Cardiopulmonary Considerations for Cardiac Surgery in Low and Middle Income Countries

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Abstract

To accomplish a successful cardiac surgery, cardiopulmonary bypass (CPB) is often utilized to give the surgeon a bloodless field while keeping the patient hemodynamically stable. The perfusionist is responsible for running the heart-lung machine and other devices such as: cell savers, anticoagulation and blood gas management or mechanical circulatory support. Critical times during CPB include going on, cross clamp on and off, cardioplegia delivery, and termination. Troubleshooting is a component that is often overlooked but can be detrimental to delivering the best patient care. To help eliminate these errors, checklists and protocols are put into place to make sure standardized measures are taken pre/intra/post CPB. Safety techniques like deep hypothermic circulatory arrest is performed for certain cardiac surgeries to prevent end organ damage. Perfusion technology is constantly evolving; however, this chapter looks to help build a solid foundation for understanding CPB and supporting devices.

Keywords

Cardiopulmonary bypass · Anticoagulation · Mechanical circulatory support · Cardiac surgery, hypothermia · Heart-lung machine

23.1 Brief History of CPB

The development of cardiopulmonary bypass was a major development in cardiac surgery and clinical medicine. Cardiopulmonary bypass allows a surgeon to correct cardiac defects while bypassing the heart and lungs. A machine takes over their function, oxygenating the blood and pumping the oxygenated blood throughout the body [1].

John Gibbon first became interested in the concept of taking deoxygenated blood from a patient with a pulmonary embolus and injecting oxygenated blood to help survival in 1931. Through the next two decades, he worked on developing a heart-lung machine [1]. Based on Gibbon's theories, several people tried to develop their own heart-lung machine and operate on patients with cardiac defects throughout the 1950s [1]. This machine would have to anti-coagulate the blood and reverse it, pump blood without destroying the red blood cells and oxygenate the

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J. Kpodonu (ed.), *Global Cardiac Surgery Capacity Development in Low and Middle Income Countries*, Sustainable Development Goals Series,
https://doi.org/10.1007/978-3-030-83864-5_23

blood and remove carbon dioxide all while the heart and lungs were at rest [2]. For anticoagulation, Gibbon used heparin which was discovered in 1916 and went into clinical trials in the 1930s and heparin could be reversed with protamine [1]. For the pump, there were already pumps in the dairy and food industry that could be adapted [2]. For oxygenation, directly introducing oxygen caused issues like air, thrombosis and hemolysis. To resolve these issues, Gibbon introduced oxygen with a series of roller pumps which controlled the rate of delivery [3]. Gibbon successfully operated on a patient in 1953 to repair an ASD using his heart-lung machine design. However, his next couple of patients expired making the development of the technology an arduous task for which he took a break to further develop and improve his heart-lung machine [1].

Around the same time in the 1950s, five medical centers were involved in trying to develop a heart-lung machine [2]. Dr. C. Walton Lillehei and Dr. John W. Kirklin created two separate cardiac surgery programs partially based off of Gibbon's research. Lillehei operated on 45 children with 28 surviving over a two-year period and Kirklin operated on 8 children with 50% survival rate [3]. Research during this time continued to develop different and improving oxygenators, pumps and heat exchangers to improve cardiac surgery outcomes. In 1966, Dr. Richard DeWall developed a hard-shell bubble oxygenator with an integrated heat exchanger that was disposable which set the standard for years to come in cardiac surgery [1]. As a result of all this research and evolving technology, approximately 500,000 cardiac surgeries are performed each year with mortalities as low as 1% for some surgical types.

23.2 CPB Hardware Including Oxygenator and Pump

For cardiac surgery to be effective, blood must be diverted from the heart and the lungs and be returned to the systemic arterial system. To achieve this, a cardiopulmonary bypass machine is used to replace the function of both the heart and lungs during the operative procedure. Many different types of hardware are used to achieve this goal.

Cannulas

Cannulas are placed in the heart to direct blood towards the cardiopulmonary bypass machine and also to return oxygenated blood back to the patient. There are many different size cannulas, each having their own configuration. Venous cannulas are typically either single stage or two stage [4]. Two stage cannulas sit in the RA and the IVC and often times provide superior drainage over a single stage cannula. Venous cannulas can also be angled or straight and most are made of wire reinforced plastic to prevent kinking.

Arterial cannulas also come in many different types and sizes and are made to be inserted into the ascending aorta, axillary artery or femoral artery [4]. The arterial cannula returns blood that has been oxygenated by the cardiopulmonary bypass machine back to the patient's arterial system. Arterial cannulas provide the highest resistance within the cardiopulmonary bypass circuit therefore, arterial line pressures are typically measured to reduce hemolysis.

Blood pumps

Blood pumps within the cardiopulmonary bypass circuit are either positive displacement pumps (roller) or rotary pumps (centrifugal) [4]. Roller pumps work via positive displacement and their output is determined by the size of the raceway and the size of the tubing. Tubing is compressed within a raceway by the roller pump creating both positive pressure to propel the blood forward and negative pressure used for suction. Roller pumps can cause high shear stress to blood resulting in hemolysis and activation of platelets and white blood cells [4].

Centrifugal pumps consist of a disposable pump that is attached magnetically to a motor. These pumps offer very small priming volume and cause less hemolysis due to the lack of shear stress. Unlike roller pumps, centrifugal pumps

are non-occlusive and are afterload dependent. However, centrifugal pumps are more expensive than roller pumps. Centrifugal pumps also require a blood flow meter to provide an accurate blood flow reading.

