Pediatric Cardiopulmonary Bypass and Hypothermic Circulatory Arrest

86

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High Yield Facts

- Pediatric cardiopulmonary bypass (CPB) is necessary to operate inside the heart and on portions of the aorta.
- Key CPB components include an oxygenator and a blood pump.
- CPB provides oxygenated blood flow while the heart is arrested, and ventilation is stopped.
- CPB has become safer, simpler, and with lower morbidity.
- Pump flow is the main determinant of oxygen delivery on CPB.
- Deep hypothermic circulatory arrest (DHCA) involves deep cooling of the patient and cessation of blood circulation.
- DHCA allows repair of very complex intracardiac defects and defects involving the transverse aortic arch.
- Antegrade cerebral perfusion decreases or eliminates cerebral circulatory arrest.

Introduction

Modern cardiopulmonary bypass (CPB) originated from the work of Gibbon who described the first artificial oxygenation device, which he termed the heart lung machine [1]. Gibbon performed the first successful use of the heart lung machine to repair an atrial septal defect in a child on May 6, 1953. Thereafter, the use of the heart lung machine and CPB was expanded to deal with more complex congenital heart defects and eventually to the repair of acquired adult cardiac lesions. Since the early era of pediatric CPB there have been major advances in heart lung machine technology, CPB equipment and techniques, and surgical interventions [2, 3] allowing for safe repair of even the most complex heart defects.

CPB is the technique of diverting venous blood as it nears or enters the heart to an extracorporeal (outside the body) circuit (ECC) and then pumping this blood (now artificially oxygenated) back into the aorta—bypassing the heart and lungs. Since the blood is being pumped by an artificial pump, the heart is often arrested (see Chap. 10). Since the venous blood is no longer flowing through the lungs, ventilation of the lungs may be stopped. This combination allows a cardiac surgeon to operate on, or inside, a heart that is blood free, in a motionless surgical field, on a fully supported patient. This allows precise surgical correction of complex acquired or congenital cardiothoracic defects.

CPB is necessary for many pediatric operations described in the following chapters. The ECC contains key disposable components including a venous reservoir, blood pump, heat exchanger, oxygenator, and arterial filter. This is attached to the heart lung machine which contains blood pumps, pressure/temperature monitoring, safety devices, blood gas analyzers, gas blenders, timers, vacuum regulators, and control/monitoring panels (Fig. 86.1a, b). The heart lung machine is operated by medical professionals known as perfusionists. Other ancillary equipment includes heater coolers, cell saver/autotransfusion devices and blood analyzers.

Conduct of Cardiopulmonary Bypass

Anticoagulation

The first step towards placing a patient on CPB is to anticoagulate the patient. This is necessary due to the large foreign

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S. G. Raja (ed.), *Cardiac Surgery*, https://doi.org/10.1007/978-3-030-24174-2_86

