The surgeon then cannulates the SVC and runs flow retrograde through the cerebral circulation for 1 to 2 minutes to allow air to exit through the aorta. Once the pump is primed and visible air in the arterial system is removed, the pump is restarted antegrade and the patient is cooled to 20°C to increase the solubility of the air embolism.

Air lock in the venous line can occur with gravity drainage and can result in loss of venous drainage and depletion of the venous reservoir. This is treated by closing the
source of venous entry, walking the air through the venous line into the reservoir, and adding fluid to the reservoir.

Pump failure can occur as a result of electrical or mechanical causes. This is prevented by frequent servicing of the equipment and ensuring a functioning backup battery. If the pump stops during CPB, if possible wean the patient off bypass. If this is not possible, then a manual hand crank can be used to continue perfusion through the pump.

EXTRACORPOREAL MEMBRANE OXYGENATION

The indications for extracorporeal membrane oxygenation (ECMO) are listed in Box 3. The ECMO circuit differs from the traditional CPB circuit in a number of ways. The ECMO circuit is a single closed system and is unable to tolerate air in the venous line. There is no separate circuit to administer cardioplegia as with the CPB circuit. ECMO is more compact than CPB, allowing for easier transportation of the patient (Fig. 3). Typical ECMO circuits have heparin bonded tubing allowing for lower levels of anticoagulation (ACT 180-220s).

Cannulation for ECMO can be performed with a variety of techniques. Venoarterial (VA) ECMO is performed for both circulatory and pulmonary support. VA ECMO is often performed for cardiogenic failure post cardiac surgery. In this scenario, the aorta is cannulated directly as aforementioned. If the aortic cannula is still present from CPB, it can be used as the arterial inflow for VA ECMO. In settings where the chest is not open, arterial cannulation is usually performed through the femoral artery. Venous cannulation is performed in the right atrium if the chest is open or through the femoral vein and/or internal jugular when the chest is not open. Femoral, arterial, or venous cannulation can be performed percutaneously or via a cutdown. When performed via cutdown, 5-0 pursestring suture is used to secure the cannulas. Once the cannulas are confirmed to be in good location providing good flows on ECMO, the cannulas and tubing are secured with heavy silk sutures to the skin to ensure they are not inadvertently moved during routine care of the patient.

Venovenous ECMO is used for isolated pulmonary support in cases of reversible pulmonary failure. Most often, cannulation is performed through the femoral and internal jugular veins. Inflow is from the femoral vein and outflow through a cannula in the right atrium positioned through the internal jugular vein.

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Complications

In addition to the aforementioned concerns with air embolism and microemboli, complications specifically related to ECMO are primarily because of the extended period of time in which a patient is anticoagulated while on cardiopulmonary support. This results in significant coagulopathy, especially when ECMO support is required for longer than 48 to 72 hours. Despite maintaining lower ACTs while on ECMO, the pump and circuit result in consumption of clotting factors and platelets. It is not unusual for patients on ECMO to receive several times their blood volume in blood component replacement while on support. The resultant transfusions can lead to reactions to the blood products and secondary injury to the lungs.

Fig. 3. ECMO circuits are smaller than CPB and are portable.

Fig. 4. LHB machine.
LHB is partial heart bypass designed to provide partial blood flow to limited sections of the body during surgery (Fig. 4). LHB is primarily used to provide support and perfusion of the visceral vessels and lower extremities during reconstruction of the descending aorta, allowing the perfusionist to divert a portion of the patient's saturated blood from the patient's circulation after it has passed through the lungs and returns it to the arterial system by way of the distal aorta or femoral artery (Fig. 5). This parallel circuit technique permits the perfusionist to vary the preload of the left ventricle, controlling the volume of blood being ejected into the aorta, and it provides blood flow to the lower intercostals, lumbar, renal, and visceral arteries. The use of LHB has been shown to decrease the incidence of paraplegia and renal failure, and it limits intestinal ischemia during operations on the descending thoracic and thoracoabdominal aorta.11–13

Access to the thoracic and thoracoabdominal aorta is obtained through a left thoracotomy and a thoracoabdominal incision, respectively. Following exposure of the aorta, heparin is administered (100 units/kg) and ACTs are maintained at 200 sec. The femoral artery is cannulated with a 15F Bio-Medicus arterial cannula percutaneously or through femoral artery cutdown through a 5-0 polypropylene pursestring. If cannulating directly into the distal aorta, a 12F Bio-Medicus arterial cannula is used through a 4-0 polypropylene pursestring. The cannula is then attached to the outflow side of the circuit, with great care being taken to ensure the system is devoid of air bubbles. The left atrium is cannulated through the left inferior pulmonary vein with a 14F Bio-Medicus venous cannula and secured with a 5-0 polypropylene pursestring.
The inferior pulmonary ligament should be divided entirely and the inferior pulmonary vein should be isolated circumferentially. As noted on the arterial side, the cannula is secured to the circuit ensuring no air bubbles in the line.

A blood flow rate of 20 to 40 mL/kg, or a cardiac index of 1.3 m² (2.0–2.5 L/min) is generally acceptable for perfusing the viscera and lower extremity. Following the initiation of bypass and aortic cross-clamping, there are two parallel circulations. Circulation to the great vessels and heart is dependent upon the patient’s native cardiac function and preload in the left ventricle, whereas the lower circulation is dependent on the bypass circuit. The regulation of blood flow and pressure is controlled by the rate in which the blood is removed by the bypass circuit. As the pump flow of the bypass circuit increases, the blood flow into the ascending aorta is decreased along with the upper extremity blood pressure; whereas the distal blood flow and pressure increases. By altering the flow through the circuit, the radial artery pulsatile pressure is maintained around 100/60 mm Hg, whereas the femoral artery mean pressure is maintained to roughly equal the radial diastolic pressure.

The LHB circuit is a simple circuit consisting of a centrifugal pump, tubing, and cannulae. The use of a centrifugal pump offers the advantage of providing a negative pressure on the inflow blood, allowing the pump to be close to and at table level, thus reducing the tubing length. This arrangement traps air bubbles that may entrain into the circuit, and it minimizes blood element trauma. In addition, two cell savers are used to process and return the patient’s shed blood.

Complications

LHB does possess some unique hazards in addition to the aforementioned risks for CPB. Although meticulous care must be taken to avoid air embolism in other modes of CPB, this cannot be overstated using LHB. Excess flow through the circuit or relative hypovolemia will result in proximal aortic hypotension and suboptimal perfusion of the brain and upper extremities. Excessive rpm of the centrifugal pump may cause vortexing, which can generate microemboli that can be passed distally into the patient. Finally, femoral cannulation can result in limb ischemia by the arterial cannula obstructing flow in the distal femoral artery.

SUMMARY

CPB, ECMO, and LHB have revolutionized our ability to operate on the heart, great vessels, and aorta in addition to providing means of short-term support for reversible causes of cardiac and/or respiratory failure. The success of these approaches is dependent upon excellent communication between the surgeon, perfusionist, and anesthesiologist as well as constant vigilance and troubleshooting by the caregivers.

REFERENCES