Cardiopulmonary Bypass Strategies in Aortic Surgery: Partial Bypass, Cerebral Perfusion and Rewarming

Objectives:

At the conclusion of the lecture the participant will understand:

1. Techniques of circulatory support during aortic surgery
2. Methods of CNS protection employed during aortic surgery
3. Clinical practical tips useful during aortic surgery

Introduction of new techniques of perfusion as well as a better understanding of the pathophysiology of ischemic injury of central organs during aortic surgery has improved overall outcomes. However, despite these significant advances in aortic surgery, substantial neurologic morbidity still occurs especially in long cases of aortic arch repair involving deep hypothermic circulatory arrest as well as in the repair of the descending thoraco-abdominal aorta. Studies have shown that several modifiable factors could impact the neurobehavioral outcome.

Partial Bypass

Partial bypass is employed in descending thoracic aortic surgery in order to provide perfusion to distal organs (spinal cord and visceral organs) while the aorta is cross-clamped. The main use of partial bypass is aimed to decrease ischemic time especially to the spinal cord thereby minimizing the risk of neurologic complications (paraplegia). Partial bypass is characterized by the fact that a part of the stroke volume is deviated to the descending aorta. However, during partial bypass pulmonary perfusion is present thus the integrity of the cardiac and respiratory functions of the patient are maintained. There are two types of partial bypass: left heart bypass and femoral artery-femoral vein bypass.

Left heart bypass is represented by the left atrial to femoral artery bypass. The bypass circuit is composed of an inflow and outflow cannula and a centrifugal pump connected by circuit tubing. The inflow cannula is positioned in the left atrium via the superior or inferior left pulmonary veins or the left atrial appendage. The outflow cannula is positioned in the femoral artery (usually left) or, if this is severely diseased, directly in the descending aorta. The proximal aortic cross-clamp is placed distal to the left carotid artery. Usually the left subclavian artery will be below the proximal aortic cross-clamp and thus not be perfused. The distal aortic cross-clamp is usually placed on the thoracic aorta between T4 and T7, depending on the anatomy of the diseased aorta. In cases of extensive thoraco-abdominal aneurysms the distal cross-clamp can be placed lower on the abdominal aorta. In such situations, selective visceral perfusion can be performed by attaching perfusion catheters connected to the Y limb of the return line to the ostia of the celiac, superior mesenteric and renal arteries. Because this circuit does not utilize a membrane oxygenator less heparin is necessary (usually 1mg/kg).

In left heart bypass, part of the blood volume of the left atrium is drained to a centrifugal pump (without oxygenator or heat exchanger) and infused into the descending aorta or femoral artery. The rest of the blood volume of the left atrium represents the stroke volume and is pumped by
the heart into the ascending aorta and aortic arch proximal to the aortic cross-clamp. This blood will perfuse the coronaries and the head and neck vessels (innominate artery and left carotid artery).

Monitoring of the systemic arterial pressure should be performed via an arterial catheter placed in the right radial artery. During surgery, efforts should be made to maintain normal proximal systemic pressures. This goal can be achieved by replacing the lost blood volume and titrating various vasoactive medications. Studies have shown that pressures in the descending aorta should be maintained at means of 60-70 mmHg in order to provide adequate perfusion to the spinal cord. However, some surgeons elect not to perfuse according to these pressures but rather to establish a constant flow rate depending on the patient size. It is crucial to understand that proximal aortic pressures are more important to be maintained normal as compared to distal aortic pressures. Thus, if during surgery, major blood loss produces significant proximal hypotension the flow rate in the distal aorta can be decreased. Therefore, less blood will be drained from the left atrium allowing for an increase in stroke volume.

When left heart bypass is not feasible then femoral artery-femoral vein bypass can be used. In this type of partial bypass, the circuit is composed of a venous and an arterial cannula. Since blood is drained from the right atrium, the femoral-femoral bypass requires an oxygenator. The venous cannula is inserted into the femoral vein and advanced over a guide wire to the level of the right atrium. Its position is checked with transesophageal echocardiography. The arterial cannula is placed in the femoral artery. A part of the blood volume of the right atrium is drained, oxygenated via the membrane oxygenator and infused into the femoral artery. This circuit requires full heparinization of the patient. The functioning principal of the femoral-femoral bypass is similar to the one of left heart bypass.

**Cerebral Perfusion during Deep Hypothermic Cardiac Arrest**

Issues pertaining to cerebral perfusion arise when patients undergo ascending aorta and aortic arch operations under deep hypothermic circulatory arrest (DHCA). Under circulatory arrest the brain is depleted of metabolic material and thus can incur significant injury. In order to decrease the metabolic demand of the brain deep hypothermia is employed. It is estimated that at 25˚C the cerebral metabolic rate is 37% of baseline and at 15˚C cerebral metabolism is decreased to 16% of baseline. However, significant hypothermia may also be detrimental to the brain by producing degradation of proteins and creation of intracellular ice crystals. Thus there is a limit to the degree of hypothermia which can be used. Currently there are four methods used to provide neuroprotection during circulatory arrest: DHCA alone, DHCA and retrograde cerebral perfusion (RCP), DHCA and antegrade cerebral perfusion (ACP) and a combination of all three methods.

