ELSO Guidelines for Adult and Pediatric Extracorporeal Membrane Oxygenation Circuits

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***Disclaimer*: This guideline describes the ECMO circuit for all patient populations. These guidelines describe safe practice based on extensive experience and are considered consensus guidelines. These guidelines are not intended to define standard of care and are revised at regular intervals as new information, devices, medications, and techniques become available.**

The Extracorporeal Membrane Oxygenation (ECMO) circuit

The extracorporeal membrane oxygenation (ECMO) circuit is composed of three main components including a pump, oxygenator, and heat exchanger. Venous blood is drained and then pumped through the heating component (which is usually integrated in the oxygenator), the oxygenator, and then returned to the patient. The circuit blood is returned to an artery (venoarterial ECMO [VA ECMO]) or a vein (venovenous ECMO [VV ECMO]). Circuits can have multiple access ports added as needed. The benefit of circuit access ports is the ability to administer medications, perform continuous renal replacement therapy (CRRT) through the ECMO circuit, and offer additional monitoring capabilities. However, too many connectors and access points in the circuit can lead to blood stagnation and clot formation, as well to an accidental rupture or disconnection. Highly complex ECMO systems will require a more skilled and knowledgeable ECMO specialist (the technical specialist trained to manage the ECMO system and the clinical needs of the patient on ECMO under the direction and supervision of an ECMO trained physician [ELSO Guidelines for Cardiopulmonary Extracorporeal Life Support, 2019])

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available at the bedside. An ECMO specialist should have a strong intensive care background in neonatal, pediatric, or adult critical care. (ELSO Red Book 5th Edition Ch 4).[1]

Venoarterial or Venovenous Extracorporeal Membrane Oxygenation

VA ECMO is indicated in conditions of acute cardiac failure in which the heart is unable to maintain the perfusion and metabolic demands of the body. VA ECMO is used for respiratory support in neonates and some small children, also can be used for children and adults for concomitant respiratory and cardiac failure. (ELSO Red Book 5th Edition Ch 4).

VV ECMO is traditionally used in patients with any potentially reversible condition in which the lungs are unable to ventilate and oxygenate despite the use of optimal mechanical ventilation and treatment. VV ECMO may be used in neonates due to respiratory failure. The neonate must be in a facility that has expertise in neonate respiratory failure and has double lumen cannulas available for placement. It is also available to be used as a bridge to lung transplantation, enabling patients to be weaned from mechanical ventilation and mobilize, while waiting for the transplant procedure.

Venoarterial Extracorporeal Membrane Oxygenation Cannulation Sites

Neck Cannulation

The venous cannula is inserted in the right internal jugular vein and the arterial cannula is inserted in the right common carotid artery.

Using the internal jugular vein for drainage, an alternative cannulation strategy for a larger pediatric patient and/or adult patient can be used to deliver oxygenated blood using the right subclavian artery or axillary artery.

Alternative cannulation technique (subclavian or axillary) can be used as it may permit increased mobility for the patient whereas reducing complications seen with groin cannulation all while preserving the carotid artery (**Figure 1**). (ELSO Red Book 5th Edition Ch 5).

Central Cannulation

Central cannulation includes direct venous cannulation into the right atrium and direct arterial cannulation of the ascending aorta.

Central cannulation is most used for patients who cannot be weaned from cardiopulmonary bypass (CPB) in the operating
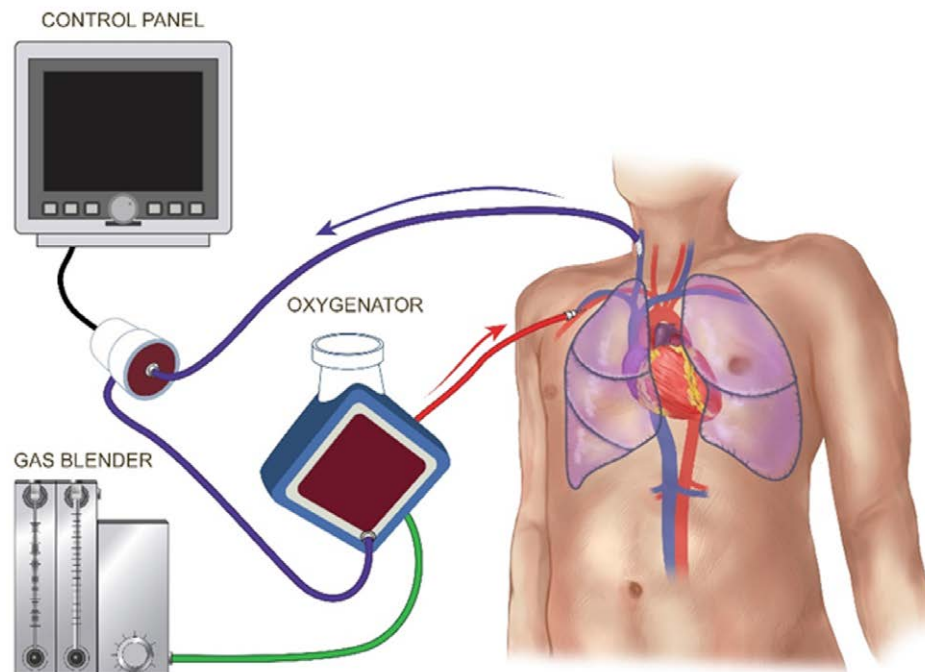
Figure 1. Venoarterial (VA) Internal Jugular Vein Subclavian Artery.

room (OR). CPB is for short-term heart and lung support during cardiac surgical intervention. It uses a reservoir as well as an open circuit configuration for medication and volume access. ECMO is for long-term use and uses a closed configuration. Conversion between CPB and ECMO can be performed using the existing cannula.

Central cannulation may be used to obtain higher bloods flows to fully support the patient's metabolic needs during clinical conditions such as sepsis.

Central cannulation enables more optimal drainage and thus better unloading of the heart than peripheral VA ECMO (**Figures 2 and 3**).

Femoral Vein and Femoral Artery Cannulation

Femoral vein and femoral artery cannulation are generally used for VA ECMO cannulation in adults and potentially children that are larger than 30 kg.

If the femoral artery is cannulated, a reperfusion cannula to that limb will ideally be placed to prevent limb ischemia, unless the cannulation was performed using a graft technique ensuring adequate blood flow to the lower limb.

It can be beneficial during extracorporeal cardiopulmonary resuscitation (ECPR), either percutaneously or *via* cutdown, due to the ability to cannulate with less interference or cessation of chest compressions as in central cannulation.

Due to the dual circulations (native output *versus* ECMO output), there will always be a degree of differential oxygenation between the upper and lower body, depending on the degree of native left ventricle and lung function. This will become more pronounced when the native lung function

is poor, and the left ventricle contractility is improving. This mixing of deoxygenated blood *via* native cardiac output should be assessed as it can lead to myocardial and/or cerebral ischemia (ELSO Red Book 5th Edition Ch 4). It will be important to ensure the presence of a right upper extremity arterial line (right radial arterial line is preferred), cerebral oximetry, and/or pulse oximetry in the same position as the arterial line (**Figure 4**).

