An introduction to extracorporeal circulation during open heart surgery

1. Introduction
During open heart surgery, the surgical intervention is typically performed on a non-beating heart, and hence requires establishment of extracorporeal circulation (ECC). During ECC, a heart-lung-machine temporarily replaces the functionality of the heart and lungs. This technique is therefore also called cardio pulmonary bypass (CPB).
During closed heart surgery, the incision is performed without use of a heart-lung-machine. Coronary bypass operations can therefore in a number of cases be performed on a beating heart without use of ECC. The method is called OPCAP (Off Pump Coronary Artery Bypass).

2. The Primary Extra Corporal circuit
During ECC the blood from the right side of the heart is drained through a venous catheter to a venous reservoir. Following this, the blood is pumped to an artificial lung – the oxygenator – where oxygen is added and carbon dioxide is washed out. Finally the blood is pumped back into the systemic circulation by an arterial canulla in aorta ascendens. The oxygenator has a built-in heat-exchange system, which gives the blood the desired temperature.
The individual components in the primary extracorporal circuit are described below from venous catheter to arterial canulla.
Figure 1. The primary extra corporal circuit.

The right side of the heart is drained through a venous catheter to a venous reservoir. Following this, the blood is pumped to an artificial lung – the oxygenator – where oxygen is added and carbon dioxide is washed out. The oxygenated blood is pumped back into the systemic circulation through an arterial filter and by an arterial canulla in aorta ascendens.

Venous drainage
A venous catheter can be a single or a so-called two-stage catheter. The two-stage catheter has a wider part with holes in the side, which is placed in the right atrium and a smaller tip likewise with side holes that is placed in vena cava inferior. For the single-stage catheter, two single catheters are positioned in vena cava superior and inferior, and the venous blood is drained by aid of gravity from the patient to the heart-lung machine (Figure 2).
Figure 2: Venous cannulation
A: The two-stage catheter has a wider part with holes in the side. It is placed in the right atrium and a smaller tip likewise with side holes is placed in vena cava inferior.
B: Venous cannulation through two single catheters positioned in vena cava superior and inferior.

During total by-pass, vena cava superior and inferior is tied to the single venous catheters, such that all retuning blood enters the heart-lung machine. This is necessary when opening of the right atrium is needed. During partial by-pass, a small amount of the blood continues to flow through the pulmonary circulation. A height difference between patient and machine of 60-80 cm, low canullae resistance, and a sufficient tube diameter, are necessary conditions to obtain a venous pressure low enough to avoid volume backup and oedema. The central venous pressure should be kept between 5 and 15 mmHg. Negative venous pressures can cause collapses of the thin-walled venae cava surrounding the catheters and hence obstruct the flow to the heart-lung machine. The pressure can in that case be elevated by increasing the resistance in the venous tube with a clamp, or reduce the height difference between patient and machine. On
the contrary, it is often a problem the venous drainage at periods is not
sufficient to maintain proper circulation. This can be caused by a lack of
height difference, non-optimized placement of the venous catheter or that
the heart is turned. The problem can be temporarily solved by reducing
flow for a short period of time and/or add more fluid to the system.

**The venous reservoir**
The venous blood is led into the venous reservoir of the heart-lung
machine. This reservoir functions as a large “atrium” or buffer for
changes and the imbalance that can appear between the venous drainage
and the arterial flow back to the patient. The reservoir also functions as a
storage facility for periodical surplus blood, that then later can be pumped
back to the patient. It has built-in filters, that also works as a bubble-trap
for the air that possible has entered the venous tube. Finally, the venous
reservoir has the very important safety function that can give the
perfusionist that operates the heart-lung machine the necessary time to
react if the venous drainage suddenly is reduced significantly or possibly
stops completely.

**The systemic pump**
The oxygenated blood is pumped back to the patient’s systemic circulation
by the aortic cannulae in aorta ascendens with a pump that typically is
placed upstream of the oxegynator as shown in Figure 1. The placement
depends on the particular type of oxegynator and its hemodynamical input
resistance. The pump generates a steady (non-pulsatile) flow, and the
flow-rate is adjusted according to the venous drainage and the calculated
cardiac output for the patient.
The most commonly utilized pump types are the roller pump and the
centrifugal pump. The roller pump is still the most utilized blood pump in
heart-lung machines. It is a flow-pump, which means that it can be set to
deliver a constant flow, almost non-dependant of the hemodynamic
resistance of the receiving circulatory system. The generated arterial
pressure is therefore determined by the flow and the hemodynamic
resistance of the receiving circulatory system. The roller pump consists of
a tube segment, which is placed at the perimeter of the half-circular pump
housing. Two rollers placed 180 degrees apart at each end of a rotating axel is alternates in pressing blood in the tube forward in front of the roller in a peristaltic wave-like motion (Figure 3).

