Chapter 9
Cardiopulmonary Bypass

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Basic Components of the Heart-Lung Machine

The heart-lung machine is both intricately complex and at the same time simple in its principles. The core functions of CPB establish mechanisms to (1) drain the body's deoxygenated blood, (2) oxygenate, heat, and pump extracorporeal blood, (3) re-introduce oxygenated blood to the body, and (4) establish cardioplegia while providing the heart with oxygenated blood (Fig. 9.1). The role of the perfusionist in managing the heart-lung machine cannot be overstated and is further discussed in Chap. 33 of this text.

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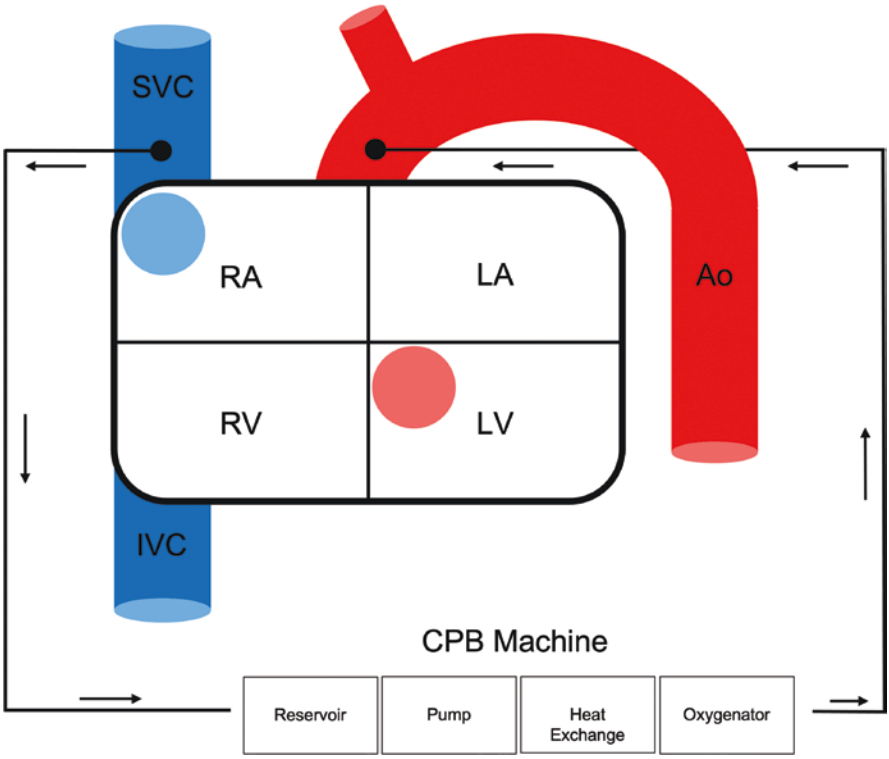

Fig. 9.1 Diagram of cardiopulmonary bypass

Heart-Lung Machine Safety

The heart-lung machine incorporates several safety devices to minimize the two greatest risks of the machine: circuit disruption and gaseous embolism. Standard safety devices include servo-regulated pressure control of the arterial and cardioplegia pumps to prevent high pressure due to kinking or inadvertent clamping of tubing. In addition, servo-regulated bubble and level detection are routinely utilized to avoid drainage of the venous reservoir and introduction of a massive air embolism. If air is introduced into the circuit, or if the reservoir level drops, the arterial pump will stop to allow the perfusionist to remove air.

Cannulation Strategies

Figure 9.1 demonstrates common access sites for cannula when initiating CPB, but multiple access sites are suitable for each cannula. Venous cannulas are often placed in the vena cava and right atrium (also known as dual stage cannulation), but

bicaval, femoral vein, and internal jugular vein access are suitable alternatives. Bicaval cannulation is useful to fully drain the right heart. Oxygenated blood can be returned to the body via aortic, innominate, axillary, or femoral artery access. Common indications for peripheral access include aortic arch surgery and minimally invasive operations. To "vent," or drain, the left ventricle, a cannula may be inserted into the aortic root, the left ventricular apex, the left ventricle via the right superior pulmonary vein, or the pulmonary artery.

