CHAPTER II - Extracorporeal Circulation (ECC)

ECC is a complex method that allows substitution, for a certain period of time, of heart and lung functions: circulation, gas exchange, acid-base balance, regulation of temperature.

![Schematic ECC Components](image)

**Figure 1. Schematic ECC Components**

**History.** A major finding of the century is the invention and improvement of the artificial extracorporeal circulation technique of the heart-lung machine. The efforts of several groups of researchers have made possible this fantastic medical progress. In 1916, McClean discovers heparin, without which the extracorporeal circulation of blood (which otherwise would clot) would not be possible. The person who had the idea of such a machine was the American engineer Charles Lindberg, who performed the first trans-Atlantic flight, an audacious and visionary man.

Dr. John Gibbon is the one who first used in practice the heart-lung machine, in 1953, while working in Jefferson Medical College laboratories in Philadelphia. At first the heart-lung machine was massive, complicated, producing hemolysis blood and massive bleeding. Despite such inconveniences, the possibility of working inside the heart, on stopped heart, in order to repair heart defects, the heart-lung machine was accepted and gradually improved (Fig.)
Working together in 1955, DeWall and Lillehei improved cross-circulation and the first bubble oxygenator. Everything that followed led to the improvement of heart-lung machine (from 1965 Bramson: first membrane oxygenator, 1974 the first use of a computer centrifugal pump), until today to its routine use, day by day, in thousands and thousands of operations carried out successfully all over the world.

2. 1. The principles of extracorporeal circulation.

ECC is based on knowledge of physics and simultaneously on understanding human physiology and pathophysiology.

Using ECC ensures balance between the events occurring during open heart surgery. This provides the normal parameters of body functions: perfusion, gas exchange, adjusted pharmacological data (heparin, protamine, catecholamine, vasodilators, etc.) and the biological response of the body (systemic inflammatory response).

Perfusion. The basic role of the ECC is to maintain systemic circulation to physiological values during heart stop and hypocontractility (reperfusion).

Adequate perfusion of organs is performed by maintaining cardiac output (CO) and perfusion pressure.

Adequate cardiac output (CO) varies depending on body size (area), patient’s age, temperature and can be calculated for these variables.

<table>
<thead>
<tr>
<th>Condition</th>
<th>CO (L/min/m²)</th>
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<tbody>
<tr>
<td>Normothermia</td>
<td>2.5 – 2.8</td>
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<tr>
<td>Mild hypothermia (up to 300°C)</td>
<td>2.2 – 2.4</td>
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<tr>
<td>Moderate hypothermia (below 280°C)</td>
<td>1.6</td>
</tr>
<tr>
<td>Profound hypothermia (below 200°C)</td>
<td>1.2</td>
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Recommended value of perfusion pressure is between 50-80 mmHg.

The blood flow in the arterial line, and thus in the vascular systemic bed is non-pulsatile and generated mechanically by a pump. There are technical devices that allow generation of a
pulsatile flow. During ECC, organs which are vulnerable to hypoperfusion and hypotension: brain, kidney, should be particularly protected.

**a) Cerebral perfusion in mild hypothermia** - is controlled by self-regulatory mechanisms depending on the oxygen needs of brain tissue and PaCO2 (partial pressure of CO2) in arterial blood. Hypercapnia increases cerebral perfusion while hypocapnia decreases it. Perfusion pressure of 40 mm Hg and accurate CO allow self-regulatory mechanisms to ensure adequate cerebral flow.

**b) Kidneys** - they may also be affected by inappropriate perfusion, especially in diabetics and the elderly.

**Gas exchange**

Physiological gas exchange in pulmonary circulation during ECC is stopped. O2 and CO2 partial pressures of venous desaturated blood must be adjusted to arterial blood values. O2 and CO2 exchange is achieved by adjusting the oxygen flow and the composition of gas mixture (air and O2).

O2 in arterial pressure is adjusted by changing the concentration of O2 in gas mixture (O2 concentration increase leads to a proportional increase in arterial O2 concentration). O2 pressure in the arterial line should not exceed 250mm Hg. Higher values cause the toxic oxygen effect and favor the formation of microbubbles.

