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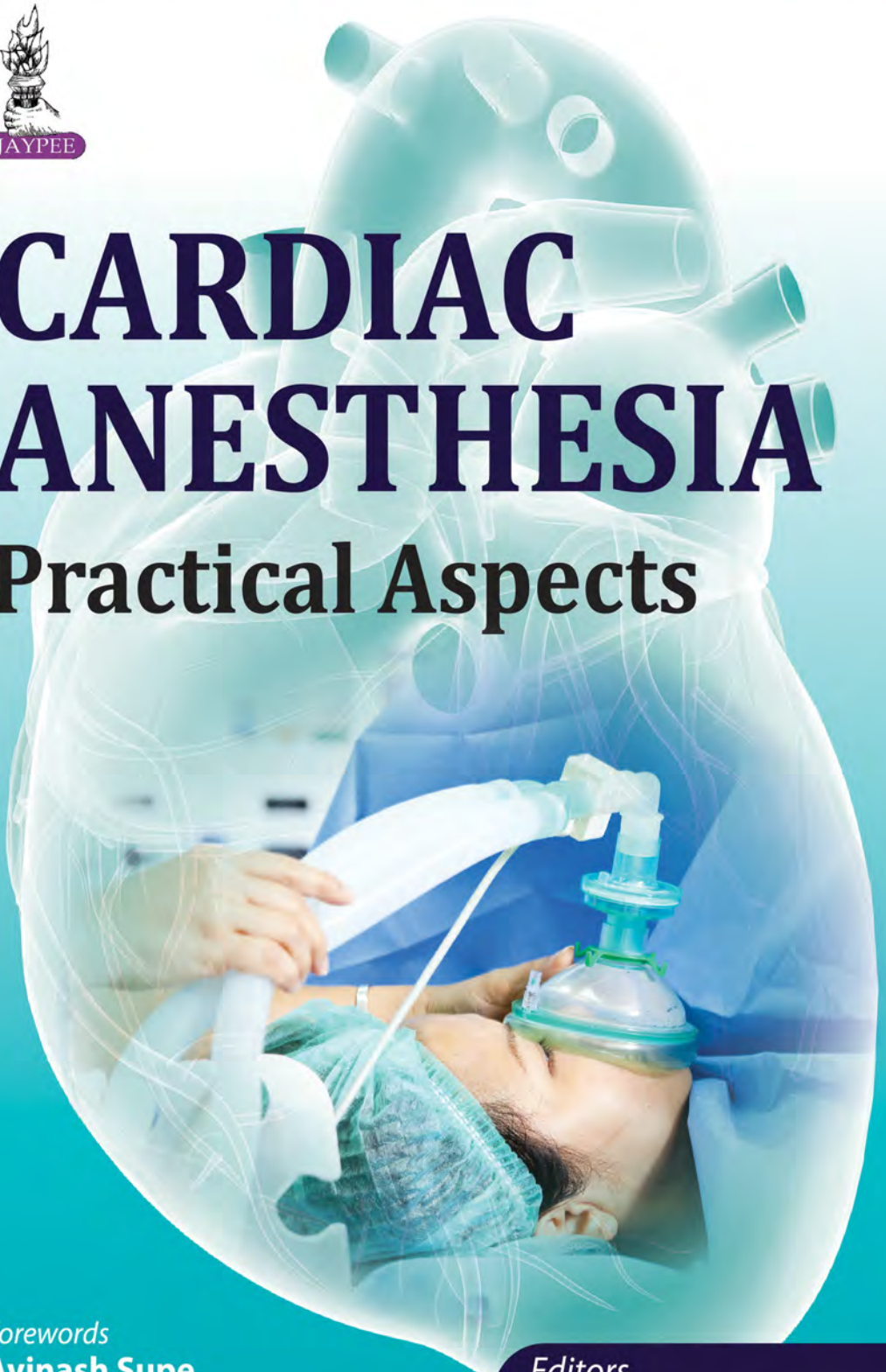
CARDIAC ANESTHESIA

Practical Aspects



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Chapter 4

Cardiopulmonary Bypass

Manjula Sudeep Sarkar, Shraddha Mathkar

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INTRODUCTION

The heart-lung machine (also called as cardiopulmonary bypass [CPB] machine) is an important surgical development of 20th century, and John Gibbon deserves the major share of credit for its success. The first successful open heart surgery using cardiopulmonary bypass was done by John Gibbon on May 6, 1953. The surgery was done for the closure of an atrial septal defect. The patient, Cecelia Bavolek, was healthy on the 50th anniversary of that operation in May 2003.