Oxygenators

An integral part of the cardiopulmonary bypass machine is the oxygenator which replaces the function of the lungs during the operation. CO_2 is removed from venous blood and also an increase in PO_2. Currently oxygenators used for cardiac surgery are hollow fiber membrane oxygenators. The fibers of the cardiopulmonary bypass oxygenator are made from polypropylene [4]. With hollow fiber oxygenators, blood flows around the fiber bundle and oxygen flows through the fibers of the oxygenator. These oxygenators are typically used for a time period of hours (less than 6), sufficient time for the cardiac operation to be completed and to reduce the incidence of plasma leakage. For longer term oxygenation, like extracorporeal membrane oxygenation (ecmo), oxygenators are made from polymethylpentene. These fibers resist plasma leakage and therefore are a better option longer periods of support.

23.3 Hemodilution and Priming Solutions

Historically, studies have shown that hemodilution is effective in reducing morbidity associated with CPB. The type of priming solution and volume of prime vary between institutions. Broadly they are classified as

- Crystalloid solutions (Lactated Ringers, Plasmalyte, Normal Saline)
- Colloid solutions (Albumin, Plasma)

Modern priming solutions have osmolarity and electrolyte content which are very similar to plasma. Most commonly used priming solutions are crystalloid, although some practices, add a colloid to their prime for longer pump runs to reduce excessive edema [1]. Some institutions have a standard priming volume for all adult patients whereas, others vary their priming volume based on patient weight or body surface area (BSA). The degree of hemodilution can be determined based on patient weight, preoperative hematocrit (HCT), amount of fluid administered pre CPB and the priming volume.

$$\text{Predicted Hct on } CPB = \frac{\text{Patient RBC Volume before CPB}}{\text{Patient estimated blood volume} + CPB \text{ volume} + pre\,CPB\,IV \text{ fluid volume}}$$

- I unit of RBC/whole blood = 150 ml RBC volume
- Estimated blood volume = patient weight*0.08 for infants, 0.075 for children and men, 0.07 for women.

Hemodilution has a positive effect on perfusion by reducing blood viscosity and improving regional blood flow thereby increasing oxygen delivery to the tissues. Most centers try to achieve a HCT <30% on CPB to ensure end organ perfusion. This can be achieved with a priming volume of 1000 ml-1500 ml in adults. Patients with a high pre-bypass Hct or higher blood volume may require pre-pump phlebotomy or additional dilution on CPB [1]. Conversely, a technique known as retrograde autologous priming (RAP) is employed in some centers to reduce hemodilution. Hypothermia also plays a role in determining the level of hemodilution on CPB. Studies show that HCT <20% may be associated with abnormal distribution of flow to organs.

Hemodilution can lead to a decrease in the plasma colloid oncotic pressure due to dilution of plasma proteins. Some institutions use a colloid solution (like 5% or 25% albumin) in the prime to attenuate these changes. Studies have shown no significant differences between the two groups post operatively [1].

Additionally, following components may be added to the prime depending on the institution [1].

- Heparin 10–25 mg—to provide additional safety to systemic heparinization
- Mannitol 25–50 mg—helps prevent tissue edema and induces osmotic diuresis

- Corticosteroids-prevents activation of inflammatory process during CPB
- Calcium 200 mg/L of prime-used in pediatric patients to prevent chelation of circulating calcium if citrated blood is added to prime.

23.4 Conduction of CPB

The conduct of cardiopulmonary bypass (CPB) involves staff from different disciplines who function together as a team. These members include the surgeon, anesthesiologist, perfusionist and nursing that must effectively use communication throughout the case for a successful outcome for the patient [1].

Satisfactory CPB means that the circuit has effectively taken over for the heart and lungs in order for the surgeon to perform the surgery on the heart. To do this the circuit must first be assembled, consisting of disposable items and reusable equipment. The patient's chart must also be reviewed to choose the appropriate equipment based on the patient's needs, i.e., different size circuits are used based on patient size in pediatric cardiac surgery but in adult cardiac surgery the circuit is usually standardized [1]. Once the circuit is assembled, the perfusionist then primes it with a crystalloid solution to remove all air. If there is air present on the arterial side then the patient could get an air embolism or if air is present on the venous side, the perfusionist may experience an air lock so it is crucial that all air is removed, including micro-air, from the circuit [5].

Once the circuit is primed and the surgeon is ready, heparin is then administered as an anticoagulant based on the patient's size. The surgeon can then cannulate the patient, arterial and venous, to connect to the circuit. Once an adequate activated clotting time (ACT) is achieved, a goal of 480 s at many institutions, the perfusionist can then initiate bypass [6]. The perfusionist opens up the venous and arterial clamps, initiates adequate flow and oxygenation for the patient and anesthesia stops ventilating [6]. Adequate flow is usually based on a cardiac index of 2.2 to 2.4 L/min/m^2 [1]. While initiating bypass, many factors need to be assessed to achieve flow and oxygenation and if there are any issues then the perfusionist needs to troubleshoot the problem [6].

Once full flows are obtained then the surgeon can now cross clamp to continue the surgery. Cross clamping causes the heart to be ischemic and cardioplegia is given, either antegrade or retrograde or both into the coronary arteries, for myocardial protection. The cardioplegia solution contains potassium and is usually cold to achieve an electromechanical arrest and reducing myocardial oxygen consumption [5]. After this occurs, the surgeon can now perform the surgery. During the bypass period, the perfusionist must monitor and adjust as necessary many physiologic and circuit variables including blood pressure, temperature, arterial blood gases with oxygenation, EKG, coagulation status and renal function in the form of urine output among many other variables [5].

Towards the end of the surgery, the perfusionist will be instructed to warm up the patient to normothermia. Once the surgery is complete, the surgeon removes the cross clamp, reintroducing warm blood to the heart and reestablishing sinus rhythm or at least an acceptable EKG. At this point the perfusionist will prepare to wean off bypass and anesthesia will start to ventilate again. To do this, a partial clamp is placed on the venous line and arterial flow is reduced while the arterial pressure is brought to an acceptable level. Once flow is at low levels and the patient's pressure has normalized, the perfusionist will clamp the venous and arterial lines to terminate bypass. The remaining blood in the circuit will either be given directly to the patient through the arterial line or salvaged in the cell saver [6].