**Fig. 2. The effects of hypothermia**

CO2 pressure in the blood that returns to the systemic arterial bed is regulated through the flow velocity of gas mixture by the oxygenator (increased blood flow decreases CO2).

**Temperature (T)**

The patient's body temperature (T) is regulated during ECC by changing the temperature of the pumped blood. This technique is used to achieve various degrees of hypothermia and restore normothermia at the end of surgery. Hypothermia: reduces the rate of cellular metabolism which reduces tissue oxygen requirements (Fig.). This protects some organs which during surgery are not perfused with oxygenated blood.
Historically speaking, hypothermia was a basic method of myocardial protection in early cardiac surgery. The role of hypothermia has gradually diminished and now more and more cardiac surgery clinics prefer normothermia. Profound hypothermia (150 - 200°C) is a procedure used in surgery on the aortic arch, sometimes on the ascending aorta and in some operations for congenital heart malformations that require circular stop. In these cases, profound hypothermia is a method of protecting brain and other organs (kidney, liver, intestine, etc.). Setting hypothermia and later returning to normothermia is performed regularly. This is done by the heat exchanger and the water mattress on which the patient lies during surgery. The body temperature is influenced by the temperature of perfusion solutions, temperature of the operating room and local applications of ice (around cephalic extremity during circulation stop).

**Heparin**

Heparin is a mixture of mucopolysaccharides with molecular weight between 3000-30000 daltons. Heparin is administered before canullation and is designed to prevent blood clot formation in contact with the artificial surface of the ECC system. The efficiency of heparinization is essential because the total obstruction of ECC system with blood clots causes patient’s death. The heparinization level is continuously controlled during ECC by measuring ACT (activated clotting time). 500S ACT value is considered effective heparinization to ensure normal development of surgery in the ECC. This level of the ACT is obtained by intravenous administration of 2-3 mg / kg of heparin. Half-life of heparin varies from one patient to another and has a value between 1-3 hours. The degradation of heparin is faster in normothermia and based on ACT values. It is often necessary to readjust it through repeated administrations. The anticoagulant effect of heparin is neutralized at the end of the ECC by administering a dose of 1 mg protamine for each mg of heparin administered. Protamine is a protein with low molecular weight which inactivates heparin by forming a complex with it. Protamine can cause side effects: anaphylactic reaction, pulmonary vasoconstriction (right ventricular failure), hypotension, their severity sometimes requiring serious treatment. The rebound phenomenon is the postoperative release of heparin from its protamine complex, with the recurrence of heparin specific anticoagulation effect (postoperative bleeding).

**Inflammatory response**

The setup and use of the EEC is a stressful situation to which the human body is exposed. The blood contact with the nonendothelized surface of tubes, canullae and oxygenator triggers a
systemic inflammatory response. Thus, action occurs as humoral and cellular response cascade (complement system, kinine - kalikrein, coagulation and fibrinolytic system, activation of thrombocytes, leukocytes and endothelial cells). This generalized systemic inflammatory response is sometimes as clinical manifestation the postperfusion syndrome. Clinical postperfusion syndrome can create the following symptoms: respiratory failure, diffuse brain damage, renal failure, acute pancreatitis, acute septic lesions, disseminated intravascular coagulation or hyperthermia. Serious lesions may take the form MSOF (multiple organ system failure).

Microembolizations (gas or small solid embolic particles) are responsible for transient cerebral and renal dysfunction. Gas embolisms are caused by microscopic bubbles mostly nitrogen and solid microembolisms are the result of fibrin particles, erythrocytes, leukocytes, fat cells, particles of atheromatous plaques, talcum, powder, bone fragments, pieces of muscle, etc.. Most of these microemboli are removed from circulation by using filters.

2. 2 Myocardial protection during extracorporeal circulation

Most surgical interventions using the ECC require temporary exclusion of the heart from the systemic circulation which is done by clamping the ascending aorta. Aorta clamping stops oxygenated blood flow in coronary artery bed and causes a period of myocardial ischemia. The role of myocardial protection techniques is to maintain the viability of myocardium and its functional capacity during ischemia and subsequent reperfusion.