Venovenous Extracorporeal Membrane Oxygenation Cannulation Sites

Single Site Cannulation

Dual lumen cannula with the tip in the right atrium; here blood is drained *via* the superior vena cava (SVC) and right atrium (RA) with the oxygenated blood returned into RA towards tricuspid valve into the pulmonary artery (PA).

Bicaval cannula with the tip of the cannula in the inferior vena cava (IVC); here the blood is drained *via* IVC/SVC and the oxygenated blood is returned *via* RA towards tricuspid valve into the PA.

A dual lumen cannula with a single drainage site might also be positioned into the main PA; here the venous blood is drained from the RA and the oxygenated blood is directly reinfused into the PA (**Figures 5 and 6**).

Two Site Cannulation

Femoral vein/jugular vein: drainage from the femoral vein and return into the internal jugular vein or drainage from the jugular vein with blood return into the femoral vein.
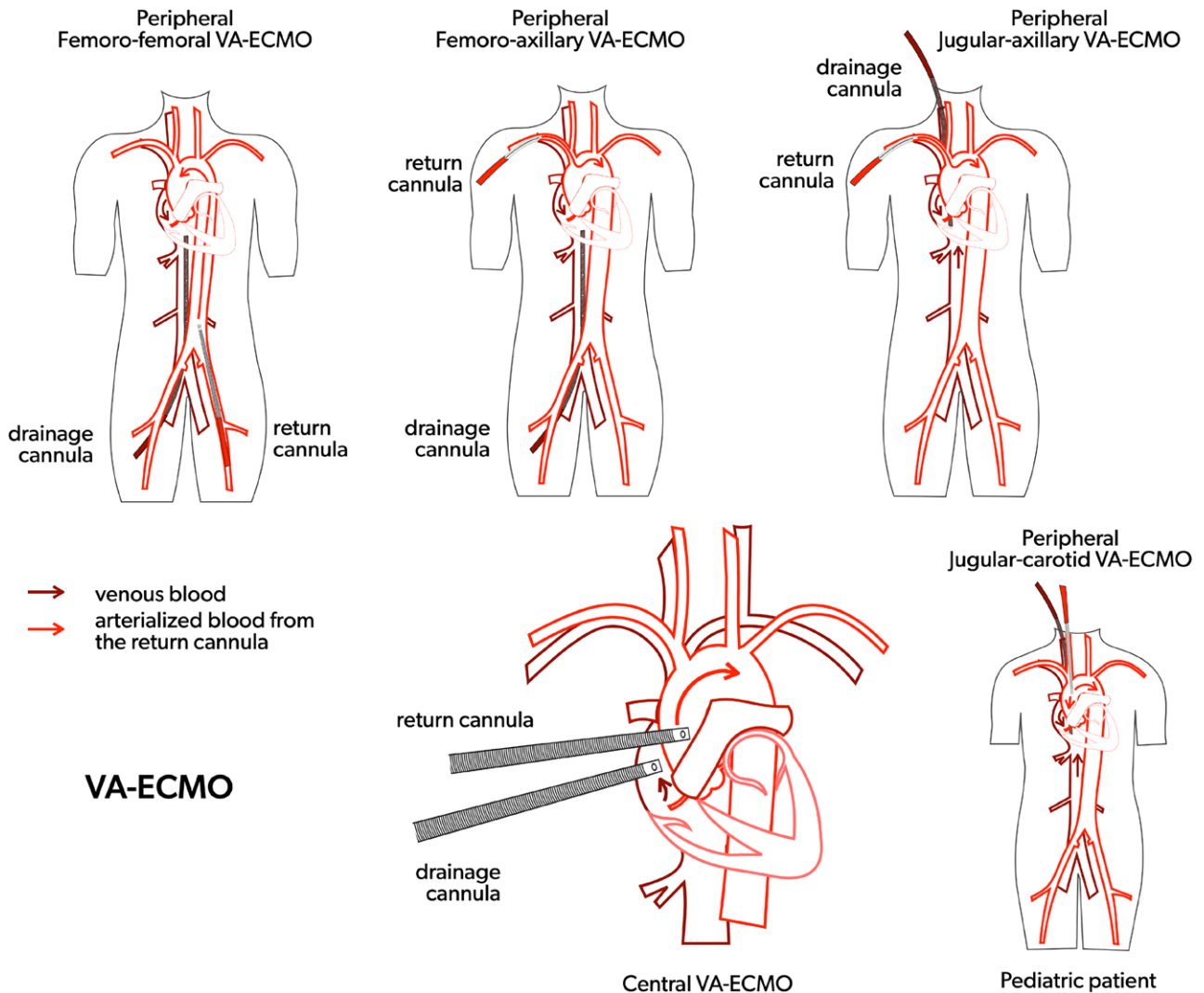
Figure 2. Venoarterial extracorporeal membrane oxygenation (VA ECMO) cannulation strategies.

Femoral vein/femoral vein: drainage with a shorter cannula in the bifurcation of the femoral vein with a longer cannula returning in the right atrium or inferior vena cava.

Femoral vein/pulmonary artery: drainage *via* a cannula positioned in the RA *via* femoral vein and reinfusion of oxygenated blood *via* a second cannula positioned in the main PA through a direct or percutaneous (*via* the right internal jugular vein) cannulation (**Figures 7 and 8**).

Recirculation

Recirculation occurs in VV ECMO when the reinfused oxygenated blood is drained back into the ECMO circuit causing low systemic oxygenation and high ECMO circuit inlet saturations. (ELSO Red Book 5th Edition Ch 4).

The amount of recirculation is directly related to the cannula position, pump flow, and cardiac output.

Malposition of the cannula can greatly affect the amount of recirculation *i.e.* Right IJ catheter is too low with two site VV or rotated the wrong way with dual lumen catheters.

It occurs when the pump blood flow rate is higher than the patient's native cardiac output, due to left/right cardiac failure or severe pulmonary hypertension.

With adequate cardiac output and proper cannula position, pump flow increases oxygenation delivered to the patient.

Recirculation can be estimated by calculating the recirculation fraction:

$$S_{pre}Ox - SVO_2 / S_{post}Ox - SVO_2$$

Effective Flow calculation:

$$Total\ Flow - (Total\ Flow * Recirculation\ Fraction)$$

Recirculation Symptoms:
Patient arterial desaturation
SVO_2 and SpO_2 will have a small differential between them. (Example: SVO_2 87% and SPO_2 92%) or in severe cases the SVO_2 may be higher than the SPO_2 (SVO_2 92% and SPO_2 87%).