23.5 Troubleshooting During CPB and Management

CPB emergencies can be categorized into two broad categories based on the origin of the event they are patient emergencies and equipment emergencies. Although uncommon, CPB

emergencies may happen suddenly and requires a team approach to achieve the best patient outcome. Team communication is crucial when encountering CPB emergencies and the communication must be promptly initiated by the perfusionist. Perfusionists utilize safety checklist in every case to ensure perfusion-related problems are prevented wherever possible, and backup equipment is available and functional for when they are needed. Perfusionists should always have a high index of suspicion for CPB-related emergencies when monitoring equipment and patients, to ensure problems are diagnosed early and managed quickly when they do occur

Patient emergencies during CPB

1. Malposition of arterial cannula

Malposition of the arterial cannula into the arterial wall may lead to dissection of the aorta when initiating CPB. This happens in 0.06% of cases [7]. This can be detected by checking the pressure and pulsatility of the arterial tubing prior to the initiation of CPB. In addition, whenever possible, the position of the aortic cannulae should be visualized on TEE for second confirmation. If the malposition was not detected prior to the commencement of CPB and an aortic dissection is created, CPB must be discontinued. A protocol for surgical repair of aortic dissection must then be followed.

Another common malposition of the arterial cannula occurs when aortic cannula tip is very close to the opening of the innominate artery or the left carotid artery, leading to the hyperperfusion of the head [7]. Hyperperfusion of the head may lead to cerebral edema, even arterial rupture. Symptoms of hyperperfusion of the head are facial flushing, pupillary dilation, and conjunctival edema. Hyperperfusion of the head may also involve hypoperfusion of the lower body. This may exhibit as low MAP measured on left radial and femoral arterial lines. When this occurs, surgeon will need to reposition the aortic cannula and attempt to reduce cerebral edema with medication (Mannitol) and reverse Trendelenburg position [7].

2. Reversed cannulation

Reversed cannulation happens when the arterial line of the CPB circuit is connected to the venous cannula, and the venous line is connected to the arterial cannula. One will suspect this misconnection of the tubing to cannula when observing very low arterial pressure and very high central venous pressure despite being on full CPB flow [7]. When vacuum is used for venous drainage assistance with reversed cannulation, there is a high risk of entrainment of air in the aortic cannula, which may lead to massive air embolism in the patient if not handled properly. The management of this emergency requires cessation of CPB, putting patient in Trendelenburg position, de-airing cannulas, reverse the tubing-cannula connections and initiate massive air embolism protocol if required [7].

3. Obstruction to venous return

Obstruction of the venous return will lead to a sudden drop in the level of venous reservoir, leading perfusionist to drastically turn down the forward flow. This will manifest in patient in the form of low MAP. In addition, with the sudden reduction in venous return, there is a higher chance of emptying the venous reservoir. In order to maintain flow, crystalloid fluid may be added to the reservoir to maintain flow temporarily until the root cause is found.

One of the reasons for a sudden obstruction of venous return may be the presence of air lock in the venous tubing [7]. As large air bubbles accumulate in the venous drainage cannula or tubing, an air lock is created, due to the lower pressure gradient and the surface tension in the air-blood interface. Air lock can be “walked out” by sequentially elevating the tubing until the air enters the venous reservoir. However, the source of venous air must be investigated to prevent further air lock from forming.

Another common cause of sudden reduction of venous return is due to the mechanical positioning of the heart by the surgeon. As heart is lifted and repositioned for better surgical exposure, the venous cannula may be malpositioned

or kinked. This should be communicated with the surgeon immediately for repositioning [7].

4. Massive air embolism

Massive air embolism is when gaseous emboli reach the patient via the arterial line. This event is associated with high risk of stroke, myocardial infarction and death. This emergency happens in 0.01% of cases with a high percentage experiencing adverse patient outcome [7].

Some causes that may lead to massive air embolism in the patient include empty venous reservoir level, leaks in the negative pressure part of the CPB circuit, entrainment of air around the aortic cannula, inadequate de-airing when preparing the circuit or when connecting tubing with cannula, reversed roller pump direction, pressurized cardiotomy reservoir, runaway pump head and various septal defects that channels air from right to left side of the heart [7].

To manage massive air embolism, it requires a team effort to follow the massive air embolism emergency protocol [7]. Often times, perfusionist is the person noticing air in the circuit, and will stop CPB and clamp out the venous and arterial lines. The perfusionist will communicate with the rest of the OR team. Patient will then be put in a reverse Trendelenburg position and the source of air must be located and resolved. The arterial tubing and cannula must then be properly de-aired before re-establishing CPB. The surgeon will request to cool the patient if suspect massive air embolism has gone into the patient and retrograde perfusion through the SVC will be initiated as per protocol.

Equipment emergencies during CPB

1. Failure of oxygen supply

Failure of the oxygen supply will result in hypoxemia in the patient, as venous blood can no longer be oxygenated before returning to the patient. The perfusionist will notice that the arterial blood is turning darker, patient SvO2 will steadily drop, and the oxygen analyzer will show lower percentage of oxygen in the air-oxygen mixture by the blender. It is part of the safety checklist to ensure that there is a full oxygen tank nearby and available to provide oxygen supply in case of central oxygen supply failure. The priority is to re-establish oxygen supply and then investigate the cause of oxygen supply failure.

2. Pump failure

Pump failure may be due to electrical or mechanical reasons. A runaway pump is where pump flow can no longer to controlled and often requires the module to be shut down and reset. All CPB pumps should have hand cranks available. If the pump is operated by electromagnetic signals, then a second motor drive should be available to restore flow. The priority in this case is to re-establish flow to the patient. Then the root cause should be investigated.

3. Oxygenator failure

Oxygenator failure may take the form of oxygenation defect, mechanical obstruction, exterior leakage of blood, or water-to-blood leak in the heat-exchanger [7]. Oxygenator must be replaced during the operation. This requires the perfusionist to communicate and work with other OR team members to ensure the least of amount of time for the disruption of perfusion to the patient. This requires good planning, communication, and preparation of backup equipment readily available in the OR.