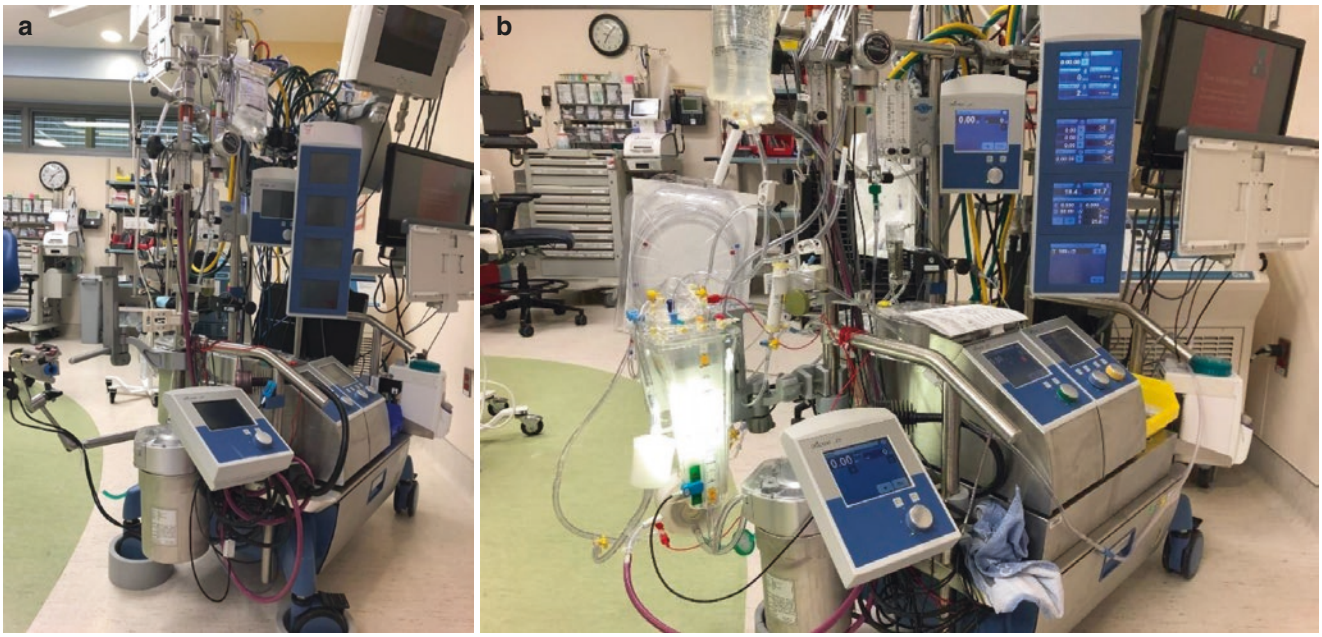

Fig. 86.1 (**a**) Heart lung machine. (**b**) Heart lung machine with disposable cardiopulmonary bypass circuit attached

surface that the blood will be exposed to in the ECC. Heparin is the most commonly used anticoagulant due to the ease of measuring its effectiveness via a test known as the activated clotting time (ACT), and the fact that it has a reversal agent (protamine). Heparin works by binding with antithrombin III (ATIII) and potentiating ATIII's effects on thrombin and factor Xa. Heparin dosing regimens vary but range from 300 to 500 units/kg with a target ACT to commence CPB of >480s. Other anticoagulants, such as the direct thrombin inhibitor bivalirudin, may be used in the case of patients with heparin-induced-thrombocytopenia (see Chap. 12). Once the ACT is adequate, pump suckers from the heart lung machine may be turned on. This suction allows shed blood during cannulation, and CPB, to be pumped from the surgical field into the venous reservoir of the ECC where it remains in the circulation.

Arterial Cannulation

Once heparin is administered cannulation is performed. Cannulas are large catheters that are inserted into the patient and serve as the interface between the patient's vasculature and the ECC. For pediatric CPB many sizes and shapes of cannula are necessary (Fig. 86.2a, b). Arterial cannulation is usually done first. The typical location is the ascending aorta but depending on the operation and patient anatomy, different, or additional locations may be cannulated. The size and location of the arterial cannula is very important as this is where oxygenated blood from the ECC will be pumped into the patient. An arterial cannula that is too small may not allow for adequate pump flow to meet the patient's metabolic demands and may result in damage to the red blood cells and the patient's vasculature. The arterial cannula is attached to tubing that comes from the outlet of the ECC oxygenator. A common practice is to perform a "test infusion" from the heart lung machine to the patient. This confirms successful placement of the arterial cannula tip in the lumen of the cannulated vessel. Aortic dissection is a possibility from aortic cannulation and must be quickly diagnosed. After a successful test infusion, volume from the venous reservoir can be pumped into the patient. This is often necessary due to blood loss from aortic and venous cannulation and helps maintain patient stability just prior to CPB initiation.

Venous Cannulation

A single venous cannula (single-stage or 2-stage) or multiple cannulas (bi-caval) are inserted to allow drainage of venous blood to the ECC. The method of venous cannulation used depends on the operation and individual surgeon's discretion. Appropriately sized venous cannulae are important, to assure proper venous drainage and avoiding venous congestion in the patient.

Femoral Cannulation

Many pediatric cardiac operations involve redo median sternotomies. In this case, it may be necessary to proactively