**Figure 3: Blood Pumps**
The roller pump (left) consists of a tube segment placed in a half-circular pump house. Two rollers are placed 180° in relation to each other at the end of a rotating axel, and they are in an alternating fashion pressing the blood in the tube forward in front of the roll in a peristaltic movement. The centrifugal pump (right) consists of a rotating shovel-wheel, that slings the blood out towards the outer wall of the pump house and out though a pipe towards the arterial side of the circulation. The blood from the venous side comes through a tube at the top of the pump house.

The flow is determined by the diameter of the tube segment, the effective compression length, and the rotation speed of the rollers. The degree of occlusion, meaning the amount of closing of the tube between the roller and the pump house, can be adjusted and is critical with respect to damage to the blood elements. At too large of a distance between the roller and the pump house the efficiency of the peristaltic movements will be reduced and to a larger extend be influenced by the hemodynamic resistance of the
receiving circulation. A too high occlusive setting of rolling pumps elevates the load on the blood elements, which can lead to haemolysis and activation of thrombocytes. In addition, the mechanical wear on the pump tube is increased, resulting in small fragments of the tubes inner side that can be released into the circulation. Investigations indicate that the optimal adjustment of the roller pump is “just not occlusive”.

The centrifugal pump is a pressure pump, where the flow is determined by the hemodynamical resistance that is loading the pump. It is therefore necessary to monitor the amount of flow by a flow-meter inserted in the circulation. The flow is changed by adjusting the rotation velocity of the pump wheel. This consists of a rotating shovel-wheel, that slings the blood out towards the outer wall of the pump house and out though a pipe towards the arterial side of the circulation. The blood from the venous side comes through a tube at the top of the pump house (figure 3). When the pump is stopped, it is necessary to clamp the arterial tube, since the blood would flow backwards through the pump. In addition, a return valve can be added. One of the large advantages with the centrifugal pump is that there is no risk of extremely high pressures by occlusion of the arterial tube. And it will also not, as the roller pump, be able to create a harmful negative pressure during occlusion of the venous inlet, thereby avoiding capitation. The core construction of the centrifugal pump prevents that larger air emboli can be pumped into the patient: They will rise to the top of the pump house, from where they can be aired out. Also, the pump is gentler to the blood elements. On the contrary, the roller pump is simpler, less expensive, and has a lower volume. It is easier to “prime” (see below) the roller pump and air out, and finally it generates a constant flow – independent of after load. Due to these circumstances the centrifugal pump is mainly used to extra corporal “assist devices” and long term perfusion.

The Oxygenator
The oxygenator is the artificial lung of the heart-lung-machine, hence the name is not very descriptive, since the oxygenator besides adding oxygen to the blood also removes carbon dioxide. In other words, it is a gas exchange device. The oxygenator is usually placed following the systemic
“arterial” pump, since the hemodynamic resistance in modern oxygenators is so large, that it requires a larger pressure than the passive venous drainage systems can provide. The gas exchange is executed by diffusion over a thin silicone membrane that separates blood and gas phases. A large combined membrane surface and appropriate large differences in concentration for oxygen and carbon dioxide ensures the necessary gas exchange even at large blood flow velocities. The traditional membrane oxygenator is almost entirely replaced in use today by the more efficient micro-porous oxygenator (figure 4)
Figure 4: Oxygenator and heat exchanger combined. The blood first passes by the heat exchanger, which is based on continuous flow of thermostat controlled water through a large surface that separates the blood and water (top left). Then the blood is fed to the oxygenator part, where the gas exchange consists of diffusion through a micro-porous material made out of thousand of hollow artificial fibers. Usually the gas is fed through the hollow fibers and the blood is fed through the individual fibers (top right).