4. Clotted oxygenator or circuit

Clots found in the oxygenator will interfere with the gas exchange capability of the oxygenator. Clots found in other parts of the circuit will predispose patient to embolic risks and obstructing flow in the circuit. The causes of a clotted oxygenator are often related to inadequate heparinization prior to the commencement of CPB or inadvertent administration of protamine during CPB [7]. The management of this emergency requires the perfusionist to change out the oxygenator and tubing where clots are present. The root cause must be investigated before re-establishing CPB.

23.6 Deep Circulatory Arrest

In humans, hypothermia is defined as body temperature below 35° C or a state in which the body temperature of a homeothermic mammal is below normal [8]. The four categories of hypothermia are

- Mild hypothermia (32 °C to 35 °C)
- Moderate hypothermia (26 °C to 31 °C)
- Deep hypothermia (20 °C to 25 °C)
- Profound hypothermia (<20 °C)

The rationale for hypothermia in cardiac surgery is to

- Reduce metabolic rate
- Reduce oxygen consumption
- Preservation of phosphate stores
- Lower pump flows

Hypothermia has a positive effect on gas transfer by increasing the affinity of hemoglobin to oxygen, decreases carbon dioxide production (by reducing metabolism) and increases the solubility of oxygen and carbon dioxide.

Systemic temperatures of 20 °C–22 °C (deep hypothermic circulatory arrest (DHCA)) less are used to allow cessation of circulation for periods up to 40–60 min often without detectable organ injury [1]. In pediatric population, DHCA is used to achieve an exsanguinous surgical field during complex congenital repairs. In adults, DHCA is primarily used in surgeries like aortic arch repair, cerebral aneurysm resection etc. which require occlusion of cerebral vessels. Brain is the organ which is at the greatest risk of injury. Studies have shown that at 20 °C, circulatory arrest period of 30–45 min is typically tolerated [1]. The rate of cooling is important to prevent organ damage.

Cooling phase

- Maintain a gradient of 10 °C to 12 °C between the perfusate and patient
- Employ pH stat during initial cool down
- Pack head with ice
- Reduce flows as needed
- Monitor temperature (nasopharyngeal, arterial, venous)
- At required temperature (<22 °C), shut off pump stopping all circulation
- Allow patient volume to drain into reservoir (exsanguination allows vascular decompression as well as reduces blood stasis)

Adjuncts to increase safe ischemic time:

- Target temperature (<22 °C)
- Antegrade cerebral perfusion (ACP)
- Steroids
- Intermittent low flow

Antegrade cerebral perfusion (ACP): Once systemic circulation is stopped, ACP can be initiated via the same axillary cannula at a rate of 10 ml/kg/min and occluding the innominate artery. This technique provides adequate cerebral protection with an intact Circle of Willis. Studies have shown that when ACP is used as an adjunct, it extends the safe duration of ischemic time [1]

Rewarming phase

- Re-establish circulation
- Maintain a temperature gradient of 8 °C to 10 °C between perfusate and patient)
- Employ alpha-stat to blow off excess carbon dioxide
- Vasodilation as needed to ensure global reperfusion
- Treat acidosis with sodium bicarbonate
- Rewarm adequately to achieve a systemic temperature of 37 °C

Complications of DHCA

- Stroke
- Cognitive degeneration
- Seizure
- Choreoathetosis (1–20% of children due to basal ganglia injury)

23.7 Non-cardiac Use of CPB

There are many practical applications of CPB in surgical areas aside from cardiac surgery these applications include neurosurgery, urologic surgery, thoracic surgery, vascular surgery and liver transplantation.

The first area of CPB application is to achieve profound hypothermia using CPB, so that circulatory arrest can be established. Hypothermia circulatory arrest is utilized in surgeries that repair vascular abnormalities. Examples of surgeries that utilizes CPB to establish circulatory arrest include repair of intracranial vascular aneurysm and vena cava tumor resection [4].

The second main area of the application of CPB is in thoracic surgery an example would be resections various malignant tumor in the thorax. The rationale of the use of CPB is that the technique allows blood to bypass the lungs where the operation is performed. Depending on the surgery type, full CPB may not be required, and veno-venous bypass is established that would reduce the requirement of heparization significantly [4]. The advanced thoracic surgical techniques have steered more surgeries away from the use of CPB technique however, for major reconstruction, CPB remains to be an essential component of surgical care. To this date, full CPB is used in bilateral/unilateral pulmonary endararterectomy and double lung transplantation.

The third area of CPB application is in the form of isolated left heart bypass and veno-venous bypass. Isolated left heart bypass can be used to facilitate catherization laboratory interventions on patients who are not surgical candidates. Veno-venous bypass has its greatest application in liver transplantation; approximately 5% of the liver transplantation procedures require the use of veno-venous bypass that shunts blood from lower extremities to the right atrium [4].

The last major area of CPB application is in the treatment of rare conditions, such as accidental hypothermia and treating cancer patients using regional perfusion technique. In the case of accidental hypothermia, CPB is used to gradually perfuse and warm patient in a controlled fashion. CPB can support patient's cardio-pulmonary function and balance metabolic parameters as patient slowly warms up and may develop ventricular fibrillation [4]. In the case of cancer patients, a modified CPB circuit can be used to administer high concentration of chemotherapy agents at an ideal temperature (high perfusing temperature has synergistic effect on the chemotherapy drugs) to a specific region of the body. The complete isolation of the limbs can be accomplished by cannulating small artery and vein, and then applying tourniquet proximal to the vessels [4].