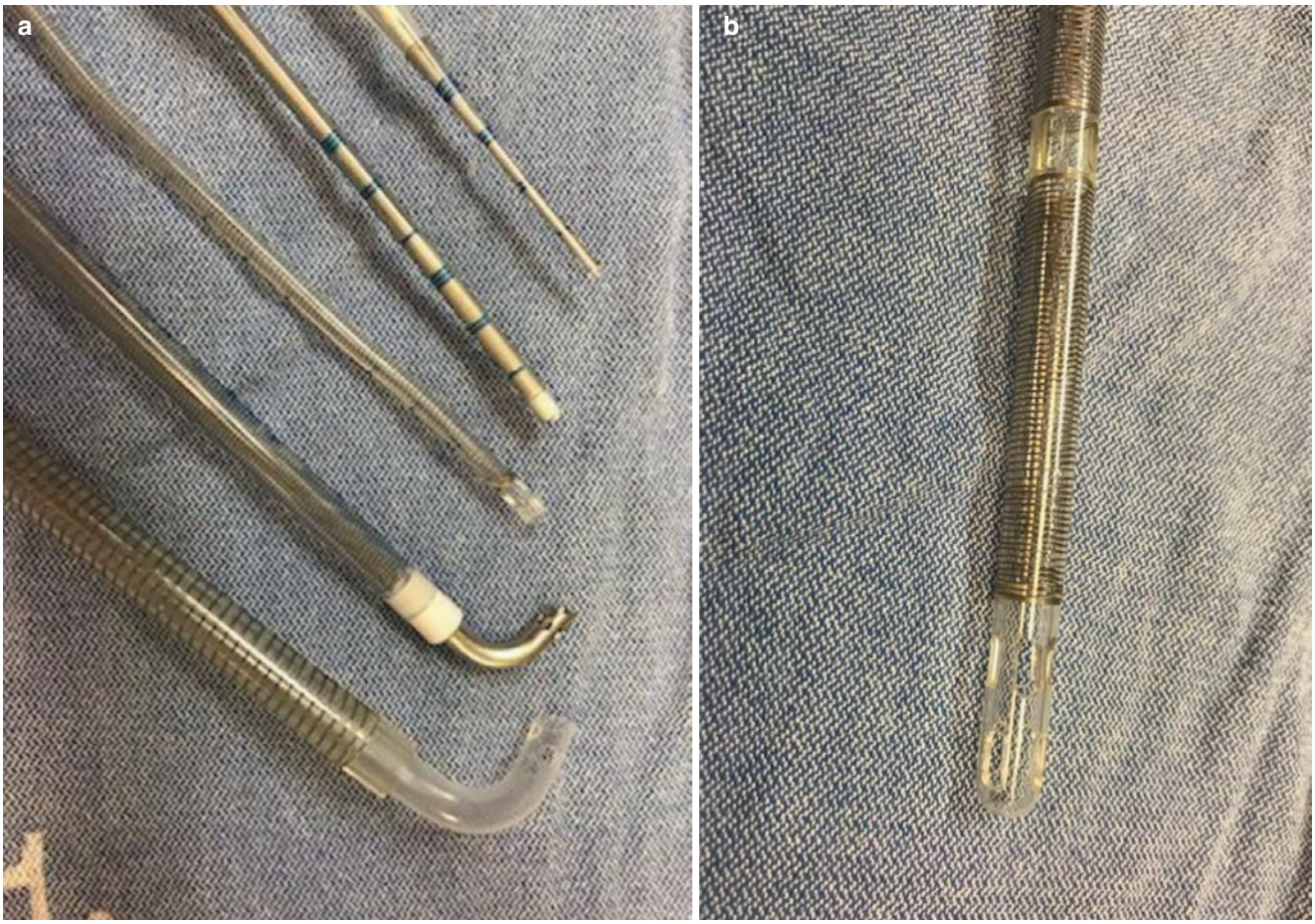

Fig. 86.2 (**a**) Different types of pediatric venous and arterial cannulae. (**b**) Bi-caval venous cannula: for larger pediatric patients/adults; gets inserted through the right atrium with the tip placed in the inferior vena cava. Upper holes drain the right atrium

cannulate the femoral artery and femoral vein (fem-fem) and initiate CPB. This allows decompression of the heart prior to risky redo sternotomies. In the case of massive hemorrhage during redo sternotomy a plan should be in place to rapidly initiate fem-fem CPB, or otherwise stabilize the patient until direct cannulation can occur.

Initiation of Cardiopulmonary Bypass

Once the arterial and venous cannulas are attached to the ECC, and the patient is adequately heparinized, the patient may be placed "on bypass". Clamps are removed from the venous and arterial lines of the ECC and drainage of venous blood to the venous reservoir is achieved either by gravity (siphoning of blood due to the height difference from the right atrium to the venous reservoir) or via vacuum assisted venous drainage (VAVD). VAVD, commonly used for pediatric CPB, is achieved by applying negative pressure to the venous reservoir. This allows the venous reservoir and oxygenator to be raised to a level nearer the patient and for adequate venous drainage with shorter tubing length, smaller diameter tubing and smaller venous cannulas. This reduces the prime volume and foreign surface of the ECC, potentially reducing transfusion requirements.