Here the gas exchange consists of diffusion through a micro-porous material made out of thousand of hollow artificial fibers (120-200 micrometers in diameter). Usually the gas is fed through the hollow fibers and the blood is fed through the individual fibers. The opposite is also possible, but since turbulence and secondary flow is best created outside of the fibers, which increases the diffusion capacity and hereby the oxygen saturation in the blood, keeping the oxygen inside of the fibers and blood outside the most optimum. The disadvantage with this construction is elevated “wall shear stress” and hereby a larger mechanical load on the blood elements, as well as a large pressure drop (80-100 mmHg) through the oxygenator.

The Heat Exchanger
To control the core body temperature of the patient during the extra corporal circulation, a heat exchanger is integrated into the oxygenator or venous reservoir. This is based on continuous flow of thermostat controlled water through a large surface that separates blood and water. Water is supplied from a free standing heater/cooler, where the temperature typically can be adjusted from 2-42 °C. It is therefore capable of both add to and remove heat from the blood. Fast perfusion of very cold blood into a warm patient should be avoided to prevent the creation of air embolies in the patient. Fast heating of the blood will also create these air embolies in the extra corporal circulation, but these will be dissolved when they arrive in the colder patient. For safety reasons, the temperature difference between water and blood should not be larger than 10°C.
The Arterial Filter
Before the oxygenated blood is pumped back into the patient by the arterial canulla in aorta ascendens, it is passed through a filter that catches micro embolies, thrombocyte aggregates and particles from the blood which is vacuumed from the surgical field. The efficiency of the filter with respect to catching gas- and solid embolies is reverse proportional with the size of the pores, however a small pore size elevates the load on the blood elements, and hereby the risk of haemolysis and thrombous creation. Moreover, the hemodynamical resistance is increased and hence the pressure drop though the filter is increased at any given flow. The pore size for a typical arterial filter is from 20-40mm, and will at a flow of 5 l/min create a pressure drop of approximately 30mmHg.

Arterial Cannulation
The arterial tube of the heart-lung machine is connected to the patient through an arterial canulla that is usually inserted into aorta ascendens through a purse-string. The tip of the arterial canulla is usually the narrowest part of the extracorporal circulation and can therefore be treated as a resistance equivalent, that at high flow rates create large pressure drops and high blood velocities, resulting in turbulence and cavitation. Pressure drop between 50 and 100 mmHg are typical values at a flow of 5 l/min – depending on the diameter of the canulla and type. Pressure drops over approximately 100 mmHg is not acceptable, since the turbulent shear stresses in the blood will cause haemolysis and activation of thrombocytes. The key characteristic for an arterial canulla is therefore the pressure drop as a function of flow at different diameters of the tip – for blood at 37°C.

Secondary Suction Circulation
Besides the primary arterial-venous circulation, the heart-lung machine has a number of secondary circulations. One of these is a suction or vacuuming system, which typically consists of one of two hand suction units for removal of blood from the surgical field and one suction catheter - a so called vent - typically placed in the left ventricle by the left atrium or in aorta ascendens (figure 5).
This circulation must prevent that the stopped heart is dilated passively by blood from the venous system and the lung circulation. In addition, it helps the surgeon to avoid unnecessary blood in the operating field. The blood from these vacuums is gathered in a special reservoir – a so called cardiotomy reservoir, where it is filtered and any foam is removed. The necessary vacuum is created by small rolling pumps, that are adjusted such that the addition of air and mechanical damaging of the blood elements will be minimized. From the cardiotomy reservoir the blood is fed back to the primary circulation and the patient through the venous reservoir. Hence, the blood that escapes the surgical field can be “recycled”, and thereby reduce the need for blood transfusion. Monitors of pressure, flow, fluid level, bubbles, and blood gasses are placed several places in the circulation. This is done to control and adjust
the perfusion as safe and as physiological optimally as possible. This increased usage of in-line monitoring continuously increases the quality of perfusion techniques.

3. The Perfusion

Priming
When the components of the heart lung machine – which are primarily disposable one time use components, is gathered, the system is filled with crystalloid fluid with heparin added. For the adult setup, the so-called priming volume is typically 1.5-2.0 liters. This will at start of ECC give a thinning that results in the hematocrit of the patient drops to 0.25-0.30, when the patient is connected to the machinery. This is an advantage at surgery during hypothermia, since the viscosity of blood rises by dropping temperature, whereby the circuit resistance rises. But by hemodilution the viscosity falls again and eliminates to some degree the problem. Hemodilution also results in an improved microcirculation in the tissues of the patient. During priming of the heart-lung machine one needs to be very thorough by venting all components and tubes in the ECC.