The venous blood will be similarly bright red as the post oxygenator blood. If pre and post oxygenator O_2 saturations are measured, both O_2 saturations will be very high and only small differences will be noted (**Figure 9**).

abdominal aorta

ECMO arterial return cannula

Distal Perfusion Cannula
(femoral introducer)

common femoral
artery

deep femoral artery

arterial cannula
side port

superficial femoral
artery

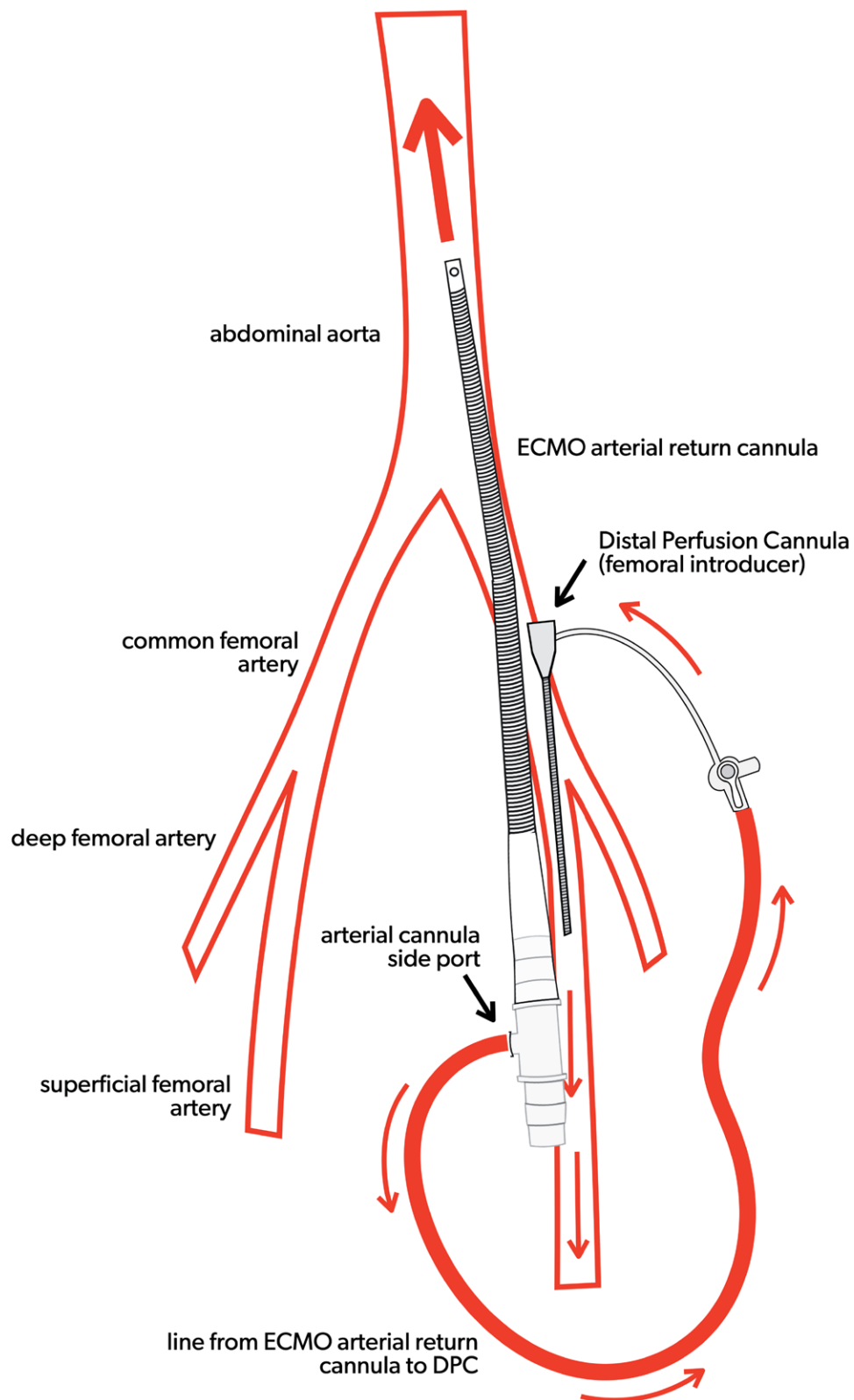line from ECMO arterial return
cannula to DPC

Figure 3. Venoarterial extracorporeal membrane oxygenation (VA ECMO) arterial cannula with distal perfusion cannula.
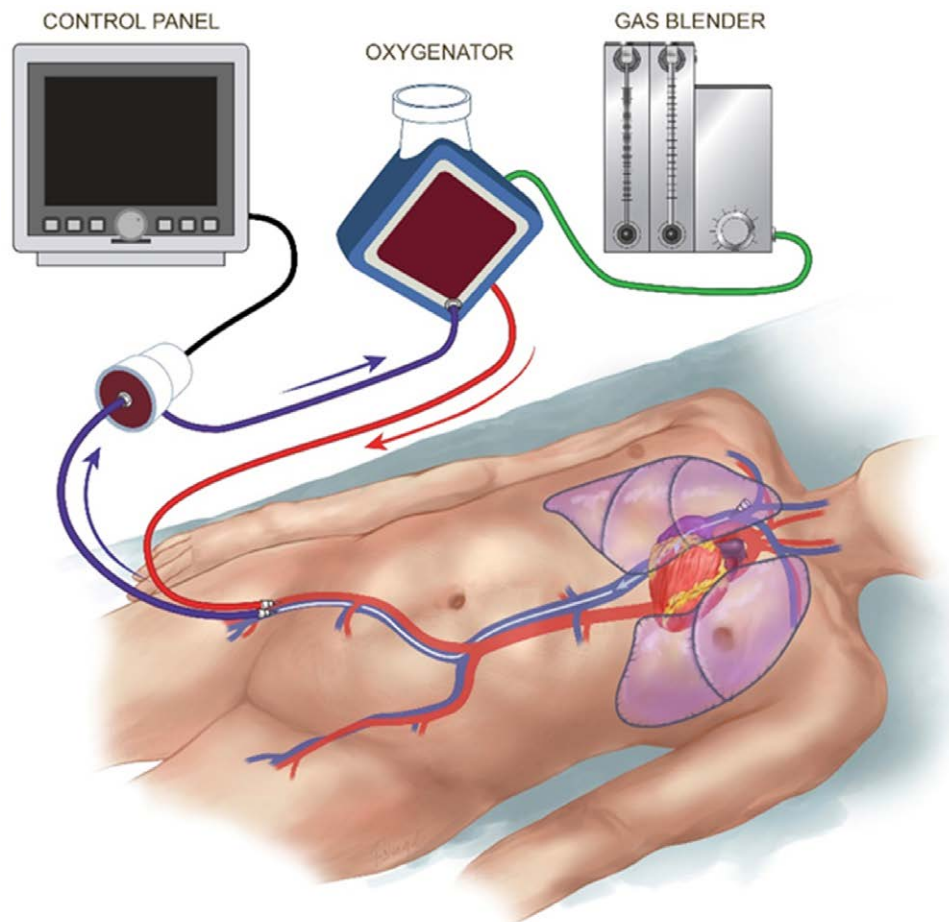
Figure 4. Venoarterial (VA) femoral vein femoral artery cannulation.

Cannulation Selection

Selection of the right cannula is vital for a successful ECMO run and needs to be carefully selected for each individual patient. Blood flow needs to be sufficient in quantity, but also important is the efficiency in terms of where blood is drained and returned. The choice of the cannula is not only guided by the aimed degree of support, but also by the size and condition of the vessel, patient size, possible site of placement, type of insertion procedure, and desired location of blood drainage/return. (ELSO Red Book 5th Edition Ch 4).

Cannula size or diameter refers to the outer diameter of the cannula and is expressed in French (1 FR = 0.33 mm). Diameter size should be selected in accordance with the desired amount of flow for the individual patient and can be guided using the pressure drop/flow charts of the available cannula (instructions for use).