The principle of myocardial protection techniques is to reduce the metabolic needs of the myocardium during ischemia.

Cardioplegia

Stopping heart electromechanical activity after aortic clamping (interruption of coronary circulation) is the optimal protection of myocytes. This is done by administering intracoronary cardioplegic solution whose main effect is to induce cardiac asystole because of high concentration of potassium (K +).

Cardioplegia can be crystalline or blood (cardioplegic concentrated solution is mixed with oxygenated blood at a rate of 4:1). Blood cardioplegia ensures better myocardial ischemic protection through superior oxygen and blood buffering capacity.

Cardioplegia may be administered antegrade (in the aortic root, in coronary artery ostia or through saphenous venous grafts in coronary surgery) or retrograde through the coronary sinus (advantageous especially in coronary heart diseases with stenotic arterial bed) and a combination of both methods.

Circulatory stop and deep hypothermia

After the ECC setup, the temperature is lowered to 150-200 C. At the same time, the patient’s body is cooled by external application of ice bags. Safe estimated duration of circulatory stop is
about 40 minutes. This technique is used especially in aortic and congenital heart defect surgery.

**Intermittent clamping of the aorta**

This technique is used in coronary surgery and consists in the induction of ventricular fibrillation in mild hypothermia (330°C) followed by clamping the aorta. The heart fibrillates during distal anastomoses and then it is declamped and defibrillated. Although theoretically fibrillation is disadvantageous to myocytes in terms of energy, clinical experience with this technique is favorable.

**Betaplegia**

A similar effect to heart stop can be achieved pharmacologically by administration of esmolol in the ascending aorta (short-acting beta-blocker). Myocardium is perfused with normothermic blood during surgery.

**2. 4. ECC Components**

**Venous drainage** - is the diversion of a part of the patient's desaturated venous blood into the ECC. Blood reaches the extracorporeal circuit by gravity or active suction systems.

Technically, venous drainage is achieved by inserting venous cannulae into vena cava or femoral vein. The best place to put cannulae is in superior and inferior vena cava at their junction with right atrium. Two cannulae can be used (one for each vena cava) or a single venous cannula introduced in the right atrium through the right lug whose tip is positioned in the inferior vena cava. Special design of this unique cannula allows blood suction from IVC through its tip and blood from the right atrium (and SVC) through the holes in the cannula placed in the right atrium (RA).

Venous drainage can be achieved through femoral vein using special longer venous cannula.

**Arterial cannula** - is to transport oxygenated blood from the ECC to the arterial bed of the patient. The most common place of arterial cannulae is the distilled area of ascending aorta near the brachiocephalic trunk. In some circumstances cannulation of ascending aorta is impossible or disadvantageous. The alternative is the cannulation of femoral iliac or axillary arteries which requires special cannulae.

**Venous reservoir** - is connected in the venous part of the ECC and collects the patient's venous blood. Filtering processes are performed here and medication can be administered. It is before the pump in the ECC.

**The pump itself** - is a component of ECC. It plays the role of the heart: it pumps (pushes) distorted venous blood into the oxygenator and then into the patient's arterial bed, with cardiac
output calculated for each patient, with smaller lesions of blood elements. There are several types of pumps: roller pump, axial pump, centrifugal pump.

* **roller pump** - is the most used. Blood is driven through elastic tubes by the motion of rolls which compress their lumen. It is a high-performance pump but it can cause lesions of blood elements. An important term is "occlusiveness" and it represents the external pressure exerted on the plastic tubes by the pump rollers. Excessive oclusiveness may cause significant haemolysis.

* **centrifugal pump.** Blood is propelled by falling on smooth surface of a rotating cone. When the acceleration of blood required is sufficient, blood is discharged by the centrifugal force through the external tube system. Lesions of blood elements are minimal, risks of microembolisms are low, but it is a very expensive pump, which limits its use.

* **axial pump.** Blood is induced through a tube being propelled by a rotating turbine. This "internal" pump is introduced in the aorta, the aortic transvalvular left ventricle (left ventricular assist device) in acute heart failure or circulatory support in surgery performed without aortic clamping (beating heart cardiac surgery).