As the venous blood is being drained from the patient, the arterial pump flow is increased to a flow that is roughly equivalent to the output of the native heart. Once on "full flow" the heart should no longer be ejecting, the central venous pressure should be zero, volume that was in the heart and pulmonary vasculature is now in the venous reservoir of the CPB circuit (Fig. 86.3), and the arterial pressure tracing should be relatively flat. Unlike the pulsatile pumping of the heart the mechanical pumps commonly used for CPB are continuous flow pumps (like a garden hose). For pediatric CPB an arterial roller-pump is most common. This style pump offers finer control of pump flow at lower flows (particularly important for procedures like antegrade cerebral perfusion in neonates). While still considered continuous flow pumps they do actually generate a pulse pressure which

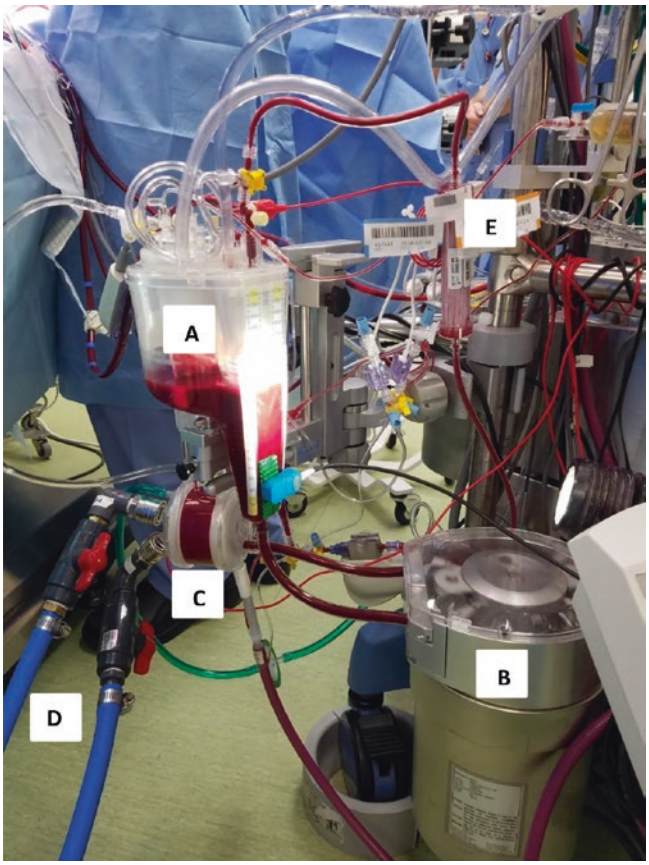

Fig. 86.3 Venous reservoir (**a**); arterial roller pump (**b**); oxygenator with integrated arterial filter (**c**); water lines attached to the heat exchanger portion of the oxygenator (**d**); ultrafiltration device (**e**)

may be confused with cardiac ejection when evaluating the arterial pressure tracing (Fig. 86.4a–c). Centrifugal pumps are true continuous flow pumps which are more frequently used for adult CPB, larger paediatric patients, and ECMO.

Blood Flow Through the Cardiopulmonary Bypass Circuit

The CPB pump pulls venous blood out of the venous reservoir and pumps it into the heat exchanger portion of the oxygenator at a rate that is controlled by the perfusionist. The heat exchanger is often integrated into the oxygenator and is most commonly made of stainless steel. Blood flows on one side of the stainless steel with water being pumped through the other side by a separate heater-cooler device. The temperature of the water is adjusted which indirectly affects the temperature of the blood. This provides precise control of patient temperature allowing the patient to be cooled to as low as 18 °C and then rewarmed to normal body temperature.

After the heat exchanger blood flows through the gas exchange portion of the oxygenator. This is commonly made up of micro-porous hollow-fibers with blood flowing on the outside of the fibers and gas (mixture of room air and oxygen) flowing through the inside of the fibers. Gas molecules such as O_2 and CO_2 are small enough to travel through the micropores of the hollow-fibers (blood cells are much too large). Just like in the lungs, O_2 and CO_2 flow from high concentration to low concentration (Fick's Law). In an oxygenator, this means O_2 flows from the gas side to the blood side (eventually binding with hemoglobin to make oxyhemoglobin), and CO_2 is transferred from the blood side into the gas side, where it exits the oxygenator through an exhaust port. Inhalation anesthetic agents are also commonly added to the oxygenator gas flow to maintain anesthesia while the ventilator is off.

The perfusionist evaluates and controls blood oxygenation and CO_2 removal. This is accomplished via continuous arterial blood gas monitoring, blood gas analysis, and adjusting the FiO_2 and the rate of continuous gas flow (sweep rate) through the oxygenator. Increasing the FiO_2 of the ventilating gas results in an increase in the patient PaO_2. The oxygenator sweep rate is similar to adjusting the rate on a ventilator—sweep rate and patient $PaCO_2$ have an inverse relationship. For pediatric CPB it is often necessary to add CO_2 to the ventilating gas of the oxygenator due to the relatively large surface area for gas exchange, efficiency of modern oxygenators at removing CO_2, and the use of hypothermia (decreased patient CO_2 production).

As blood exits the oxygenator it goes through an arterial line filter (ALF) (either a stand-alone device or often integrated into the oxygenator). The ALF is an important safety device that protects the patient from emboli (gaseous or particulate) from the ECC. From the ALF the blood travels up the arterial line to the arterial cannula and into the patient.