Pressure Drop

Pressure drop is the difference in pressure entering the cannula and the pressure leaving the cannula. It is directly proportional to the cannula length and the viscosity of the fluid, and inversely proportional to the fourth power of cannula diameter. So, doubling the length will double the pressure drop, and doubling the size will reduce the pressure drop to 1/16th of baseline.

Common practice is not to exceed a pressure drop of 100 mmHg. Hemolysis might be monitored routinely to determine nonturbulent blood flow through the cannula. Pressure drop *versus* flow charts are commonly used to determine the right size cannula. It should be noted that the manufacturer charts are tested using water which is an underestimation of the actual pressure drop in the blood. The Hagen–Poiseuille equation can be used to describes the relationship between pressure, resistance and flow rate (**Figures 10 and 11**).

Cannula design

Tip design and side ports

The number and position of side ports are important as it has an impact on pressure drop, the location of blood drainage, and blood reinfusion. The most common cannula designs:

Blunt tip cannula: one central hole at the tip.

Lighthouse tip cannula: central hole with some distal side holes around the tip.

Multistage cannula: side holes at different stages along the cannula.

Interrupted multistage cannula: multiple drainage ports along cannula.

Number of lumen (1 or 2): dual lumen for ECMO with single insertion site (VV ECMO).

Connection with tubing: with or without connector, connection size (1/2", 3/8",1/4", and 3/16").
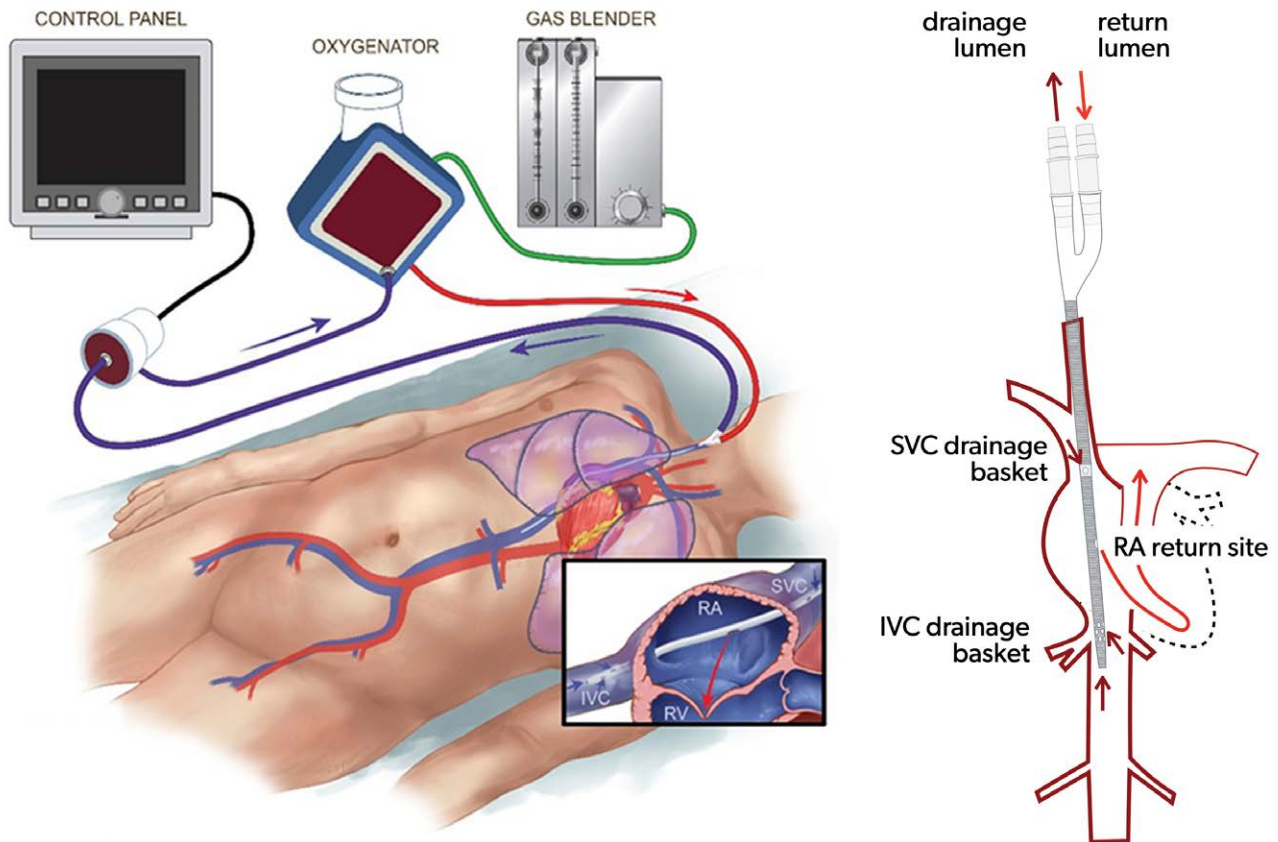
Figure 5. Venovenous (VV) single cannulation (RIJV).

Coating: to optimize biocompatibility.

Wiring and stiffness: to avoid cannula kinking or collapsing.

Cannula insertion tools: suited guidewires (length, stiffness, and curves) and vessel dilators (tip design, smooth transition with cannula tip) are important for uncomplicated percutaneous insertion.

Cannula indicators: for placement control (**Figure 12**).[2]

Overview of an extracorporeal membrane oxygenation circuit

ECMO circuits are similar for VV and VA ECMO, except that there might be extra cannulas/lines added in VA ECMO; an extra drainage line can be added if direct left ventricular unloading is performed *via* the ECMO circuit, or a return line can be added if distal perfusion of the cannulated limb is performed *via* ECMO. In cases of hybrid ECMO (veno-venoarterial or VP), additional drainage and return lines are hooked up to the extra cannula. These lines need to be safely incorporated in the circuit all while monitoring the additional flows. Understandably, there are different ECMO circuit sizes depending on the size of the supported patient, or the degree of required support. Size can be influenced by the choice of the oxygenator, pump, and diameter/length of the tubing (**Figure 13**). (ELSO Red Book 5th Edition Ch 5).

Circuit composition

The length of the tubing is center-specific. The longer the tubing, the more resistance, and the more artificial surface the patient will be exposed to. However, there needs to be enough tubing to be able to properly mobilize the patient, operate in other areas in the hospital such as the catheterization lab or the OR, and transport if needed (**Figure 14**).

Bridge (optional): A bridge connects the venous side of the circuit to the "arterial" side or post oxygenator using additional connectors. Centers have used various types of bridges to accommodate other needs such as continuous arterial blood gas monitoring or maintaining safe flows with weaning. The bridge is used mainly for weaning neonatal and pediatric patients from VA ECMO to maintain the circuit integrity during the weaning period.

Bladder (optional): A bladder can be used to attenuate the negative venous line pressures generated by the centrifugal ECMO pump. The idea of the bladder is to act as a buffer by eliminating any trauma caused by excessive suction with the drainage catheter. The bladder is mandatory for roller pumps because it also acts as a servo-controller for the pump. The Better-Bladder allows the venous line pressure to be measured in its chamber without accessing the circuit, reducing the risk of air embolism. If no bladder is present, an additional connector with a luer-lock may be used to continuously monitor venous line (pump inlet) pressures.