23.8 Heparin-Protamine Axis

During cardiac surgery, the cardiopulmonary bypass (CPB) machine is utilized to create a clear field for the surgeon while keeping the patient hemodynamically stable. When the blood comes into contact with a foreign substance, the circuit for example, a systemic inflammatory response is activated. Thereby initiating the extrinsic and intrinsic coagulation systems, leading to clot formation without sufficient anticoagulation to inhibit this response [9]. The most common drug utilized to attain anticoagulation is heparin. Unfractionated heparin binds with antithrombin III inhibiting clot formation [10]. Maintaining anticoagulation is necessary throughout the bypass run to ensure the prevention of thrombin formation

The activated clotting time (ACT) is the gold standard test for measuring anticoagulation. This test measures the time it takes for whole blood to clot, primarily by activation of the intrinsic coagulation pathway [11]. There are currently no definitive guidelines on how much heparin will determine anticoagulation for CPB or what number of seconds will ensure inhibition of clot formation. While traditionally the minimum number of seconds needed for anticoagulation is 480 s, some studies suggest a minimum of 400 s will warrant safe CPB [12]. Also, many institutions will dose heparin based on weight in

kilograms, either 300 or 400 IU/kg [12]. Another alternate method is the Hepcon Hemostasis Management System (HMS): this device will calculate the heparin dose based on patient blood volume and utilizes a heparin dose response curve to signify anticoagulation. It is still unclear which method better achieves adequate anticoagulation [12].

The benefit to using heparin as the anticoagulant drug of choice is the ability of protamine to achieve a reversal effect. The amount of protamine needed for neutralization is determined by how much total heparin was administered during the bypass run. A simple way of calculating how much protamine is needed is administering between 1 to 1.5 mg for each milligram of heparin that has been given [13]. There are some devices such as the Hemochron RxDx or the HMS that can predict the amount of protamine needed to reach baseline ACT levels [13]. Developed by Bull et al., some institutions will use the Heparin Dose Response Curve. Towards the end of the bypass run, a heparin concentration is calculated that provides a protamine dose needed to neutralize the amount of heparin in the patient's blood [13]. With the help of the ACT, the heparin dose response curve can be utilized. After 3–5 min from when protamine is fully administered, an ACT is performed to ensure baseline coagulation levels and full heparin reversal.

23.9 Perioperative Cell Salvage

The risks of homologous blood transfusion during cardiac surgery are well documented. One of the simplest ways to provide intraoperative autologous blood collection is with an auto transfusion device (cell saver). Blood is collected via a double lumen tube and simultaneously anticoagulated with either heparin or citrate-phosphate-dextrose [14]. Blood is collected into a filtered reservoir, washed in a centrifugal bowl and reinfused back to the patient. The finished product is red cells suspended in normal saline with a hematocrit between 45% and 60% [14]. One potential problem with overuse of this device is dilutional coagulopathy. If large quantities of shed blood are collected and processed, washout of clotting factors, plasma proteins and platelets will occur requiring replacement [14].

23.10 Brief: Off Pump CABG Role of a Perfusionist

In patients with coronary artery disease (CAD), blood vessels that supply oxygen to the heart are blocked therefore needing surgical intervention. For this type of operation, a patient's great saphenous vein or radial artery is taken and used to perfuse blood passed the blockage site. This allows for optimal gas exchange to keep the heart tissue functioning to its best ability. Typically, the cardiopulmonary bypass machine is needed to give the surgeon a clear field and a quiet heart. While not routinely done, an off pump coronary bypass graft operation can be performed on select patients. Patients who may benefit from this include those with heavily calcified aortas, liver cirrhosis, or compromised pulmonary or renal function [15]. In this case, the cardiopulmonary bypass machine is not utilized. Instead, the heart remains beating and stabilizers are placed to keep a section of the heart immobile [16]. As a perfusionist, it is important to always be prepared to go on bypass if necessary.

Some alternate devices that will still need to be managed by the perfusionist include the cell saver and potentially the carbon dioxide (CO2) blower. The cell saver processes whole blood, washes it with normal saline and saves the red blood cells collected from the field. This is often processed throughout or at the end of the case and given to anesthesia to increase patient blood volume and hematocrit. Hopefully this is enough to reduce the use of blood products. A limiting factor of the cell saver is that it does not keep the patient's clotting factors [17]. The surgeon can utilize the CO_2 blower, especially in this case, to dissolve blood that is in his surgical viewpoint. A benefit of carbon dioxide is that it has a 20-fold higher solubility coefficient in blood as compared to oxygen. Therefore, using this technique can minimize air embolism of the patient.

This method is found to be simple and safe and should be used when performing an off-pump CABG [18].

23.11 IABP, VADS, ECMO

Intra-Aortic Balloon Counterpulsation

Introduction

The clinical objectives in utilizing any form of ventricular support are to restore adequate blood flow while preserving end-organ function. Whether a patient in cardiogenic shock resulting from acute heart failure (postcardiotomy) or in congestive heart failure, the indications for the support are hemodynamic compromise, reduction in myocardial contractility and low-output syndrome.

Intra-aortic balloon pump (IABP) counterpulsation has been the most widely used left ventricular assist device for nearly five decades. The first clinical application of a successful treatment with IABP was reported in 1967 [19]. Intra-aortic balloon pumping was advocated successfully in a 45-year-old female who had sustained a myocardial infarction and was hypotensive, comatose and anuric in severe cardiogenic shock [20].

The goal of IABP is to support a failing heart by increasing the myocardial oxygen supply and decreasing myocardial oxygen demand. To do so, the balloon inflates in diastole, augmenting coronary perfusion, and deflates in early systole (counterpulsation).

IABP Theory

Intra-aortic balloon pump counterpulsation is the most common form of mechanical circulatory support used in patients with myocardial ischemia and cardiogenic shock. Intra-Aortic balloon counterpulsation can provided cardiac and circulatory support for patients exhibiting marginal to severe cardiac compromise. IABP is mainly used in high-risk patients with acute myocardial infarction, especially when complicated by cardiogenic shock.