Nowadays specialized personnel, the perfusionists manage the CP bypass machine. But still, the anesthesiologist has to ensure the smooth, safe pump function, provide anesthesia and coordinate with the perfusionist during weaning off bypass.

DEFINITION

CPB machine is an artificial heart and lung; in which the blood is drained from the heart into a venous reservoir (containing a priming solution) , is oxygenated by an oxygenator at a desired temperature by heat exchanger and pumped back to the aorta. Cardioplegia chamber is incorporated into the machine to deliver cardioplegia and arrest the heart.

COMPONENTS OF CARDIOPULMONARY BYPASS (FIGS 1 TO 3)

The Pump

An ideal pump should:

- Move large amount of blood against lower pressure
- Prevent lysis of blood cells
- Elicit minimal inflammatory response
- Occupy less dead space
- Be equipped with safety alarms.

The pump should be able to generate flow by overcoming the resistance according to an equation—Blood flow rate = pressure/resistance.

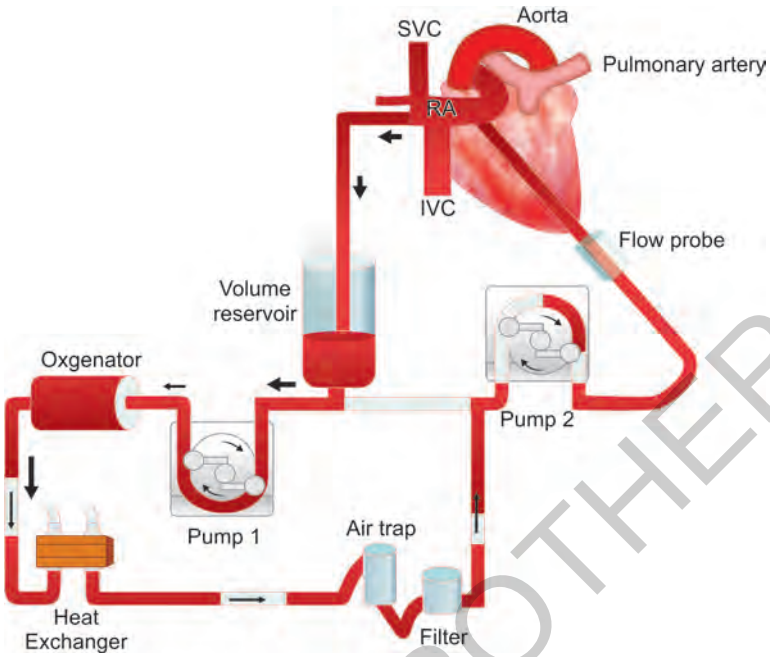

Fig. 1: Schematic diagram showing CPB components

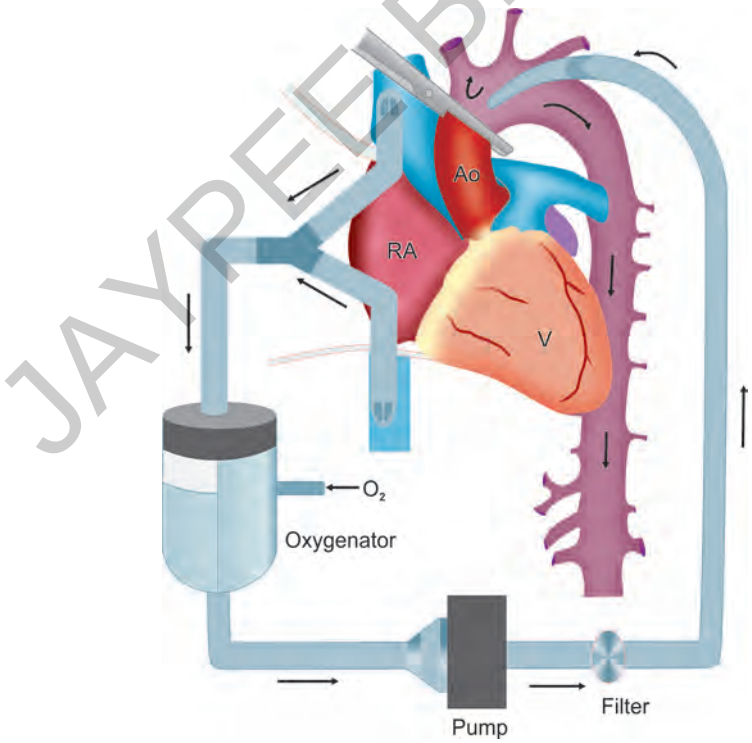

Fig. 2: Simplified diagram showing CPB components

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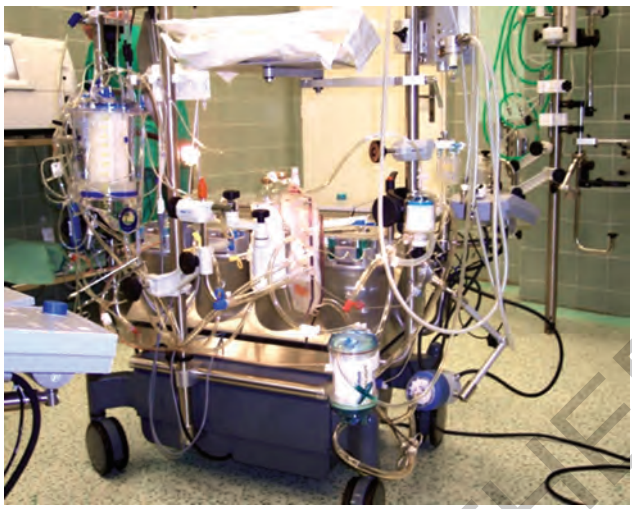

Fig. 3: CPB machine

Types of Pump

Roller pump

It consists of a tubing compressed by roller placed at 180° apart on rotating arms on a horse-shoe shaped metal backing plate (raceway). The direction of compression of the tubing by the rotating arm determines the direction of the blood flow and rollers propel the blood further (Fig. 4).

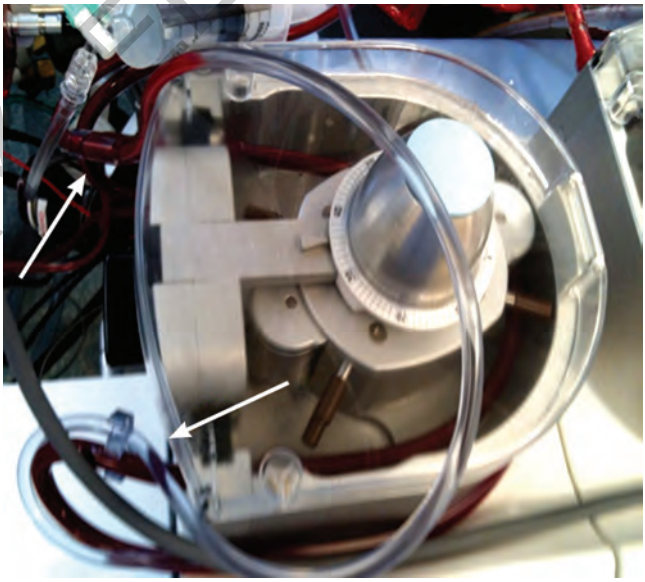

Fig. 4: Roller pump

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Centrifugal pump

It consist of a nest of smooth plastic cones or a vaned impeller located inside a plastic housing. These pumps generate a pressure differential that causes the movement of fluid when rotated rapidly. Table 1 shows the comparison of roller pump and centrifugal pump.