Oxynator- is an essential component of the ECC. Its role is to ensure control of gas exchange between the patient's blood and a gas mixture. The functional capacity of oxygenator is related to its surface that allows gas exchange. This is done according to the pressure gradient of gases on both sides of exchange surface. At the same time, however, contact of blood with the large foreign surface, triggers a systemic inflammatory response.
Types of oxygenators:

- **Bubble oxygenator:** gas exchange occurs during direct contact between blood and oxygen bubbles. This type of oxygenator was abandoned because of numerous microembolisms, damage of blood elements and the inflammatory response triggered.

- **Membrane oxygenator:** Blood and gas mixture are separated by a membrane with a large area of 2-5 m², which allows only gas diffusion. The advantage of this type of oxygenator is the possibility of its long use. Disadvantages are represented by the need for far greater volume-priming, the large exchange surface and very high price.

**Heat exchanger** - performs cooling and heating of patient’s blood. It is located in the venous part of ECC before oxygenator. A necessary component is the unit of heating-cooling which brings thermal agent (water) exactly at the desired temperature. The water is led through a spiral tubular heat exchanger which mediates heat exchange and patient's blood.

**Accessories.** Aspirators, Filters, Hemoconcentration Filters
• Aspirators are cannulae placed in different heart cavities (left atrium, left ventricle, aorta, etc.) during ECC. They prevent cardiac chamber dilation, flooding of the operating field and ensure deairing of the heart.

• Filters are designed to retain the solid particles and gaseous microembolisms of ECC. There are filters located beyond the oxygenator and filters of priming that are used about 10-15 minutes before the start of the ECC and seek to retain solid particles within the tubular system.

Figure 3. Hemoconcentration Scheme

• hemoconcentration filters are designed to remove excess of crystalloid fluids from ECC (Fig.). Their performance is achieved by filtering water and substances with small molecular weight through a semipermeable membrane. Instructions for use of hemoconcentration filters are decreased hematocrit below 20%, water retention preoperative heart failure and renal failure.

Priming solution - is the solution that fills the original circuit ECC. Blood was first used for priming but because of the many disadvantages (viscosity increased risk of infection, etc..) use has been replaced by other solutions. Currently, during surgery, ECC system is filled with these solutions that achieve a global haemodilution to a hematocrit of 20%. Addition of blood priming is that hematocrit falls below 20% after starting the ECC. 1400-1800 ml priming volume is varying by type of oxygen tank and pipe length. It contains crystalloid priming solution (Ringer’s or Hartmann) plus colloid solutions (dextran, albumin) that increase the osmotic activity of priming reducing fluid accumulation in the interstitial tissue. The priming is added: heparin, mannitol, bicarbonate, corticotiroids, antibiotics, magnesium ions, etc.
2.5. Standard procedure for ECC

**Perfusionist’s Preparation**

Perfusionist is the person responsible for the operation of the ECC and is endorsed on the type of surgery and the patient's medical data. He is the one who calculates, based on the patient's body surface area, the needs for priming, cardiac output (to avoid haemodilution) and selects the type of cannula used. Perfusionist fills with priming the entire system and ensures its deairing. The ECC is now ready and heparin can be administered.

**Patient Preparation**

Surgeon dissects and exposes the main places of insertion of cannulae (ascending aorta and right lug), which are provided with sutures using monofilament yarn sized 3 / 0 or 4 / 0. After administration of heparin the surgeon asks the perfusionist to move priming inside the ECC pipe to remove air bubbles from its arterial part. Tubular circuit is clamped and divided into two segments: arterial and venous. Aortic cannula is inserted through an incision in the ascending aorta and connected to the ECC system; similarly venous cannulae are inserted into the right atrium. The patient and the ECC system are prepared for the start of cardiopulmonary bypass.

**ECC Initiation and Development**

Starting the ECC is made at surgeon’s order who maintains a clear bilateral communication with the perfusionist. Perfusionist repeats and confirms orders and informs the surgeon on his activity.