Augmentation of diastolic pressure during balloon inflation contributes to the coronary circulation and the presystolic deflation of the balloon reduces the resistance to systolic output. Consequently, the myocardial work is reduced.

Indications of use:

1. Cardiac Failure
2. Refractory unstable angina
3. High risk catherization procedures
4. Perioperative treatment of complications due MI

Contraindications to IABP

1. Severe aortic insufficiency
2. Aortic aneurysm
3. Aortic dissection
4. Limb ischemia
5. Thromboembolism

IABP Instrumentation and Techniques:

1. Flexible dual lumen catheter
   a. Shuttle helium gas to and from the balloon
   b. Pressure monitoring line
   c. Balloon should be catheters sized to patient size
   d. Polyethylene or PU balloon mounted at the distal tip of a large bore catheter

2. Balloon Catheter Insertion

Insertion is carried out percutaneously using the Seldinger technique and in some case under mild anticoagulation with heparin.

Common practice dictates the intra-aortic balloon catheter be inserted via the femoral artery and the tip of balloon is positioned 2 cm below the left subclavian artery. The proximal balloon end should be lying above the renal vessels. Incorrect balloon position results in reduced diastolic augmentation or vascular morbidity due to direct intimal injury or plaque distortion and embolization or finally direct occlusion of the arterial lumen. Position should be verified by x-ray or TEE.

3. Portable IABP console capable of transferring helium gas to and from the balloon synchronized to the cardiac cycle.

IABP Triggering Modes and Timing

There are 6 Triggering modes which can be used to trigger the balloon console.

1. ECG—using QRS wave form to detect trigger point
2. Arterial pressure wave form—arterial internal balloon or radial arterial wave forms
3. Fiberoptic cable—internal within balloon catheter
4. Internal Trigger Mode
5. Pacer Mode
6. Pacer V/Pacer A-V

For the IABP to function properly, its inflation-deflation cycle must be synchronized to the appropriate events in the cardiac cycle. The central lumen of the double-lumen IAB catheter allows monitoring of the pressure in the descending aorta during the cardiac cycle. This arterial line provides data to the IABP console. Timing of the IABP is always performed using the arterial waveform as the guide.

The IABP console continuously monitors the patient's arterial pressure. When it recognizes the dicrotic notch (the onset of diastole), it triggers rapid balloon inflation; pressure within the aortic compartment increases and an increase in coronary artery perfusion occurs. The pressure during diastolic augmentation is often considerably higher than both the normal diastolic pressure and even the peak systolic pressures. High diastolic augmentation pressure is one of the indicators of effective IABP function [21].

Balloon deflation is timed to occur with the onset of systole. When the IABP console identifies the beginning of the patient's R wave, the balloon is rapidly deflated, lowering the pressure in the proximal aorta. In the second waveform of the illustration, the *assisted aortic end-diastolic pressure* is lower than the previous pressure waveform's *unassisted aortic end-diastolic pressure*. The lowering of the end-diastolic pressure from balloon deflation is another physiologic indicator of proper IABP function.

Summary

The use of the IABP counter pulsation has shown efficacy due to the increase in diastolic pressure during balloon inflation augments the coronary circulation. Also, pre-systolic deflation of the balloon reduces the resistance to systolic output, thus a decrease in myocardial work. The efficacy of the IABP is reflected by the positive outcomes of the high number of patients who are weaned from the device. The success rate is higher for patients, in whom the device is deployed early.

Ventricular Assist Devices

Introduction

Heart failure (HF) is a major public health issue associated with significant morbidity, mortality, and healthcare expenditures. Mechanical circulatory support devices (MCS) such as left ventricular assist devices (LVADs) provide an alternative to heart transplantation for patients with advanced HF.

Definition of Left Ventricular Failure

Cardiac Output <2.0 Lpm/m2
Systolic Blood Pressure <80–90 mmhg
Left atrial pressure >20 mmhg

MCS Classification

1. Acute Devices
   * Post-Cardiotomy support <24 h
   * Recoverable Post-Cardiotomy 24–48 h
   * Transition to Chronic VAD
2. Durable Devices
   * Bridge to Transplantation
   * Destination Therapy

I. Acute Ventricular Assist Device

A. Centrifugal Blood Pumps
B. Catheter based Technology

Post Cardiotomy Support

- 2–6% post-cardiotomy ventricular failure despite improvements in myocardial protection techs and tech successful operation

- .5–1% CPB failure to wean despite max inotropic support in conjunction with IABP

Acute Device selection criteria

- Extended Bypass time
- Unable to wean from bypass
- Most in a state of coagulation imbalance
- Bank blood, FFP and Platelets
- Intractable ventricular tachycardia
- Neurological status in question

Historical Timeline for Centrifugal Pump Ventricular Support

- 1960 Saxton and Andrews
- First report of use of a centrifugal pump
- 1963 Spencer
- First successful post cardiotomy LVAD
- 1966 Dorman et al.
- Impeller centrifugal pump
- 1978 Golding et al.
- Clinical use of Medtronic LVAD
- 1980 Magovern
- Clinical use of Bio-Medicus LVAD

Cannulation Techniques

Traditional Approaches [22]

- Interatrial Groove
- Left Atrial Appendage
- Left Ventricular Apex
- Dome of Left Atrium
- Right Superior Pulmonary Vein
- Femoral Cannulation

A. Centrifugal Blood pumps

1. Centrimag Blood Pump

Overview

The Centrimag Blood Pump is electronically driven, based on bearing-less motor technology. The centrifugal pump allows pumping without mechanical bearings and seals. The Blood pump has a magnetically levitated rotor to attempt to decrease the incidence of heat and thrombus formation.

Pump Speed Range 0–5,500 revolutions per minute (RPM)

Pump Flow Range 0.0–10.0 L per minute (LPM)

2. The Tandem Heart

Overview

Tandem Heart Blood pump is a left atrial-to-femoral artery bypass system comprising a transseptal cannula, arterial cannula, and a centrifugal blood pump. The pump can deliver flow rates up to 4.0 L/min at a maximum speed of 7500 rpms.