Anticoagulation
To prevent the blood in coagulating at contact with the non-biological surfaces of the ECC machine, heparin is added at 300 units per kilogram body weight prior to onset of ECC. The degree of anticoagulation is monitored through the surgery by continuously by measuring the ACT (Activated Clotting Time), which is the number of seconds it takes the blood to coagulate in a 37 deg. Celsius warm glass of water with kaoline particles. The concentration of heparin during the surgery is traditionally kept at a value where the ACT does not fall below 480 seconds. When the ECC has stopped and the venous catheter is removed, the heparin is neutralized with protamine by injecting 1 mg/100 Units heparine or 3 mg/kg body weight.

Cardioplegia
Cardioplegia means stunning of the heart and is most often performed by injecting a cold (4-12 deg. Celsius) calcium solution containing crystalline
or blood through the aortic root, after clamping between this and the arterial canulla (also called antegrade cardeoplegia). The high calcium concentration in the fluid causes an ongoing depolarization of the cell membranes, such that the heart stops during diastole. At these procedures it can be advantageous to administer the cardioplegia retrograde through sinus coronaries. The perfusion system to execute this crystalline cardioplegia can consist of a simple infusion system where a chilled bag with cardioplegia fluid is put under the necessary pressure with an air machete connected to a hand pump, a manometer, and sometimes a filter. If the cardioplegia contains blood, the solution is mixed online with blood from the oxygenator by utilizing a dual channel rolling pump.

Temperature, pressure, and flow of the cardioplegia need to be supervised carefully to avoid oedema and other ischemic injuries in the myocardium. Warm cardioplegia containing oxygenated blood at approximately 34 deg. Celsius from the machine requires much attention and control to avoid and prevent ischemic injuries. The advantage with this type of cardioplegia is that the metabolism is kept at an almost normal level with a totally offloaded myocardium, and can be used for patients with weak myocardium or acute myocardial infarct.

**Temperature**

Most open heart surgeries are performed under normal temperature or moderate hypothermia (34-28 deg. Celcius). Interventions that require deep hypothermia is performed at 28-20 deg. Celsius. The advantages of hypothermia are improved myocardium and organ protection. The necessary perfusion flow is less, since the oxygen requirements from organs drops with temperature. The resulting lesser blood velocities also reduces the intensity of turbulence in the critical components of the heart-lung machine and the arterial canulla and hereby the fluid dynamical load on the blood elements, resulting in less haemolysis and other benefits. If the patient is cooled to less than 20 deg. Celsius and the head simultaneously is chilled externally with ice bags, it is possible to stop the circulation entirely, for a period of up to 45 minutes. This may be necessary during certain surgical procedures on the heart, lungs, or aorta.
**pH relationships**
The temperature also has a large impact on the blood pH. Controlling pH and CO₂ is therefore especially important during deep hypothermy. When the temperature drops, more carbon dioxide is dissolved in the blood – PaCO₂ drops and pH rises. The two most ordinary methods of controlling and regulating pH are called “pH-stat” and “alpha-stat”.

During “pH-stat” the PaCO₂ is corrected according to the low temperature of the patient by adding CO₂ to the perfusion circulation and making the pH drop to 7.4 and increase PaCO₂ to approximately 40 mmHg. With the other method, “alpha-stat”, CO₂ is not added to the perfusion circulation. Here the actual PaCO₂ will at for example 20 deg. Celsius be about 20 mmHg and the pH will be about 7.6. The theory behind this method is, that the pH does not necessarily need to be maintained at 7.4 at low temperatures, but instead it is attempted to maintain the cells neutral – meaning maintaining the neutral trans-cellular pH-gradient. It is actually known, that the pH-value that keeps the cells neutral rises, when the temperature drops. By artificially adding CO₂ as during “pH-stat”, the patient will therefore become acidic.

The advantages and disadvantages by the two methods, for example with respect to cerebral blood supply and neurological dysfunction, are still discussed and no solid agreement has been reached. However, “alpha-stat” seems to be the most preferred regulation method, since the cell structure and the metabolic activity following reheating seems to be maintained, when the pH is not adjusted relative to patient temperature by addition of CO₂. Hence this method is also easier to administrate.