Pump Flow/Oxygen Delivery

Pump flow is the main determinant of O_2 delivery (DO_2) during CPB (DO_2 = indexed pump flow × 10 × arterial O_2 content). Anticipated full flow for a patient is mainly determined by calculations based on body weight in kilograms (Table 86.1). Pump flow is adjusted up or down based on the clinical scenario. The metabolic demands of the patient must be balanced with the surgeon's need for a bloodless surgical field. Pump flow should deliver oxygenated blood at a rate that meets the metabolic demands of the entire body (brain, kidney, gut, heart, etc.), as determined by SVO_2, near-infrared spectroscopy (NIRS), pH, electrocardiogram, lactate, etc. This flow should generate a mean arterial pressure (MAP) that provides adequate perfusion pressure for all major organs. Patient's systemic vascular resistance and

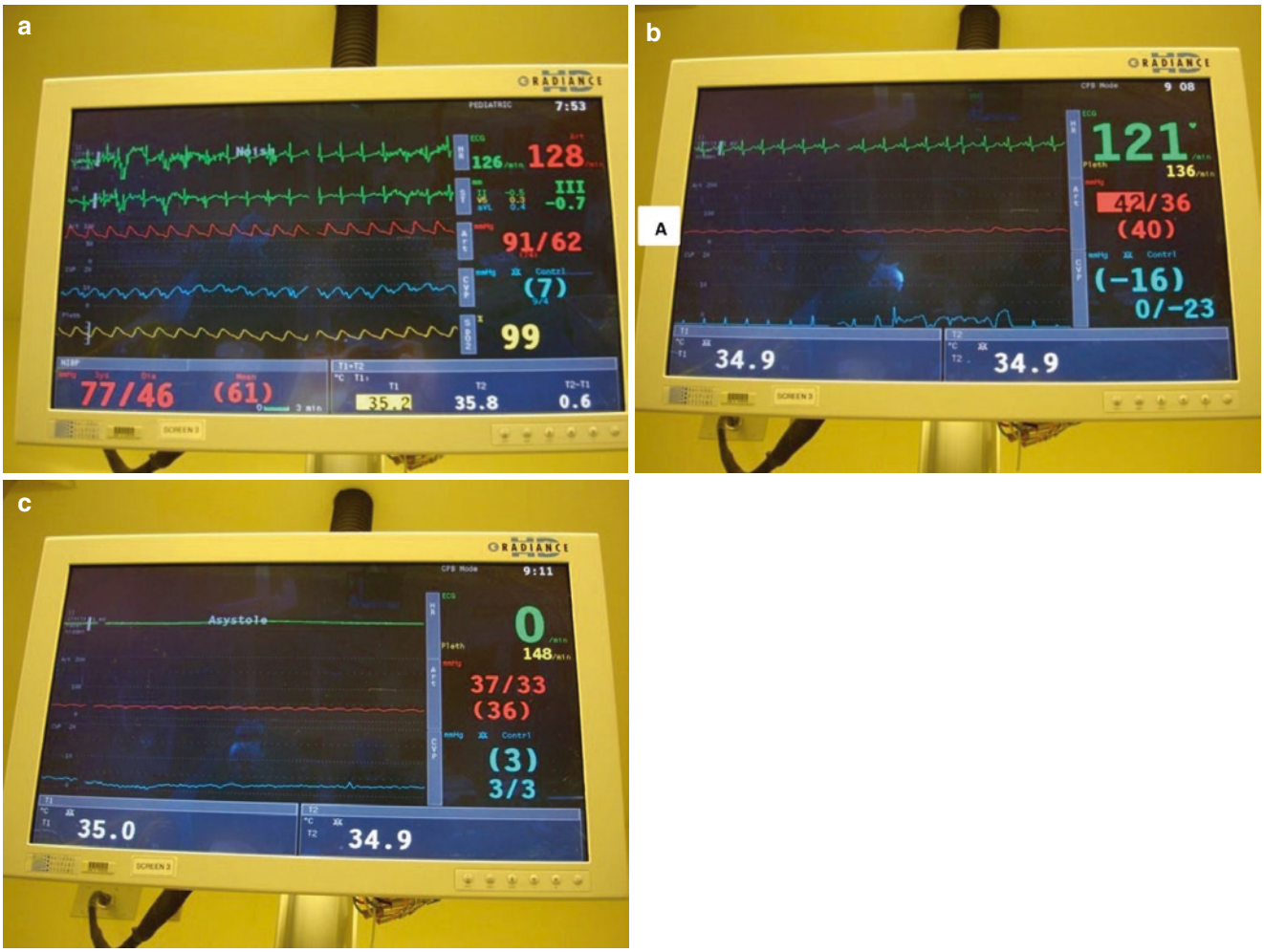

Fig. 86.4 (**a**) Pre-cardiopulmonary bypass patient hemodynamics. (**b**) On-cardiopulmonary bypass patient hemodynamics with flat arterial tracing (**a**). Minor pulsatility from arterial roller pump can be seen. Heart is beating but empty. CVP is <0. (**c**) On-cardiopulmonary bypass patient hemodynamics with aortic cross clamp on. Asystole on electrocardiogram