Impella Ventricular Assist Device

Overview

The Impella ventricular assist blood pump is a percutaneous catheter-based micro axial blood pump providing temporary hemodynamic support to the heart. The device pumps blood from the left ventricle into the ascending aorta and systemic circulation at the upper rate of 2.5 L/min to 5 L/min. It can be placed via a retrograde approach across the aortic valve using a femoral arterial access.

Durable Ventricular Assist Devices

MCS with durable ventricular assist devices has shown to be an efficacious treatment modality for patients with end stage heart failure refractory to medical treatment. With the annual volume of heart transplants in the U.S. plateauing around the 3000-mark, implanting BTT (bridge to transplant) vads became inevitable. The numbers of patients supported by Vads continues to grow, those indicate a DT are around 50%, whereas BTT constitutes 26% [23]. The REMATCH trail in 2001 by ROSE et al. demonstrated the use of Vads as a durable Destination Therapy (DT) with superior outcomes when compared to long-term medical treatment.

Current FDA approved devices

1. Heartmate II VAD (Abbott)
   FDA approved for BTT 2008
   FDA approved for DT 2010

The HeartMate II is a continuous flow, second generation left ventricular assist device (LVAD). This pump has been implanted for bridge to transplant and destination therapy indications. This is valve-less axial blood pump contains a rotor spinning on a ruby bearing.

The pump operates in the range of 6000–15000 rpms and the maximum flow range is 3–10 L/min. It is both preload and afterload sensitive.

2. Heartmate III VAD (Abbott)
   FDA approved for BTT 2017
   FDA approved for DT 2017

A new generation centrifugal flow pump, which incorporates a fully magnetically levitated rotor, wider blood-flow paths and the has the ability to provide artificial pulsatility, in order to decrease the incidence of thrombus formation. The Heartmate III is both preload and afterload sensitive.

The motor technology of this LVAD incorporates a contactless bearing technology and consists of the rotor with passive magnets for drive and bearing. The application of rotary blood pumps with magnetically levitated rotors, as opposed to pumps with mechanical bearings, improves the feasibility and safety of implanting such LVADs as alternative-to-transplant, applicable for a time span of 10 to 15 years.

The pump operates at rotor speed in the range of 3,000 to 9,000 rpms, and the maximum flow rate is 10 L/min.

Principles and Indications for Extracorporeal Membrane Oxygenation—ECMO

Introduction

ECMO uses a pump to take over the work of the heart and an oxygenator (artificial lung) to take over the work of the lungs. Extracorporeal membrane oxygenation (ECMO) is mechanical support in the form of prolonged cardiopulmonary bypass, achieved by using a modified bypass circuit and peripheral cannulation techniques. This support technique is used in patients who present with lung injury or compromised lung function that is unresponsive to optimal ventilator management. The classic indication for VA-ECMO is cardiogenic shock, defined by decreased cardiac output and myocardial contractility resulting in tissue hypoperfusion. It should be considered in patient populations with potentially reversible respiratory failure has been identified.

Some lung (pulmonary) conditions in which ECMO may be used include:

- Acute respiratory distress syndrome (ARDS)
- Blockage in a pulmonary artery in the lungs (pulmonary embolism)
- Coronavirus disease 2019 (COVID-19)
- Flu (influenza)
- Pneumonia
- Respiratory failure
- Trauma

Risks

The most common risks that may occur with ECMO include:

- Bleeding
- Blood clot (thromboembolism)
- Blood clotting disorder (coagulopathy)
- Infection
- Loss of blood in hands, feet or legs (limb ischemia)
- Seizures
- Stroke (part of the brain is damaged by loss of blood or by a blood vessel that bursts)

Historical Timeline for Adult ECMO

1972—First survivor (NEJM)—young patient with post-traumatic
respiratory failure

1979-VA ECMO (ECMO with ventilation) vs ventilation alone -> high mortality in ECMO group

1986—Gattinoni's case series, VV, used for CO2 removal, increased survival but large blood loss/day

1989—ELSO established

Note: ELSO maintains a registry of clinical characteristics and outcomes of patients supported with ECMO.

Types of ECMO

- VV = Veno-Venous
- VA = Veno-Arterial: peripheral or central

VV ECMO

Veno-Venous (VV) ECMO provides respiratory support but does not provide circulatory support. Blood is drained from the central venous system, either from the superior or inferior vena cava, oxygenated, and reintroduced into the right atrium. From the right atrium, the oxygenated blood flows to the right ventricle and is pumped by the native heart through the pulmonary artery, dysfunctional lungs, and pulmonary vein. Blood flow continues to the left atrium and left ventricle where it is pumped through systemic circulation.

Indications for Use

1. Pneumonia
2. ARDS
3. Status asthmaticus
4. Airway obstruction
5. Aspiration
6. Bridge to lung transplantation
7. Drowning
8. Covid 19 Virus

Advantages

- normal lung blood flow
- oxygenated lung blood
- pulsatile blood pressure
- oxygenated blood delivered to root of aorta
- must be used when native cardiac output is high

Disadvantages

- no cardiac support

VA ECMO

Veno-Arterial (VA) ECMO provides respiratory and circulatory support. Deoxygenated blood is drained from a central vein into ECMO circuit, oxygenated, and returned to arterial circulation. VA Ecmo provides support to both the lungs and the heart.

Indications for use

1. Support for cardiac failure (± respiratory failure)
2. Graft failure post heart or heart lung transplant
3. Non-ischemic cardiogenic shock
4. Failure to wean post CPB
5. Bridge to LVAD
6. Drug overdose

Disadvantages

- Relative lung ischemia
- Non-pulsatile blood flow

23.12 Checklists

The American Society of Extracorporeal Technology (AmSECT) has compiled a list of Standards and Guidelines in order to help institutions provide basic levels of care. One of the standards prioritized in this list is having a checklist for each cardiopulmonary bypass case and including that checklist as part of the patient's chart [24].