- Fig. ECC Setup and Start
After the final check of the entire system and achievement of the appropriate level of heparinisation, the perfusionist takes up the clamp on the arterial line and slowly increases ECC flow. (Fig.) At the same time the intravenous line is filled with patient's blood within the circuit. ECC flow is thus increased slowly up to precalculated level. The perfusionist allows the entrance of gas mixture within the oxygenator and after the flow is achieved patient’s ventilation stops. During the surgery monitoring of pump flow is achieved, circuit pressure, the patient's blood pressure, urine output, core and peripheral temperature oxygen saturation and heparinisation. At the end of surgery blood flow is gradually introduced into the patient's vascular bed. Cannulae are withdrawn and effect of heparin is neutralized by protamine administration.

Exiting the ECC

It started after restoring cardiac electrical activity, after adequate reperfusion period during surgery. The perfusionist clamps intravenous line gradually and reduces the flow of venous blood pump allowing the introduction of venous blood into patient’s circulation. Blood pressure (BP) and cardiac filling (central venous pressure) are carefully monitored. In case the BP and code filling are optimal, the ECC can be stopped.

Critical situations
Gas embolism - is by sending a large quantity of gas in the patient's vascular bed. Oxygenator thrombosis by inappropriate heparinisation and poor control of anticoagulation.

Surgical Complications
They are mostly related to incannulation sites. Incannulation technique must be gentle and safe, ensuring adequate protection during ECC when increased pressure in the arterial system in particular may occur. Most complications occur during the reconstruction of vessels to incannulation sites, the most serious is bleeding from the arterial wall rupture or acute dissection of the aorta. The risk of vascular complications is significantly increased when there is pathology of vascular wall (in atherosclerotic patients or fragility of the tissue in the elderly).

2.6. Special Procedures of the ECC

- Left Heart By-pass - is used for perfusion of the lower half of the body in the descending aorta surgery, in the emergence of subclavicular artery (aneurysm, traumatic rupture, thoracic-abdominal aneurysm or in some cases the aorta coarctation). Its role is to prevent spinal ischemia and abdominal organs (kidney in particular).
**Left Heart Circulatory Support** - is a treatment option of left ventricle failure if left ventricle performance cannot be achieved by pharmacological methods or contrapulsation flask. The system pumps blood from left atrium into the aorta and achieves left ventricular performance. The circulatory support can be used for a period of between several hours to several days. The system is composed of a cannula inserted into the left atrium (inflow), an incorporated pump with a unidirectional valve and a cannula in the ascending aorta (outflow).

**Femuro-Femoral Bypass** By cannulation of femoral artery and vein a full or partial cardiopulmonary bypass may be performed.

**Complete Femuro-Femoral Bypass** - is done in an emergency requiring the ECC before sternotomy, reinterventions or large aneurysms or thoracic surgery. It dissects femoral vessels and they are cannulated using special tubes. Bypass conduct does not differ from standard mode.

**Partial Femuro-Femoral Bypass** - is used for perfusion of the lower half of the body and the descending aorta surgery. The technique is similar to femuro-femoral bypass. Hemodynamically, there are differences: the perfusion of top half of the body depends on the cardiac performance and lower half on the ECC.

**Circulation Stop in Deep Hypothermia.** - Some operations (aortic arch surgery, some surgical procedures in congenital heart defects) may be made only in circulation stop. This is achieved using deep hypothermia of the whole body (150-200°C). If circulation stop takes more than 40 minutes it can cause irreversible brain damage. To avoid this event, cerebral perfusion can be done antigrade - through a cannula inserted through the carotid arteries or retrograde through the vena cava superior, with cold oxygenated blood.

ECMO (Extra Corporeal Membrane Oxygenation) - is a therapeutic option in cases of respiratory failure when PaO2 and PaCO2 values compatible with life cannot be maintained with artificial ventilation. Venous blood is drained from the jugular vein using a centrifugal pump and then oxygenated in oxygenator. Oxygenated blood returns into circulation through a cannula inserted into the femoral vein. ECMO is not a patient's circulatory support and is used especially in cases of premature infants with congenital heart defects with excellent results.

Long-term contact of blood with foreign surfaces of this system could result in traumatic injuries of erythrocytes and platelets with coagulation disorders. Clinical manifestations of these side effects may include: bleeding, renal failure, liver failure, generalized edema, etc.