Standard Heparin Dosage and Reversal

Anticoagulation via heparin is essential during cardiopulmonary bypass to prevent both extracorporeal coagulation and an intra-operative embolic event. The level of anticoagulation achieved is measured by point of care testing. The Activated Clotting Time (ACT) along with heparin levels (heparin-protamine titration) are the preferred tests. Prior to cannulation, a sample of the patient's whole blood is tested for heparin sensitivity and a heparin bolus is calculated to achieve an ACT ≥400 s and a heparin level ≥2.7 u/mL. During CPB, the ACT is maintained ≥400 s and the heparin level ≥2.0 u/mL. The ACT and heparin level should be checked at least every 30 min, as additional heparin bolus may necessary. At the conclusion of the operation, heparin reversal is achieved through protamine infusion. Protamine dosing is calculated by measuring the heparin level, followed by administration of protamine at 0.8–1.0 mg protamine per 100 units of heparin. Finally, ACT and heparin levels should again be checked to verify the success of reversal [1, 2]. Of note, in rare cases such as in patients with Heparin Induced Thrombocytopenia (HIT), heparin and heparin-specific monitoring cannot be used, and alternative pharmacologic agents and testing must be utilized.

Optimal Flow Rates and MAP

When a patient is on CPB, the heart cannot regulate the body's metabolic needs and accommodate for poor tissue oxygenation by increasing cardiac output. Consequently, patients on CPB must be closely monitored to ensure adequate oxygenation—a task made more difficult due to metabolic changes associated with hypothermia induced during CPB. The most common mechanisms of measuring tissue perfusion include venous oxygen saturation and lactate (a carbon dioxide-derived parameter). However, these markers are imperfect. As a result, optimal CPB flow rates have historically been initiated in the range of 2.2–2.8 L/m^2/min at 35–37 °C and adjusted based on hypothermia (guideline to reduce flow by 7% for each 1 °C reduction) and the aforementioned markers [3]. Recent studies have demonstrated that oxygen delivery—with a goal delivery ≥270 mL/min/m^2—may be used as an adjunct or alternative metric to flow rates calculated from body surface

area [4]. In addition to titrating flow rates, perfusionists closely monitor MAP. Historically, MAP has been maintained at 50–80 mmHg, but sustaining higher MAP (i.e., ≥65 mmHg and up to ≥75 mmHg for patients with cerebrovascular disease) during CPB by increasing the flow rate or administering vasopressors reflects more recent practice patterns in an effort to maintain adequate end organ perfusion. Commonly used vasopressors include α-agonist phenylephrine and norepinephrine as well as the V1 receptor agonist vasopressin. In cases of extreme vasoplegia, methylene blue or hydroxocobalamin may be administered.

Cooling and Warming

During CPB, hypothermia is induced as a cytoprotective measure, particularly for the brain and myocardium. Inducing hypothermia during cardiac surgery is difficult because of the challenges of managing heat transfer through the heart-lung machine. It is therefore critical to monitor temperature closely with multiple temperature probes; the most common sites include the pulmonary artery, nasopharynx, esophagus, and bladder. During CPB, patients are routinely cooled to a core body temperature 32–34 °C. For particularly difficult procedures such as aortic arch surgery, patients may be cooled to 18 °C. During cooling, it is important to maintain a low temperature gradient (<10 °C) between arterial outflow and venous inflow to avoid formation of gas emboli. Approximately 10 minutes prior to the release of the aortic cross-clamp and prior to weaning from CPB, patients are warmed at a rate of ≤0.5 °C, with an arterial-venous gradient ≤4 °C. During rewarming and immediately post-operatively, to avoid cerebral hyperthermia a patient's core body temperature should not exceed 37 °C.

Steps to Initiate and Separate from CPB

Initiating and separating a patient from CPB are processes that demand precise care coordination among the cardiac surgery care team. Both processes are outlined below. In addition, checklists, a crucial asset in surgery [5, 6], are employed during initiating and separating patients from CPB (Fig. 9.2).