One of the main responsibilities a perfusionist has is to provide safe cardiopulmonary bypass by means of an extracorporeal circuit every time a patient goes on bypass. A simple and effective way to help ensure this is to incorporate checklists into the perfusionist's duties. This should be done as needed throughout a case, however common times to consider using a checklist are preoperatively, intraoperatively, and postoperatively [24, 25].

Checklists are a common tool used by multiple industries. Their proper use and application can facilitate several desirable outcomes. The appropriate use of checklists helps users remember to perform each needed step, to do so correctly, and it provides continuity in task performance among colleagues. An additional

Figure 1: AmSECT's Perfusion Checklist

Patient ID _____

Check each item when completed, sign and date. If not applicable, draw line through**. Bold italicized items for expedited set-up.**

PATIENT
- ***Patient identity confirmed***
- ***Procedure confirmed***
- ***Blood type, antibodies confirmed***
- ***Allergies checked***
- Blood bank number confirmed
- Medical record number confirmed
- Chart reviewed

STERILITY/CLEANLINESS
- ***Components checked for package integrity/expiration***
- Equipment clean
- Heat exchanger(s) leak-tested

PUMP
- ***Occlusion(s) set***
- ***Speed controls operational***
- ***Flow meter in correct direction and calibration***
- ***Flow rate indicator correct for patient and/or tubing size***
- ***Rollers rotate freely***
- Pump head rotation smooth and quiet
- Holders secure
- Servoregulated connections tested

ELECTRICAL
- ***Power cord(s) connection(s) secure***
- ***Servoregulation connections secure***
- Batteries charged and operational

CARDIOPLEGIA
- ***System debubbled and operational***
- System leak-free after pressurization
- Solution(s) checked

GAS SUPPLY
- ***Gas line(s) and filer connections secure***
- ***Gas exhaust unobstructed***
- ***Source and appropriate connections of gas(es) confirmed***
- ***Flow meter / gas blender operational***
- Hoses leak-free
- Anesthetic gas scavenge line operational

COMPONENTS
- ***System debubbled and operational***
- ***Connections / stopcocks / caps secure***
- ***Appropriate lines claimed / shunts closed***
- ***Tubing direction traced and correct***
- ***Patency of arterial line / cannula confirmed***
- No tubing kinks noted
- One-way valve(s) in correct direction
- Leak-free after pressurization

SAFETY MECHANISMS
- ***Alarms operational, audible and engaged***
- ***Arterial filter / bubble trap debubbled***
- ***Cardiotomy / hardshell venous reservoir(s) vented***
- ***Vent(s) tested***

Fig. 23.1 AmSECT's perfusion checklist

Venous line occluder(s) calibrated and tested
Devices securely attached to console

ASSISTED VENOUS RETURN

Cardiotomy positive-pressure relief valve present
Negative- pressure relief valve unobstructed
Vacuum regulator operational

MONITORING

Circuit / patient temperature probes placed
Pressure transducers / monitors calibrated and on proper scales
Inline sensors calibrated
Oxygen analyzer calibrated

ANTICOAGULATION

Heparin time and dose confirmed
Anticoagulation tested and reported

TEMPERATURE CONTROL

Water source(s)connected and operational
Temperature range(s) tested and operational
Water lines unobstructed

SUPPLIES

Tubing clamps available
Drugs available and properly labeled
Solutions available
Blood products available
Sampling syringes / laboratory tubes available
Anesthetic vaporizer correct
Vaporizer operational and filled

BACKUP

Hand cranks available
Duplicate circuit components / hardware available
Emergency lighting / flashlight available
Backup full oxygen tank with flow meter available
Ice available

EMERGENT RESTART OF BYPASS

Heparin time and dose confirmed
Components debubbled
Gas flow confirmed
Alarms reengaged
Water source(s) connected

TERMINATION CHECKLIST

Venous assist off / cardiotomy / venous reservoirs vented
Shunt(s) closed
Vent(s) clamped / removed

POSTBYPASS CHECKLIST

Announce bypass terminated
Arterial and venous lines clamped
Arterial circuit bubble-free before transfusing perfusate
Pump suction(s) off

Comments:

Signature: _____

Date: _____ Time: _____

These perfusion checklists, or a reasonable equivalent, should be used in perfusion practice. This is a guideline, which Perfusionists are encouraged to modify to accommodate difference in circuit design and variations in institutional clinical practice. Users should refer to manufacturers' information, including Instructions for Use, for specific procedures and/or precautions. AmSECT disclaims any and all liability and responsibility for injury and damages resulting from following this suggested checklist. Origination 1990; revision 2004 by AmSECT Quality Committee.

Fig. 23.1 (continued)

benefit is that using a checklist gives the perfusionist additional confidence that they are adequately prepared for the needs of the patient [25].

A perfusionist's checklist should coincide with his or her responsibilities, and either directly or indirectly answer certain overarching questions. Some of which include:

- Has the patient been identified?
- Does the patient have special needs?
- Has the circuit been correctly set up, primed, and tested for use?
- Have the appropriate monitoring devices been attached?
- Have the needed supplies for bypass been gathered?
- Are backup supplies and equipment available in the event that equipment or power fails?
- Is the patient sufficiently anticoagulated before bypass?
- Once on bypass, is the patient being adequately supported?
- When not on bypass, is the circuit and perfusionist ready to go on bypass if the patient's vitals begin to deteriorate?

While checklists should be customized to the needs of the institution where it is implemented, several examples of checklists can be found in literature. A checklist commonly referenced was created by AmSECT and made available to the public (Fig. 23.1) [24]. Tasks performed by perfusionists are vital to patient safety. Using a tangible checklist that becomes part of the patient record, which requires an active acknowledgement of specific actions being completed is an effective way to ensure that performance is not compromised by tasks being left incomplete or being completed in a suboptimal manner [6].

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