Table 1: Comparison of roller pump and centrifugal pump

Roller pump	***Centrifugal Pump***
Adjustment of occlusion is required	Nonocclusive
Easy to use	Needs vigilance
Not dependent on afterload of patient	Depends on afterload of patient
Flow depends on number of revolutions, length of tube and occlusion	Flow depends on pressure and resistance
Tubing may burst due to overpressure	Maximum pressure is limited here
More risk of embolization	Risk of embolization is less
More hemolysis and platelet destruction	Less hemolysis, platelet structure and function retained, less inflammation

Venous Reservoir

- The deoxygenated blood is drained into a collecting chamber called as the venous reservoir with a capacity of 1–3 lit. It is a low pressure system in which the blood can flow by virtue of gravity (siphon effect); however, kinetic assisted venous drainage and vaccum assisted venous drainage are also practised to augment the venous return (Fig. 5).

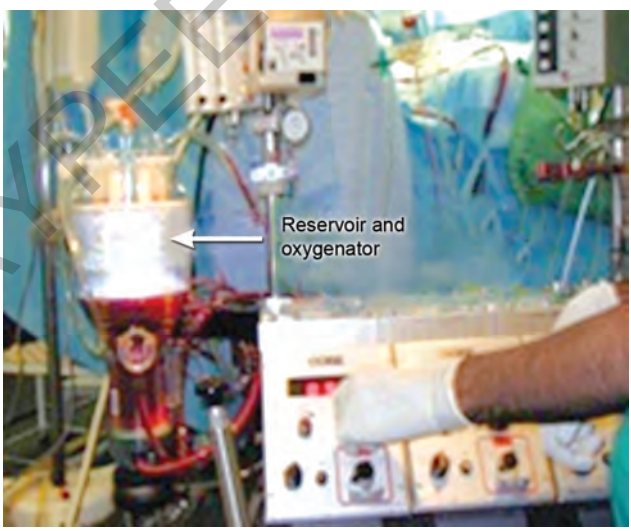

Fig. 5: Venous reservoir with oxygenator

- A reaction time of 10 seconds in case of sudden fall in venous return allows the perfusionist to avoid dry pumping and prevent massive air embolism. Defoaming agent is added to retard the formation of air bubbles.

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- Hard shell plastic open types of reservoirs are easy to operate, can store good amount of volume but the risk of air embolism is high. There is less incidence of blood cell activation, blood loss and blood administration with the closed type. Soft disposable bag adds to the cost, but sterility is better maintained and the risk of embolism is less.

Oxygenators

- It is also known as artificial lung. Its main function is to oxygenate venous blood and remove carbon dioxide. The physical process of convection, diffusion and chemical reactions that occur during gas exchange in the natural lung also apply to the artificial lung. However, gas exchange is less efficient (Fig. 6).

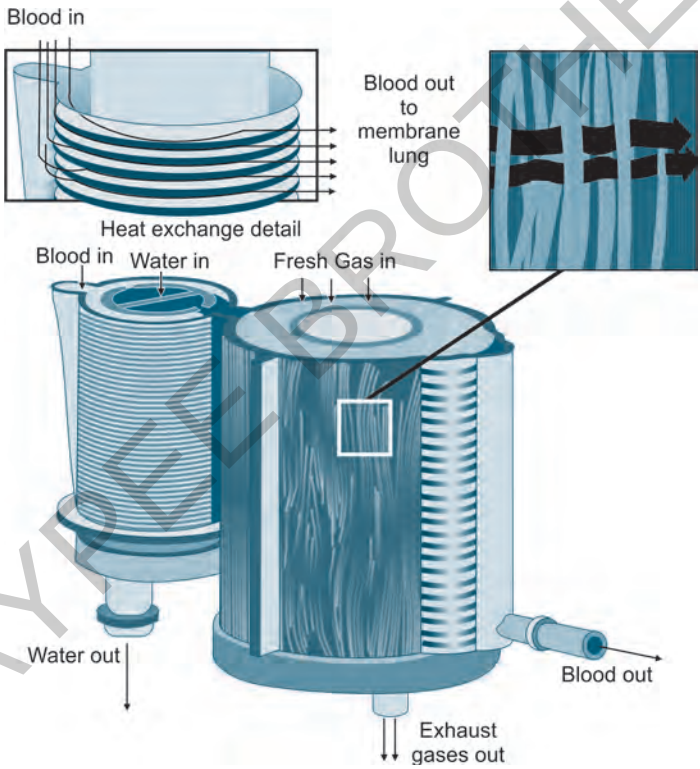

Fig. 6: Oxygenator and heat exchanger assembly

Types of Oxygenators

Bubble oxygenator

It uses a direct blood gas interface, i.e. gases are passed over the blood, time is allowed for the gas exchange and then defoaming of the oxygenated blood takes place before it is returned to the patient. The smaller the bubble size greater is the surface area available for the exchange of gases. Air embolism is a significant risk with the bubble oxygenater. Several studies have proven the efficacy of