RCP requires the interruption of antegrade flow, followed by perfusion through the superior vena cava cannula which is snared below the azygos vein. Pressurization of the venous system to 20 mmHg generates retrograde flow to the brain and upper extremities via the right jugular vein, innominate vein, right subclavian vein and anterior spinal plexus (figure 2). The retrograde blood flow in the veins eventually passes through the capillary bed into the cerebral arterial system and is drained in the open arch. For the system to work adequately it is imperative that the arch be opened to atmospheric pressure so that a pressure gradient is formed between the jugular veins.
and the arch vessels. Any amount of positive pressure in the cerebral arterial system will impede retrograde flow and may cause serious cerebral edema. For this reason the RCP may be less effective and potentially dangerous for patients with significant occlusive disease in the carotid system.

ACP appears to be more physiologic than the RCP and than no flow state during DHCA. The cannulas are placed in the carotid circulation (innominate artery and left carotid artery) (figure 3). This technique requires cannula repositioning when the head vessels are reimplanted in the graft. Thus another cannulation technique has evolved, namely via the right axillary or subclavian artery. It is important to remember that this cannulation site may provide insufficient ACP in patients with an incomplete circle of Willis. However, a retrospective study has suggested that in situations where DHCA is prolonged (>40 min), employing ACP prevents cerebral injury and potentially reduces complications and hospital stay. Various parameters such as temperature and hematocrit of perfusate or perfusion pressure utilized during ACP may further alter outcomes. A research group from the Mount Sinai School of Medicine has analyzed all these variables using a pig model. Their research has suggested that maintaining the perfusate temperature at 10-15°C versus 20-25°C provides better cerebral protection. The same group established that maintaining the cerebral perfusion pressure at 50 mmHg improves neuroprotection as compared to higher pressures. At the same time, maintaining the hematocrit of the perfusate at 30% versus 21% results in significantly superior functional outcomes implying that a higher cerebral blood flow with a lower hematocrit may be injurious possibly due to an increased embolic load.

No randomized control trials have been conducted to identify which technique provides better outcomes. The neurologic outcomes of ascending aorta and arch surgery are dependent on other factors as well such as: complexity of repair, amount of atheromatous disease in the arch and carotid circulation, surgical experience. There are pros and cons for all techniques.

**DHCA pros:** Provides a bloodless operative field  
No intruding cannulas in the operative field  
**DHCA cons:** May offer insufficient neuroprotection when extended more than 40 minutes

**RCP pros:** Provides partial metabolic substrate to the brain during DHCA  
Prevents embolic events by flushing air and debris from the arterial circulation  
Enhances cerebral hypothermia  
**RCP cons:** Potential for cerebral edema  
Operative field is flooded with blood  
Cannulas are present in the operative field

**ACP pros:** A more physiologic and effective state of cerebral perfusion during DHCA  
**ACP cons:** Higher risk of embolic events  
Complicated cannulation technique  
Cannulas present in the operative field which often require repositioning

**Rewarming**
It is of utmost importance to appropriately conduct the rewarming phase after DHCA. It is well known that hyperthermia worsens outcomes in patients after ischemic strokes. Hyperthermia has deleterious effects on the brain via different mechanisms: delayed neuronal metabolic activity, increased release of excitotoxic neurotransmitters, oxygen free radical production, intracellular acidosis, increased blood-brain barrier permeability. Hyperthermia also modulates the protein kinase activity and destabilizes the cytoskeleton. All these mechanisms ultimately lead to neuronal apoptosis.

In this context, three important questions arise regarding the rewarming phase after DHCA:
1. Which temperature monitoring site best reflects the cerebral temperature?
2. How fast should rewarming be conducted?
3. At what temperature should rewarming cease?

1. Which temperature monitoring site best reflects the cerebral temperature?
A good approximation of cerebral temperature is offered by placing a temperature probe in the jugular venous bulb (JVB). However, this is an invasive procedure and can not be done on a regular basis. Nussmeier et al, demonstrated that esophageal and nasopharyngeal temperatures monitoring underestimate the JVB temperature by 1-2˚C during rewarming and that rectal and bladder temperature monitoring underestimate the JVB temperature by 4˚C during rewarming. The study showed that a better indicator of JVB temperature was the temperature of blood in the arterial line leading to the aortic cannula.

2. How fast should rewarming be conducted?
The consensus of most clinicians is that, due to the detrimental effects of cerebral hyperthermia, rewarming should be conducted slowly, with the temperature of the CPB perfusate kept at or below 37˚C. It is best if aggressive rewarming usually employed in an attempt to circumvent the typical “after drop” of temperature at discontinuation of CPB is avoided.

3. At what temperature should rewarming cease?
The optimal temperature for separation from CPB appears to be 36.5˚C measured at the nasopharyngeal site. For patients at high risk for stroke this value may be slightly lower but the risks of postoperative hypothermia (increased bleeding, shivering and increased oxygen consumption) should be weighed against the benefits.

References:
Figure 1. Left atrial to femoral artery bypass circuit (courtesy of Dr. J. Elefteriades)
Figure 2. Retrograde cerebral perfusion circuit (courtesy of Dr. J Elefteriades)
Figure 3. Antegrade cerebral perfusion circuit (courtesy of Dr. J. Elefteriades)