Table 86.1 Recommended cardiopulmonary bypass flow rates for different sized patients

Patient weight (kg)	CPB flow rate (ml/kg/min)
2–7	120–200
7–10	100–175
10–20	80–150
➢ 20	50–75

CPB cardiopulmonary bypass

pump flow may need to be adjusted (up or down) to maintain an adequate MAP during CPB. Other factors that determine MAP include blood temperature and hematocrit (via blood viscosity).

At this point, depending on the operation, it is possible to arrest the heart and perform an operation inside the motionless, bloodless heart in a very stable patient. This allows the repair to be conducted by a surgeon in an ideal, non-hurried condition.

Goal-Directed-Perfusion

There has been a recent trend towards goal-directed-perfusion (GDP). This involves more extensive monitoring and maintaining certain parameters (DO_2, MAP, SVO_2, NIRS, etc.) within pre-determined ranges during CPB (or reducing the amount of time below these ranges), as well as the usage of newer oxygen consumption/CO_2 production based ratios to guide pump flow/DO_2. This would be an improvement to weight based flow estimates (Table 86.1). The goal is to develop individual-patient based perfusion strategies, with known critical values to avoid, with the intention of avoiding some known consequence (i.e. acute kidney injury [AKI]). Rannucci et al. and others have focused on nadir DO_2 on CPB and a correlation with post-CPB AKI in adults, as well as the ratio of O_2 delivery to CO_2 production (DO_2/VCO_2), with a ratio <5 being predictive of hyperlactatemia and AKI [4–6].

While some research has focused on pediatric GDP [7–9], most studies involve adult CPB. The development of pediatric GDP guidelines will be difficult, due to the non-homogenous patient population. Multiple strategies would have to be studied and developed for populations like: neonates, single ventricle patients, cyanotic vs. non-cyanotic patients, etc.

A problem historically with assessing DO_2 adequacy during CPB is it's based on global markers of perfusion (pH, SVO_2, lactate). Good oxygenation/perfusion in many areas can mask an area(s) with poor perfusion, undergoing anaerobic metabolism. An adjunct to pediatric GDP could be incorporating more organ specific monitoring techniques, such as renal and splanchnic NIRS.

Vents/Pump Suckers

CPB vents are suction catheters, often placed inside or around the heart, or in the aorta. The catheter is attached to tubing which runs through a roller pump, which pumps the blood into the venous reservoir of the ECC. This keeps any blood aspirated by the vent in the patient's circulation (as opposed to lost to a waste suction cannister). Intra-cardiac vents help with surgical visualization and with de-airing the heart prior to cross-clamp removal.

Pump suckers are hand-held suction that are also attached to the reservoir via a pump and tubing. The usage of pump suckers while the patient is heparinized, and cell saver suction prior to heparinization and after heparin reversal, are commonly used in both adult and pediatric CPB to prevent blood loss from the patient.

Once protamine is given, vents and pump suckers can lead to protamine getting into the ECC and clotting the circuit. This makes it unusable if the patient needed to go back on CPB. It is important to be sure vents and pump suckers are off once protamine is started.

Weaning from CPB

Once the operation is completed, weaning from CPB may occur. At this point, the heart should be beating (but empty); the ventilator should be on with appropriate settings; inotropic support and pacing should be started (if necessary); and patient's temperature and blood values (hematocrit, electrolytes, pH etc.) should be optimized. To smoothly transition a patient off CPB, the pump flow is gradually decreased as the cardiac output gradually increases to full cardiac output. This is accomplished by gradually clamping the venous line, filling the heart with blood from the venous reservoir, and reducing pump flow. Once hemodynamics are adequate, and pump flow is minimal, the patient can be taken "off bypass". The venous line is clamped and the arterial pump is stopped. Residual blood volume from the ECC circuit may continue to be transfused into the patient to keep up with bleeding and to salvage blood remaining in the circuit into the patient. The venous cannula is removed and protamine can be given to reverse the heparin. Eventually the arterial cannula is removed and the patient is no longer attached to the heart lung machine. The ECC remains primed until the chest is closed in case re-initiation of CPB becomes necessary.