Shunt (optional): If a shunt line is used, a luer connector can be added with additional tubing to direct blood flow from the positive pressure side (post oxygenator) of the circuit to the negative pressure side (pre oxygenator) of the circuit.
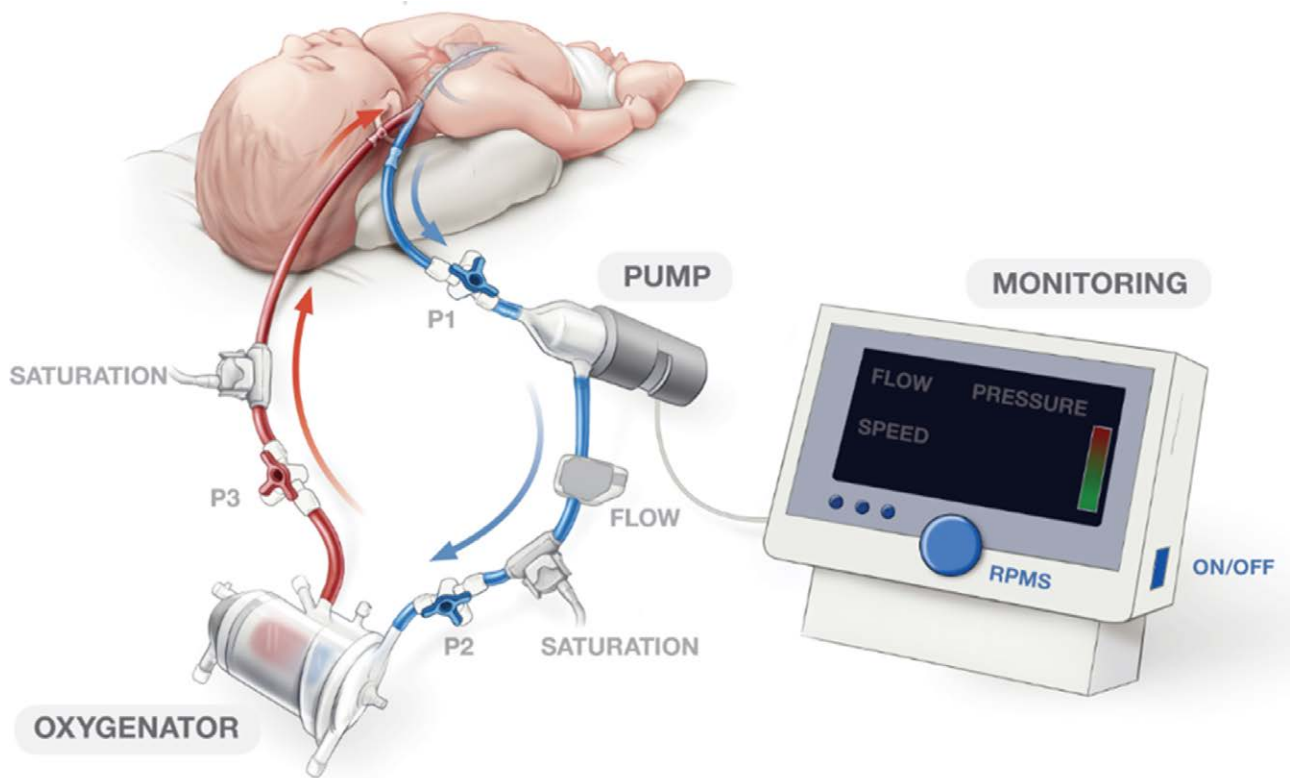
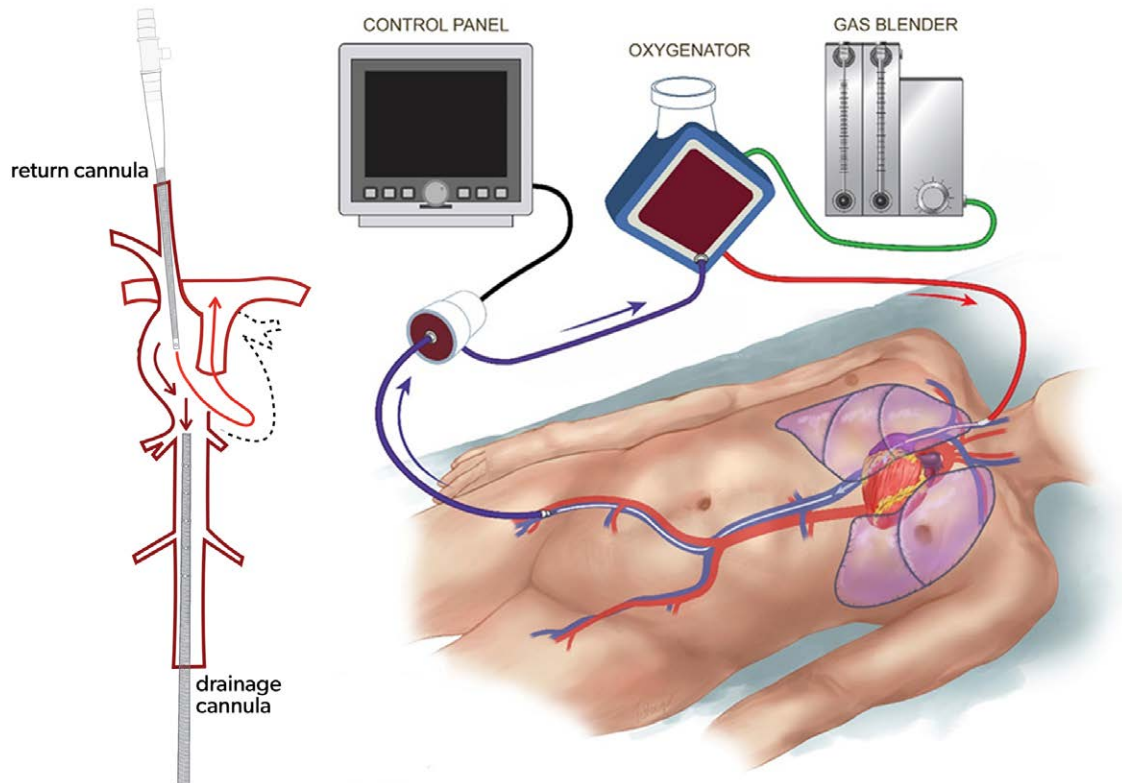**Figure 6.** Peds Venovenous (VV) single cannulation (RIJV).

Figure 7. Venovenous (VV) femoral vein right internal jugular cannulation.