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membrane oxygenator over bubble oxygenator in terms of lung and brain protection. Hemolysis, and a rise in haptoglobulin is also seen in certain cases.

Membrane oxygenator

The diffusion of gases takes place across the membrane, which separates the blood and the gas phases. Microporous polypropylene membranes are commonly used nowadays as they are biocompatible with good exchange capacity. These consist of microhollow fibers. Diffusion distance is approximately 200 μm in comparison with 10 μm in the human alveolus, surface area for gas exchange is 1.7–3.5 m^2 compared with 70–100 m^2 in the human lung. The gas transfer in membrane oxygenator depends upon partial pressure of venous oxygen and carbondioxide, blood flow, ventilation flow (sweep rate), and the gas composition. pO_2 is a function of FiO_2 while pCO_2 depends on sweep rate.

$$\text{Volume of gas transferred } (\alpha) = \frac{\text{Area} \times \text{diffusion constant} \times \text{partial pressure difference}}{\text{Membrane thickness}}$$

Heat Exchanger

- The temperature range on CPB is 4°C to 42°C. Its basic structure consists of two parallel tubings where the perfusate passes in one tube and the hot or cool water in the other. Temperature regulation is done by conduction method. Heat exchanger is commonly placed proximal to the oxygenator.
- Suction ports, filter, ports to inject drugs, and supply gases are also present.

Venous Cannulae

- It drains the deoxygenated blood from right atrium to venous reservoir.
- Single stage cannula: It is inserted in the right atrium, has multiple holes that drain blood from SVC, right atrium, IVC and the coronary sinus. It is performed during on pump CABG, where right atrium is not opened (Fig. 7).

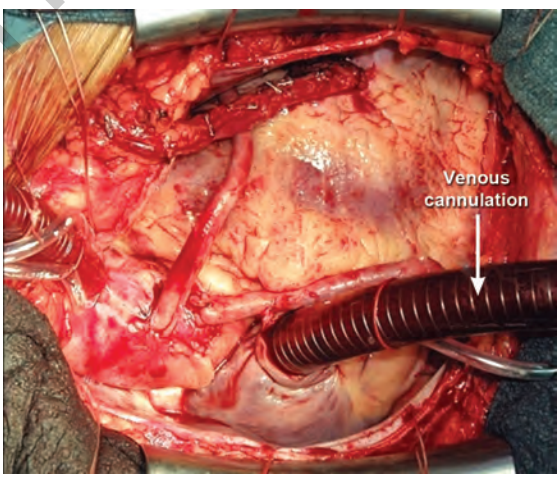

Fig. 7: Single stage venous canulation in situ

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- Two stage cannula: The superior vena cava and the inferior vena cava are cannulated separately. Both vena cavae are looped and snugged to divert the blood into the venous reservoir. It is mandatory in procedures where the right atrial access is essential, e.g. ASD repair. The coronary sinus is not drained; so an extra vent is needed to drain it.
- Femoral vein cannulation is done when patient needs to be put on CPB prior to sternotomy, e.g. redo surgery, or aortic aneurysm due to fear of sudden catastrophic hemorrhage. The cannula is long and has multiple holes, however, the venous drainage may not be complete. TEE helps in the assessment of proper placement.

It is important to check with the perfusionist if the venous return is appropriate because inadequate drainage needs readjustment of the cannulae position.