Initiation

1. Set up the CPB circuit (Fig. 9.2)
   (a) Perfusionist completes setup, priming, testing
2. Establish anticoagulation
3. Arterial cannulation

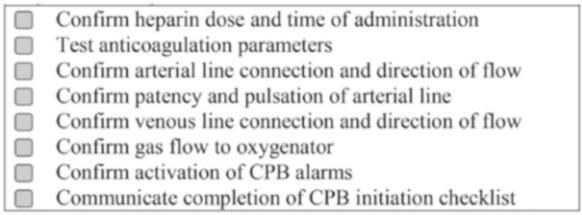
- [ ] Confirm heparin dose and time of administration
- [ ] Test anticoagulation parameters
- [ ] Confirm arterial line connection and direction of flow
- [ ] Confirm patency and pulsation of arterial line
- [ ] Confirm venous line connection and direction of flow
- [ ] Confirm gas flow to oxygenator
- [ ] Confirm activation of CPB alarms
- [ ] Communicate completion of CPB initiation checklist

Fig. 9.2 Example of perfusionist checklist for CPB initiation

4. Venous cannulation
5. Autologous priming
   (a) Retrograde/venous priming
      - Utilizes patient's blood to remove crystalloid priming solution
   (b) Reduces hemodilution to avoid low nadir hematocrit levels
6. Start "On-Pump"
   (a) The patient's heart and lungs remain functional
7. Turn off ventilator and place aortic cross-clamp
8. Induce cardioplegia
   (a) The patient is now dependent on CPB

Separation

1. Restart the heart
   (a) Rewarm the patient (0.3–0.5 °C/min)
   (b) De-air the heart—prevent air embolus
   (c) Resume electrical activity—epicardial pacing wires are used to establish normal sinus rhythm
2. Restart the lungs—ventilate the patient
3. Confirm weaning criteria—see below
4. Wean CPB
   (a) Venous line is gradually clamped, and pump flow is gradually decreased
   (b) Venous cannula is removed
5. Reverse anticoagulation
   (a) Administration of protamine
6. Arterial decannulation

Criteria for Discontinuing CPB

To facilitate CPB, normal physiology is altered. Therefore, when the cardiac procedure is complete and a patient is prepared to be weaned from CPB, the operative team must restore not only mechanical function of the heart and lungs, but also physiologic homeostasis. Criteria can be organized into four categories: heart, lung, metabolism, and anesthesia. Cardiac criteria for discontinuation of the heart-lung machine include restoration of normal sinus rhythm with a normal heart rate and blood pressure (with or without rate control agents, inotropes, and vasopressors). A transesophageal echocardiogram should also confirm an absence of air in the cardiac chambers. Pulmonary physiology is restored through mechanical ventilation and confirmed through PaO_2 monitoring. Metabolically, the patient should be warmed to 35–37 °C, normal acid-base status should be achieved (pH 7.35–7.45), and serum potassium (K^+ 4–5.5 mmol/L), hemoglobin (>7.0 mg/dL), calcium (1.09–1.30 mmol/L) should be normalized. Finally, the anesthesia team should confirm preparedness to resume full control of the patient [1].

Circulatory Arrest and Special Considerations

Aortic arch surgery presents added challenge to cardiac surgery because the surgical field must be free of CPB equipment, including cannulas and clamps. To accommodate aortic arch operations, temporary hypothermic circulatory arrest is induced. Special considerations of circulatory arrest are management of acid-base status and alternative cerebral perfusion techniques.

Alpha Stat and pH Stat

There are two common ways to manage intra-operative pH. Alpha-stat has been traditionally used for CPB (particularly for non-circulatory arrest) and provides a pH that is corrected for the patient's hypothermic state. Accordingly, the patients pCO_2 is maintained in a normal range (35–45 mmHg) at 37 °C, resulting in a low true cerebral pCO_2. Conversely, pH-stat maintains a normal pCO_2 at a patient's true intraoperative temperature. This technique increases cerebral pCO_2, leading to a local cerebral vasodilatory response and increased cerebral perfusion, which promotes complete and homogenous cerebral cooling. pH-stat is also more frequently used in pediatric cardiac surgery.

ACP and RCP

Antegrade cerebral perfusion (ACP) is a CPB technique used in aortic arch surgery to perfuse only the brain. ACP is facilitated through arterial cannulation of either the axillary artery or a branch of the aortic arch. ACP's biggest advantage is neuroprotection through minimization of brain ischemia during hypothermic circulatory arrest.

Retrograde cerebral perfusion (RCP) is another CPB technique that provides blood flow only to the brain. In RCP, the venous cannula is inserted into the SVC and the brain is perfused with oxygenated blood retrograde from the venous system that normally drains the brain. Like ACP, RCP is utilized to minimize brain ischemia during circulatory arrest.

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