Femoro-Jugular VV-ECMO

return
cannula

drainage
cannula

Femoro-Femoral VV-ECMO

return
cannula

drainage
cannula

Femoro-PA VV-ECMO

return
cannula

drainage
cannula

→ venous blood

→ arterialized blood from the return cannula

→ mixed venous/arterialized blood entering
righ heart/PA

Double site VV-ECMO
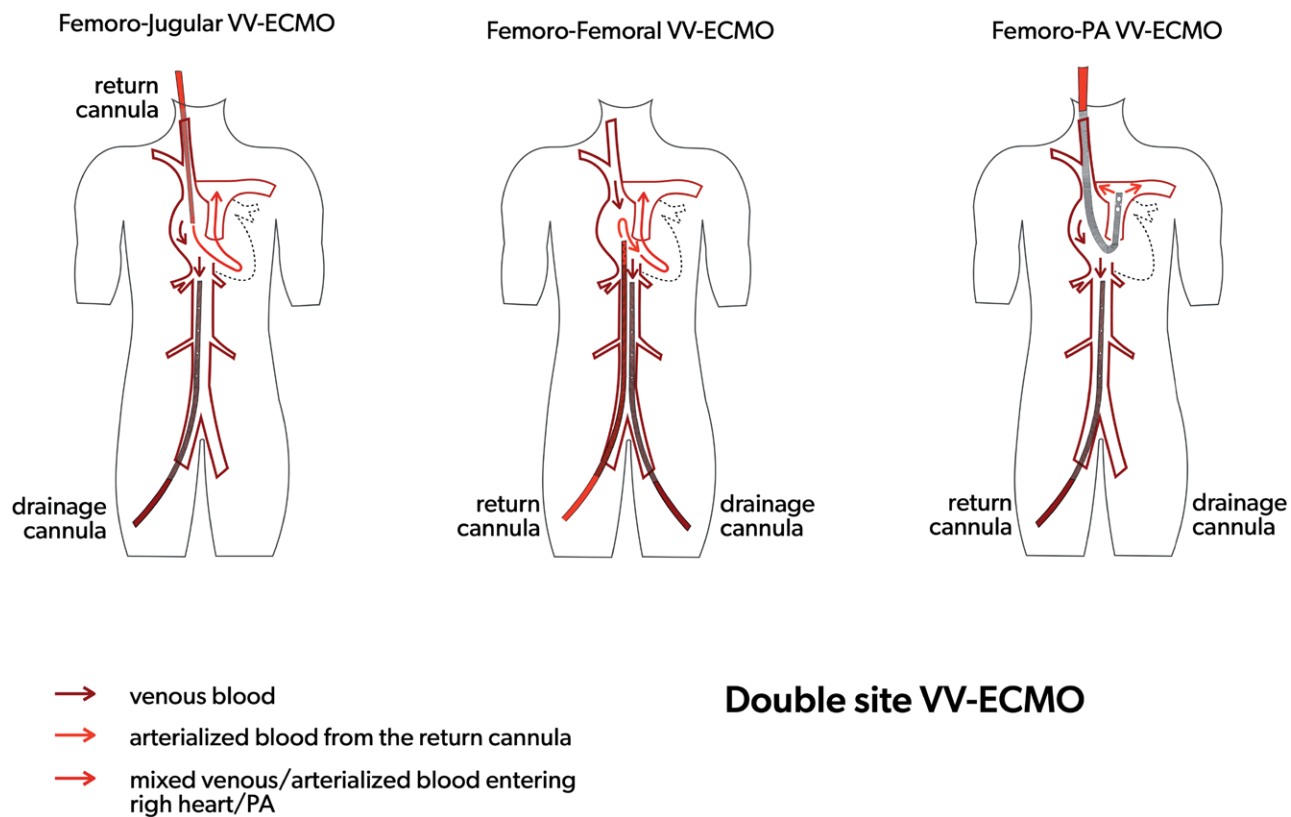
Figure 8. Two site Venovenous extracorporeal membrane oxygenation (VV ECMO) cannulation strategies.

return cannula
SVC

RA

drainage
cannula IVC

return cannula
RA

RA

drainage
cannula IVC

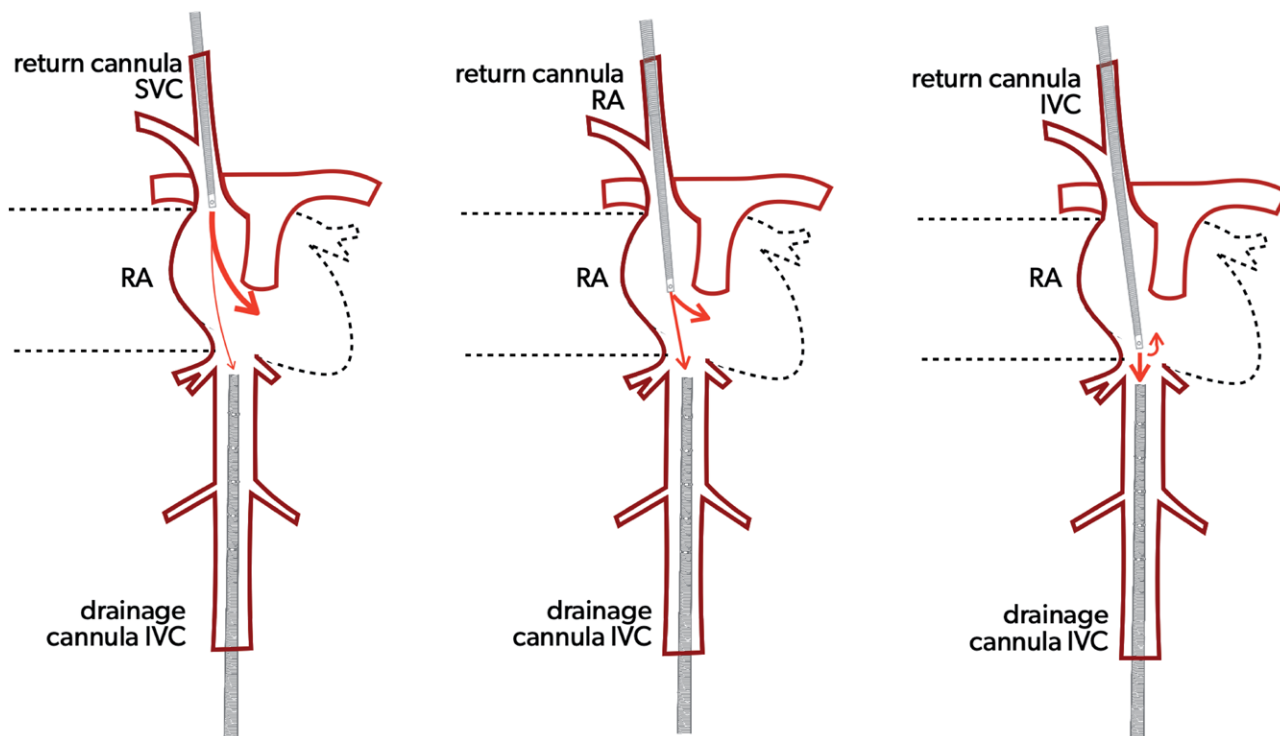return cannula
IVC

RA

drainage
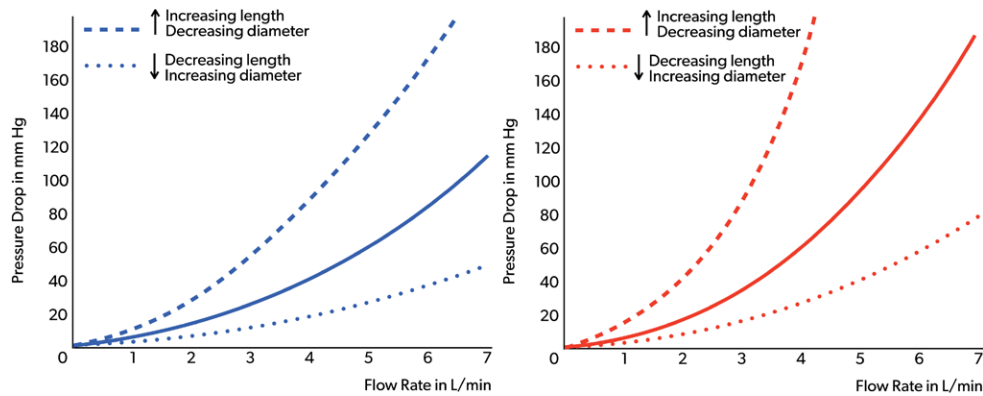cannula IVC

Figure 9. Recirculation.