Arterial Cannulation

- Arterial cannulation is the first thing the cardiac surgeon does after heparinization when target ACT (more than 400 seconds) is achieved.
- The aortic cannulation is done first to provide volume resuscitation if hypotension occurs due to major bleeding.
- The systolic blood pressure is generally maintained between 90–100 mm Hg during cannulation to avoid aortic dissection and this is achieved by additional doses of anesthetic agent or a vasodilator.
- Very low blood pressure can cause injury to the posterior wall of an aorta during cannulation due to relatively collapsed aorta. Potential complications associated with the aortic cannulation include embolization of atheromatous debris or air, inadvertent cannulation of aortic arch vessels and aortic dissection. TEE easily diagnoses the calcification and dissection of the ascending aorta. After aortic cannulation the aortic line is deaired prior to unclamping and starting the pump.
- Peripheral cannulation: Femoral arterial cannulation is done along with femoral vein in peripheral bypass. Even axillary artery can be cannulated.

Connecting Tubings

Disposable polyvinyl chloride tubings of various diameters are used to set up the pump connection with the patient.

Diameter of tubing	Volume of blood
3/6 inch	7 mL
1/4 inch	13 mL
3/8 inch	27 mL
1/2 inch	54 mL

CONDUCT OF CARDIOPULMONARY BYPASS

Setting up of the CPB Machine

Priming

The deairing of the CPB circuit is done by priming volume. The priming solution is selected according to the body surface area, hematocrit, and the volume required.

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- Cardiac index of 70 kg man with normal metabolism at 37°C is 2.4 L/m^2/min; 2.1 L/m^2/min at 32°C, 1.8 L/m^2/min at 28°C, 1.2 L/m^2/min at 25°C, 0.6 L/m^2/min at 15°C.
- Blood flow rate = Body surface area × cardiac index
- Target hematocrit = 21-24% inadults and 28-30 % in children is accepted
- Target hematocrit on CPB = $\frac{\text{Patients blood volume} \times \text{Hct}}{\text{Total circulating volume of pump}}$
- Total circulating volume (TCV) = Patient blood volume + priming volume + cardioplegia solution volume
- Blood required on prime = $\frac{(\text{Target Hct} \times \text{TCV}) - (\text{Hct} \times \text{PBV})}{\text{Hct of donor blood}}$

Priming solution

- An ideal priming solution should be iso-osmolar to the plasma with similar oncotic pressure, should be easily excreted, should result in less hemolysis and not produce any cellular edema in the post-bypass period.
- Priming results in hemodilution which improves the microcirculation, and improves oxygen delivery and perfusion even in the setting of hypothermia. Very high pressures would be needed to propel the viscous blood because hypothermia increases the viscosity of blood. But the perfusion with low and nonpulsatile flow is possible due to priming induced hemodilution. However, excessive hemodilution causes edema due to extravasation of fluids into the third compartment.
- Crystalloids, colloids, albumin, blood and plasma are popular additives used for priming.
- Balanced salt solution is a fluid of choice for priming. Crystalloid solutions are also considerably cheaper than colloids and are free of the risk of anaphylactoid reactions, but their main drawback is the inability to maintain the oncotic pressure leading to formation of interstitial and intracellular edema. Improved postoperative pulmonary and renal function using crystalloid priming solution alone has been observed in several studies.
- Colloid: Colloids like gelatins, hydroxy ethyl starch (pentastarch, hetastarch), voluven (130/0.4), and albumin are used. The advantage of colloid is maintenance of oncotic pressure; but additional adverse effects on blood coagulation and the occasional occurrence of allergic reactions have raised questions about their suitability as priming fluids.
- Blood and Blood products: Homologous blood use continues to be the gold standard for priming in infants and neonates despite exposure of the patient to potential cellular and humoral antigens.

Low hematocrit (Hct < 20) during cardiopulmonary bypass (CPB) is associated with higher mortality and other adverse outcomes. Low Hct is

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encountered in patients with small body size and in females. Hence, an aggressive approach in the care of these patients is needed. It is prevented by the use of a low-prime CPB circuit (LP) for all adult patients with a body surface area (BSA) <1.7 m^2 and use of autologous circuit priming (AP), in addition to the low-circuit volume in some patients.

Setting the Occlusion of the Pump

To ensure accurate delivery of systemic blood flow, an outflow tube is held at 30–40 cm height and occluded to hold the fluid in place and then a gradual drop is allowed at the rate of one inch/minute.