**Gas Exchange**
The exchange of O₂ and CO₂ during ECC is controlled by regulating the amount and mixture-relationship of the two gasses to the oxygenator. By continuously making blood gas analyses the PaO₂ is kept above approximately 100 mmHg, PvO₂ above approximately 60 mmHg and PaCO₂ at approximately 40 mmHg, which at normothermy results in a pH of 7.4.
Pressure and Flow Conditions
The oxygen consumption during normothermy is 80-125 ml/min/m² body surface. An indexed perfusion flow at 2.4 l/min/m² is hence sufficient to maintain the metabolism of cells and avoid metabolic acidose. At hypothermy the metabolism drops and hence also the oxygen demands, which make it possible to reduce the perfusion flow to 2.2 l/min/m². At deep hypothermy the flow can be reduced further to 2.2 l/min/m² for up to two hours.
During normothermy, the mean arterial pressure should be between 50 to 70 mmHg to avoid damage on the brain and abdominal organs. At Hypothermy with reduced perfusion flow the arterial pressure will fall accordingly, but should always be kept above approximately 35 mmHg to avoid injuries.

Complications
The non-physiological flow of blood through the various components of the heart lung machine and the exposure to air and non-biological surfaces causes damage and activation of blood elements. Bends in geometry, branching, and narrowing creates flow disturbances and turbulence resulting in shear stress. High shear stress values can create haemolysis and activate thrombocytes.
Haemolysis can appear in almost all components of the heart lung machine: around the aortic canulla and the drains, in the oxygenator and the roller pump, especially if the occlusion degree is not adjusted optimally. The critical shear stress values for haemolysis are approximately 150 N/m², but it depends on the exposure time. The combination of blood flow disturbances and contact with non-biological surfaces makes the critical shear stress values for haemolysis drop to approximately 14 N/m². The activated thrombocytes will aggregate and create embolies, whereof the largest will be caught in the filters of the ECC system.
Large negative pressures, created by for example the drains, will create turbulence and cavitation, following in micro-bubbles and embolies. In addition, the contact with the polymer- and metal-surfaces of the heart lung machine combined with the exposure to air at the drains activates the plasma enzyme systems, such as the coagulation and complementary
systems. By coating the surfaces in tubes, oxygenator and filters with heparin, the biocompatibility can to a certain degree be improved and thereby minimize trauma on the blood cells.
The heart lung machine and the extra corporal circulation technique is now so refined that the frequency of complications with respect to stroke and neurological symptoms following a coronary bypass operation seems to be similar to OPCAB, where the surgery is performed without utilizing the heart-lung machine.
Too low of a perfusion pressure, long lasting perfusion, and air embolies can result in temporary memory weakening and decreased kidney function. Serious neurological complications are seen with 1-5% of patients following coronary bypass operation. However, neuro-physiological tests indicate that up to 50% of the patients will experience small temporary implications on the brain following heart surgery.
The most feared complication is a massive air emboli, that can for example appear if the venous drainage ceases, the reservoir is emptied, and the pump is not stopped in time. This creates a risk of pumping air directly into aorta, typically with a fatal result.

The Perfusionist
During heart surgery with ECC, the control of the machine is performed by the perfusionist (figure 6), that has a two-year cross-disciplinary medical-technical education from the Scandinavian School of Extra Corporal Technology.
Prerequisites for the perfusionist education are a previous education as a nurse, engineer, bio analytical specialist, or medical doctor. The perfusionist has the responsibility for the perfusion, but the final responsibility is always with the surgeon.

Main tasks for the perfusionist are:

1. Acquiring and evaluation of relevant patient data prior to ECC (possibly in collaboration with the responsible surgeon or anaesthesiologist).
2. Planning the extra corporal circulation
3. Adjust priming fluids and medication used at ECC, using the regulations of the department.
4. Prepare and monitoring of the heart lung machine and accompanying devices in the operating room.
5. Establishment of the extra corporal circulation, including control and correction of physiological relationships during ECC – especially blood gasses, blood flow, blood pressure, degree of dilution as well as fluid and electrolyte balances.
6. Acquisition and archiving of relevant data.

The latest development within heart surgery and the extra-corporal circulation technology has resulted, that many ECC procedures are relatively complicated, and hence requires a large amount of overview and the ability to act promptly.

**Additional Literature:**