Figure 10. Arterial and venous cannula pressure drop.

(1) *Benefits of Shunt*: Additional monitoring such as a continuous pump arterial blood gas may be obtained through the shunt. The additional flow provided through the shunt to the oxygenator may prevent the bridge being opened when weaning flows of smaller patients. A hemofilter may be placed in the shunt for slow continuous ultrafiltration (SCUFF).

(2) *Disadvantages of Shunt*: Additional connectors might induce clots and/or hemolysis, it requires additional flow monitors to assess the circuit shunt, it increases the complexity of the circuit and decreases the safety of the circuit as there is an additional risk of draining air into the negative pressure side.

Access can be obtained in the tubing from the pump head to the oxygenator by inserting connectors with luers for obtaining labs, administering medication and/or blood products.

(1) *Be aware*: High pressures postpump will complicate administration of fluids and medications, and regular access may increase the risk of infection or breaking off luer locks.

Pressure transducers can be added immediately before the inlet of the oxygenator to monitor premembrane pressures and after the oxygenator to monitor postmembrane pressures. An additional transducer can be added before the pump to measure drainage pressures. Pressure transducers, although not necessary, can provide information relevant to patient care while on ECMO.

Tubing

Sizes: Generally, patients less than 10–15 kg have 1/4″ tubing. Patients greater than 15 kg typically have 3/8″ tubing. (ELSO Red Book 5th Edition Ch 5)

Coating: The addition of a precoating or surface modification to the ECMO circuit may be employed to reduce the
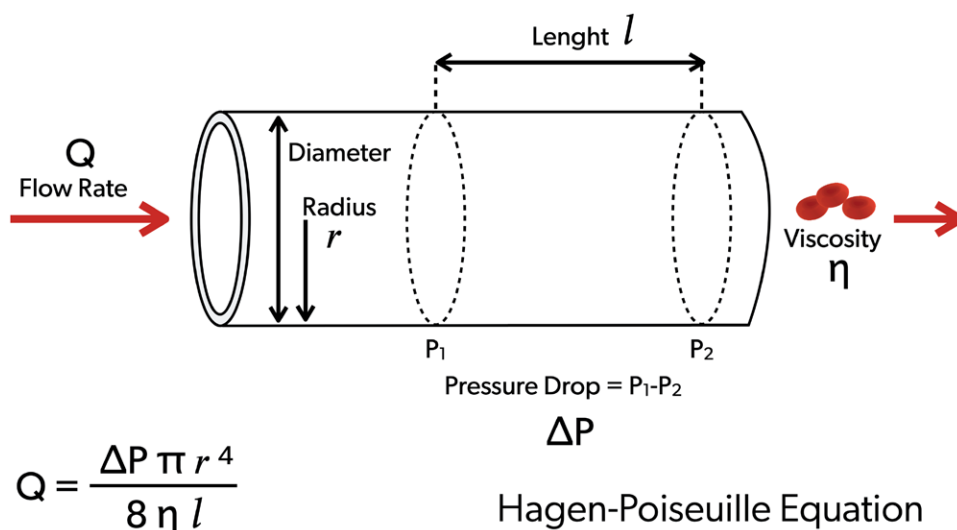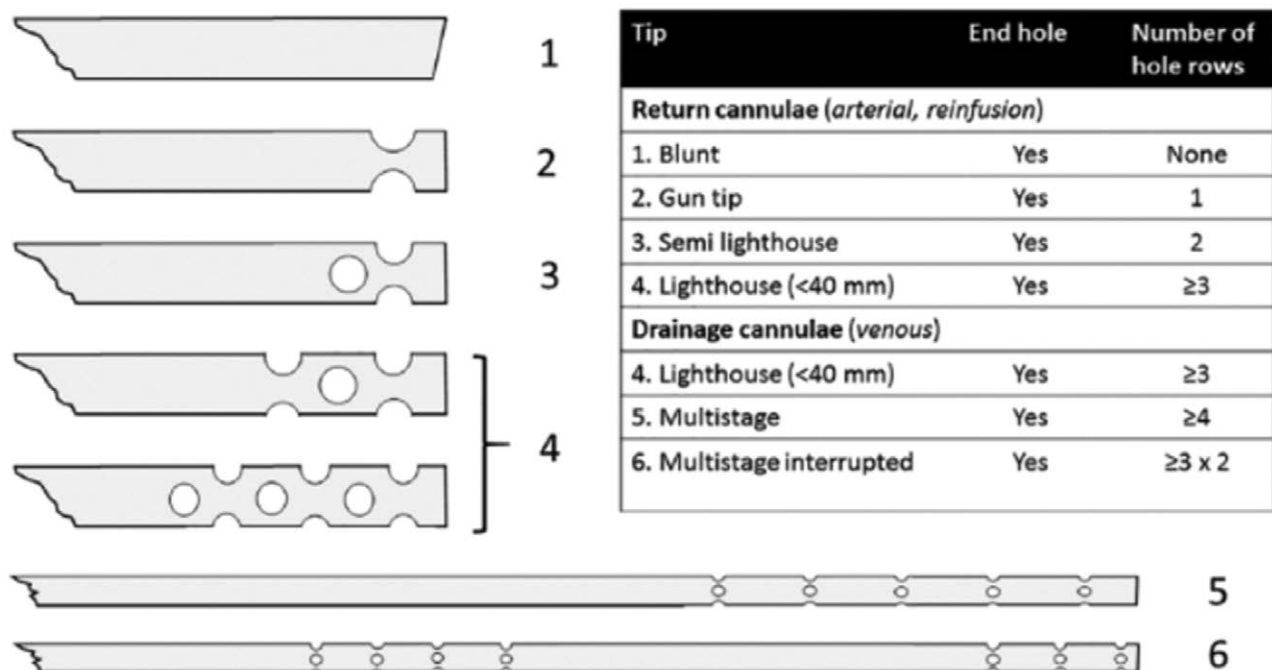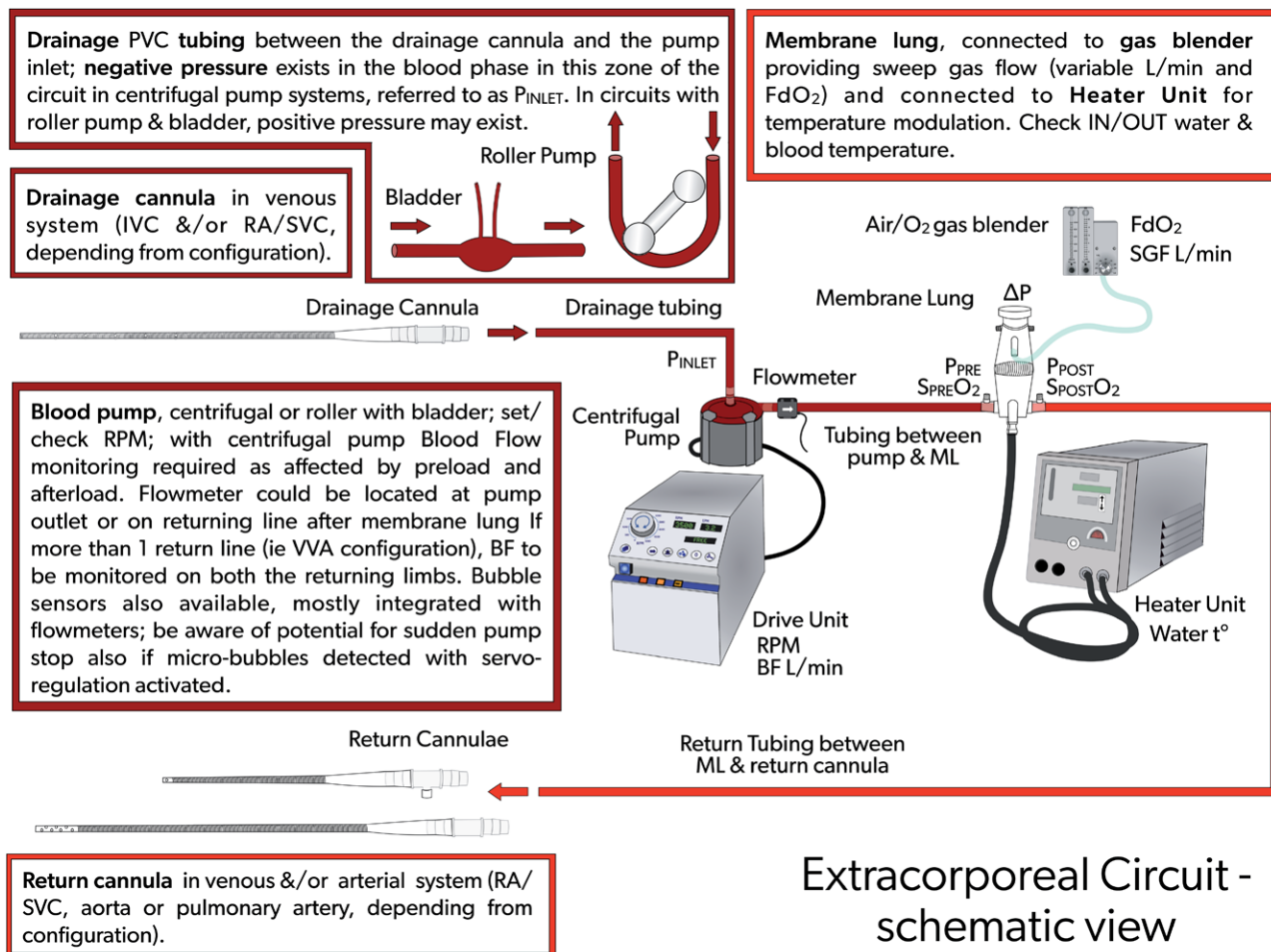