During induction of anesthesia the CPB machine should be ready in case of any emergency situation. Along with resuscitation, the patient can be heparinized and immediately put on bypass.

- Post-induction, adequate depth of anesthesia is maintained by mounting inhalational agents on bypass. Infusion of anesthetic agents can be used.
- During sternotomy, patient is disconnected from the ventilator or switched over to low tidal volume ventilation to prevent lung injury.
- After 3 minutes of heparinization ACT is done. During this period surgeon checks the lines for air bubbles.
- After adequate anticoagulation the internal suckers are used. Before the aorta is cannulated the systemic pressure is lowered to 100 systolic mm Hg. The line pressure is checked by the perfusionist to confirm lack of resistance. Any resistance raises the suspicion of aortic dissection or cannula malposition. Aortic cannula can be malpositioned in such a way that the jet is directed primarily into the innominate artery, the left common carotid artery (rare) or the left subclavian artery (rare). The latter two can occur with the use of long arch-type cannulae. 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*. However, transcranial Doppler, and more commonly available cerebral oximetry, is the monitor of choice to detect malperfusion secondary to cannula.
- As per the requirement, a single caval or bicaval cannulation is done. Adequate venous return is checked by the perfusionist, which should generate blood flow rate of 2.4 L/min/m^2 at a line pressure of 150-200 mm Hg. Poor venous return can occur due to air lock, which is corrected by removal of air. Raising the height of the table aids venous drainage by gravity.
- Gradually the venous blood is complelety drained. Ventilation is stopped once the patient is on complete bypass (perfusionist informs full flows). Normothermic or hypothermic perfusion is maintained.
- Cardioplegia cannula with a vent is inserted in between aortic root and the cross clamp. Regardless of the cannulation technique selected, some blood

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returns to the left ventricle via Thebasian veins, bronchial veins, shunts, aortic insufficiency etc. An LV vent is required in order to prevent warming and distension of LV. Additionally, the bicaval cannulation technique requires the use of a second vent to capture coronary sinus blood that bypasses the IVC and SVC cannulae.

- Aorta is cross clamped before giving cardioplegia. The duration of cross clamp is noted.
- All standard monitoring is continued, ET tube is disconnected, and IV fluids and infusions are stopped.

Besides standard monitoring, urine output and temperature at two different sites are meticulously noted.

CONCERNS DURING BYPASS

Temperature

Hypothermic CPB

The temperature is maintained below 34°C (34–28°C). The temperature is gradually reduced. The advantages of hypothermia are:

- It reduces the oxygen requirement by decreasing the metabolic rate; cerebral metabolic rate is decreased 6-7% per degree decline in the temperature.
- Flow rate of pump can be lowered in hypothermia due to decreased requirement.
- A low flow rate protects the cells from trauma.
- Better organ protection is seen with hypothermia, especially brain and kidney.

Ability of the hypothermic kidney to handle glucose is impaired, and glucose often appears in the urine. Hemodilution in combination with hypothermic CPB improves renal blood flow and protects the integrity of the renal tubules postoperatively.

Hypothermia causes adverse effects on enzyme cascade, delays repair, increases intracellular swelling due to sodium absorption, causes arrythmia, impairs coronary circulation, inhibits sarcoplasmic reticulum and calcium accumulation.

Normothermic CPB

The temperature is maintained above 34°C. It ensures adequate perfusion, as demonstrated by normal renal function, normal lactates, normal pH, and the high mixed venous saturation during bypass. Normothermic bypass does not precipitate volume overload and high doses of adrenergic drugs are not required during and after CPB. But, continuous cardioplegia delivery is required that keeps the surgical site flooded and causes technical difficulty.

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Normothermic bypass narrows the gap between oxygen demand (VO_2) and oxygen delivery (DO_2).

Current evidence suggests that maintaining normothermia during cardiopulmonary bypass in adult cardiac surgery is as safe as hypothermic surgery, and associated with a reduced risk of allogeneic blood transfusion.

Glucose

Hyperglycemia increases the risk of morbidity and mortality in cardiac surgery patients. A tight glucose control is known to reduce multiorgan complications. It lowers the incidence of wound infections, reduces hospital stay and enhances long-term survival.