Deep Hypothermic Circulatory Arrest

Deep hypothermic circulatory arrest (DHCA) is a CPB technique where patients are deeply cooled and the pump flow is stopped. Cerebral metabolism decreases by 6–7% for every 1 °C decrease in temperature below 37 °C. Different organs' metabolisms are affected at different rates. The purpose of DHCA is to decrease metabolic demand so that CPB can be interrupted for 30–60 min to facilitate surgical repair. Patients are typically cooled until they reach a core temperature of 18–20 °C, the CPB pump is turned off, and the patient is exsanguinated into the CPB reservoir (Fig. 86.5a, b). For intracardiac repairs, DHCA allows for a bloodless surgical field where collateral return may be high. During arch reconstruction DHCA allows the surgeon to work on the entire transverse arch without the high-pressure arterial flow from the aortic cannula. Rimmer et al. describe the history and development of DHCA [10].

DHCA is commonly used during congenital cardiac repairs for both neuro-protection and to facilitate many surgical approaches. For paediatric cardiac surgery, which now often involves minimally invasive techniques such as partial sternotomies and mini-incisions, cannulas used for CPB can be obtrusive and make visualization extra challenging. DHCA allows removal of venous and arterial cannulas to aid in surgical visualization.

Improvements in surgical techniques have decreased the use of DHCA for routine cases. DHCA is still commonly employed during complex aortic arch repair, specifically repairs involving the transverse aortic arch. Techniques including selective cerebral perfusion (SCP) have caused a decrease in the use of DHCA, and have allowed for a lesser degree of hypothermia during aortic repairs. Increasingly more congenital repairs are being done using normothermia or mild hypothermia without an increase in sequelae. Today many operations only involve periods of lower-body circulatory arrest with the brain being continuously perfused.

Important considerations for DHCA include: target core temperature; degree of hemodilution; cooling and rewarming rates; use of intermittent re-perfusion; blood gas strategy (alpha-stat vs. pH-stat); and hyperoxia. An advantage of using a pH-stat blood gas strategy during cooling is it prevents the

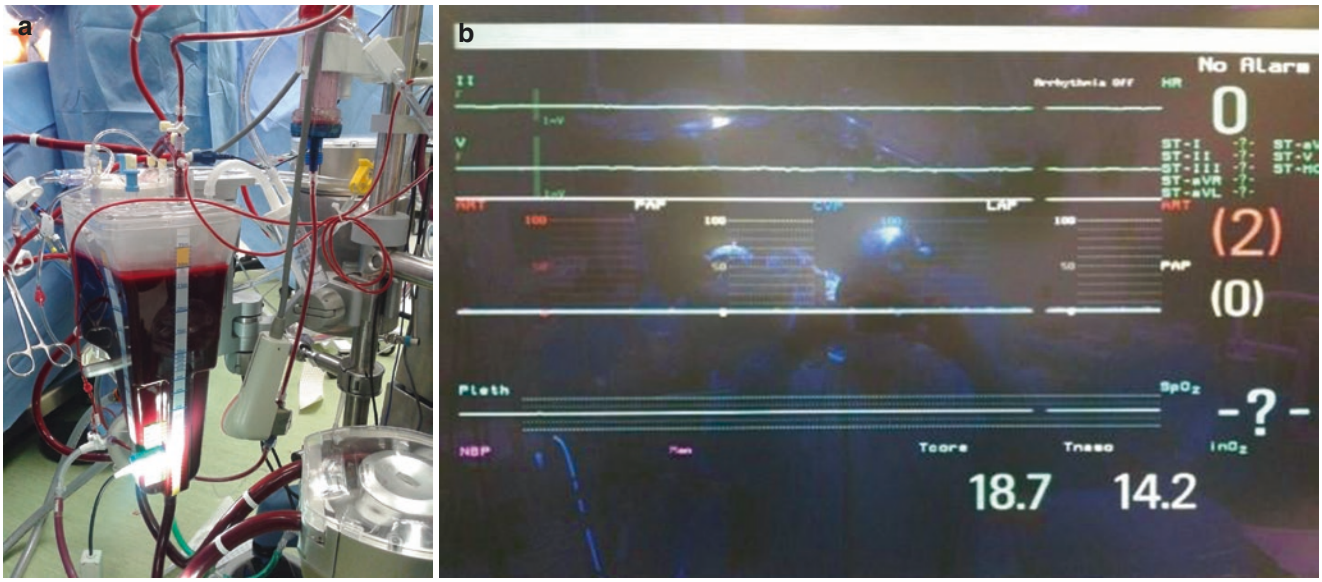

Fig. 86.5 (**a**) Venous reservoir full of blood during deep hypothermic circulatory arrest. (**b**). Hemodynamic monitor during deep hypothermic circulatory arrest. Mean arterial pressure is near zero. Core patient temperature = 18.7 °C

profound cerebral vasoconstriction that can occur at low arterial blood temperatures. This allows uniform cooling of the brain prior to circulatory arrest. The usage of cerebral monitoring is an important adjunct to DHCA.