Glycemic Control in Patients without Diabetes During CPB

Intraoperative glycemic control using intravenous insulin infusions is not necessary in patients without diabetes provided glucose values remain < 180 mg/dL. All patients should be given continuous infusion rather than bolus doses (Level A evidence). Blood glucose level should be maintained below 180 mg/dL for at least 24 hour postoperatively (Level B evidence). The intermittent rise in blood glucose can be treated with bolus dose of insulin, if high dose infusion is needed.

Patient with DM

Patients taking medium to long-acting insulin should stop insulin after dinner the night prior to surgery (level B). Insulin therapy should be initiated prior to elective surgery (level C) and blood glucose should be maintained below 180 mg/dL (level B) while the glycosylated Hb level should be ≤7%.

Intraoperative elevated glucose levels must be corrected by insulin infusion and the infusion should be continued in the postoperative period. Glucose monitoring should be done every 30–60 minutes during tight control regimen.

pH

The pH-stat and alpha-stat refer to the acid-base management strategies at different body temperatures during CPB. The solubility of CO_2 in the blood increases as the body temperature decreases.

pH Stat

pH is kept constant. Alkalosis occurs as the temperature decreases and it is corrected to desired pH by adding CO_2 to the pump. CO_2 causes cerebral vasodilation and increases blood supply to the brain. Faster cooling can be achieved with this technique, especially in DHCA. The incidence of air embolism also increases. Blood flow becomes pressure dependant as the

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cerebral autoregulation is lost. Hoover et al. suggested that in adults with high risk of impaired cerebral blood flow (i.e. aged >70 years old, diabetic, prior stroke, uncontrolled hypertension) pH-stat maintains higher oxygen tension and saturation during CPB.

The α Stat

The amino acid histidine (containing an alpha-imidazole ring with many negatively charged moieties) is the most important buffer. The "alpha" in the term alpha-stat, which denotes uncorrected blood gas measurement, refers to the α-imidazole ring of histidine. Alpha-stat strategy indicates a pH management strategy in which the pH is not corrected and the blood carbon dioxide is allowed to follow its thermodynamically mediated dissociation changes with hypothermia, which results in a decreased hydrogen ion concentration (decreased dissociation) and increased blood pH (alkaline shift). This means in clinical practice no carbon dioxide is added to the oxygenator gas to compensate for these changes in blood pH during cooling. Alpha-stat blood gas management maintains autoregulation, and limits cerebral microemboli load by control of cerebral blood flow and demand. The cellular transmembrane pH gradient and protein function is also maintained. Disadvantages of alpha-stat include less efficiency in homogeneous cooling.

Perfusion Pressure

The mean arterial pressure maintained during bypass is 60–80 mm Hg. The most important function of cardiopulmonary bypass is maintaining perfusion of the vital organs. Autoregulation of most organs is preserved above 50–60 mm Hg. Low-risk patients tolerate mean arterial blood pressures of 50–60 mm Hg without apparent complications, although limited data suggest that higher-risk patients (CVA, chronic hypertension, severe aartherosclerotic disease) may benefit from mean arterial blood pressures >70 mm Hg. Advantages of high MAP include better perfusion, opening up of collaterals, and high pump flow rate. Excessive arterial pressure increases noncoronary collateral flow to the heart during aortic cross-clamping (hence "washing out" myocardial protection with cardioplegia) and bronchial flow to the lungs (increases blood return to left heart) and places strain on arterial clamps and suture lines. With a lower MAP there is less trauma to cell, lower pump flow less blood in surgical field, enhanced cardioprotection and less embolic load to CNS.

Adequate MAP is achieved by maintaining flow rate on the pump which is equal to cardiac index in normothermic anesthetized person at normal hematocrit. Proposed advantages of reduced flow rates include less hypertension during hypothermic bypass (due to increased blood viscosity and temperature-induced increases in systemic vascular resistance), improved intracardiac exposure due to less bronchial blood flow returning to the left heart, and reduced warming of the myocardium via noncoronary collateral vessel. During CPB, pump flow and pressure are related through overall

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