Adult Versus Pediatric Cardiopulmonary Bypass

Pediatric and adult CPB have many similarities and differences. Differences can be described as they relate to CPB circuitry (and patient's physiologic interaction with the circuit); CPB management; and patient anatomy and physiology.

The main circuit components, configuration, and flow through a pediatric CPB circuit are similar to adult CPB. However, since the size range of patients for paediatric CPB varies from less than 2 kg to >100 kg, multiple size oxygenators and different size tubing and other components are often necessary.

CPB circuits are constructed of artificial polymers which activate many inherent biological systems designed to protect the body from foreign invaders [11]. Blood component exposure to foreign materials results in a systemic inflammatory response [12], and the severity of this response is directly correlated to the amount of foreign surface area and the length of time on CPB [13]. Current CPB circuits can be equal to or exceed the surface area of a neonate's body surface area. In contrast, an adult CPB circuit may be only 1/5th of an adult's body surface area. Therefore, pediatric patients are at higher risk of CPB sequelae.

In addition to the activation of inflammatory mediators, the coagulation system is commonly deranged due to a range of hemostatic defects resulting from cardiac surgery and CPB [14] (as well as immature hepatic function in neonates). This can be a result of the circuit's prime volume, contents, and shear stresses encountered as blood is exposed to the foreign surfaces and non-physiological pressures and pathways.

Unlike adult CPB, it is common in pediatric CPB to utilize a blood prime to avoid extreme hemodilution. Also, because of the lower blood volume in pediatric patients, small changes or shifts in blood volume that can occur during an operation, including bleeding into drapes, aspiration into a waste suction or cell saver, filling of vent tubing, or priming the cardioplegia circuit can have a significant impact on the venous reservoir level and the overall volume status of the patient/ECC circuit. By contrast, decreases of 100 ml or greater in the adult CPB venous reservoir is often insignificant.

Another key difference between adult and pediatric CPB is the impact of shunts. The three types of shunts are: circuit, anatomic, and surgically created. Shunts in the ECC divert blood through different components of the ECC and back to the reservoir (not to the patient). For pediatric CPB this shunting of flow away from the patient can be a significant portion of pump flow, often requiring a flow probe to measure actual blood flow to the patient to assure adequate perfusion. Circuit shunt flow in adult CPB is an insignificant portion of overall pump flow to the patient.

Anatomic and surgical shunts (aorto-pulmonary) are frequently encountered in the congenital heart disease population. It is vital that these are considered when planning for pediatric CPB. These shunts can affect the surgeon's surgical field; overall perfusion of the patient; cannulation strategy; myocardial protection; vascular line placement; sternotomy/entry strategy; and cooling and rewarming of the patient.

Pediatric patients require much higher flow rates than adults to meet metabolic demands. Neonates are often perfused at flow rates up to 200 ml/kg/min whereas adult flow rates may approximate 50 ml/kg/min. Thermoregulation in small children is also impaired necessitating close attention to temperature monitoring.

See Chap. 87 for differences between the adult and pediatric myocardium and cardioplegia strategies.

Modified Ultrafiltration

Modified ultrafiltration (MUF) is a technique that is used more commonly with pediatric CPB. The technique is performed immediately after weaning from CPB. MUF involves removal of ultrafiltrate from the patient while adding an equal volume of residual CPB circuit blood [15]. The purpose is to salvage residual CPB blood into the patient, remove extravascular water (edema), remove inflammatory mediators, increase hematocrit and concentrate coagulation factors. MUF originated in an era of very high ECC prime volumes and severe patient hemodilution. MUF's utilization varies in different parts of the world [16]. Today, patients have much less extravascular water, experience less hemodilution, less residual CPB volume, less inflammation, and often can be weaned with a higher hematocrit when not performing MUF. A disadvantage of MUF is that it adds to the complexity and prime volume of the CPB circuit as well as the complexity of the immediate post-CPB period. MUF can take up to 20 min and extends the patient exposure time to the CPB circuit. Some centers report no longer performing MUF or not performing MUF in smaller patients [17–19].

Conclusion

Historically pediatric CPB was a very risky undertaking. With advances in CPB techniques, circuitry and surgical techniques nearly all congenital heart defects may now be successfully repaired. Today even complex repairs are completed with very low morbidity and mortality rates. Future improvements should aim to make CPB even more biocompatible and further reduce the inflammatory response to CPB.

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