$$Q = \frac{\Delta P\, \pi\, r^4}{8\, \eta\, l}$$

Pressure Drop = P₁-P₂

Hagen-Poiseuille Equation

Figure 11. Hagen-Poiseuille equation.

Tip	End hole	Number of hole rows
Return cannulae (*arterial, reinfusion*)		
1. Blunt	Yes	None
2. Gun tip	Yes	1
3. Semi lighthouse	Yes	2
4. Lighthouse (<40 mm)	Yes	≥3
Drainage cannulae (*venous*)		
4. Lighthouse (<40 mm)	Yes	≥3
5. Multistage	Yes	≥4
6. Multistage interrupted	Yes	≥3 x 2

Figure 12. Different cannula tips.[2]

Drainage PVC **tubing** between the drainage cannula and the pump inlet; **negative pressure** exists in the blood phase in this zone of the circuit in centrifugal pump systems, referred to as P$_{INLET}$. In circuits with roller pump & bladder, positive pressure may exist.

Drainage cannula in venous system (IVC &/or RA/SVC, depending from configuration).

Membrane lung, connected to **gas blender** providing sweep gas flow (variable L/min and FdO$_2$) and connected to **Heater Unit** for temperature modulation. Check IN/OUT water & blood temperature.

Blood pump, centrifugal or roller with bladder; set/check RPM; with centrifugal pump Blood Flow monitoring required as affected by preload and afterload. Flowmeter could be located at pump outlet or on returning line after membrane lung If more than 1 return line (ie VVA configuration), BF to be monitored on both the returning limbs. Bubble sensors also available, mostly integrated with flowmeters; be aware of potential for sudden pump stop also if micro-bubbles detected with servo-regulation activated.

Return cannula in venous &/or arterial system (RA/SVC, aorta or pulmonary artery, depending from configuration).

Extracorporeal Circuit - schematic view

Figure 13. Overview of an extracorporeal membrane oxygenation (ECMO) circuit.

Main principles in building an ECMO Circuit

✓ Keep it **safe, simple** & **safely transportable**

✓ **Adapt size** of tubing, pump and oxygenator **in function of desired support**

✓ **Lines as short as possible** *(while keeping safe patient care, safe mobilization, component change-out,... in mind).*

✓ **Avoid stagnant blood zones** *(avoid Y-lines, bridges, pressure isolators)*

✓ **Minimize change of diameters** : 3-way stopcocks, connectors & inline probes *(preferably use 360° rotatable stopcocks & online monitoring)*

✓ **Streamline** orientation of lines, pump & oxygenator

✓ **Secure**/tie all non-sealed connections

✓ Ensure sufficient & appropriately situated **access ports** *(priming, hemofiltration, air removal, blood sampling, pressure monitoring)*

Figure 14. Main principles in composing an extracorporeal membrane oxygenation (ECMO) circuit.

adsorption of plasma proteins to the ECMO circuit and thus thrombus formation.

Plasma protein adsorption to the biomaterial surface leads to platelet adhesion/activation and thrombin activation, ultimately resulting in the formation of a thrombus.

Varieties of coatings exist as the perfect biocompatible surface has not yet been discovered.

The addition of 25% albumin can be administered to the crystalloid primed circuit as a coating and potentially add oncotic properties (ELSO Red Book 5th Edition Ch 5).

There are heparin and nonheparin surface coatings available. In case of heparin-induced thrombocytopenia, it is advisable to use a nonheparin leaching circuit.

Extracorporeal Membrane Oxygenation Oxygenator

The ECMO oxygenator is designed to administer oxygen, remove CO_2, and in most designs warm the blood (**Figure 15**). The membrane most used is made of polymethylpentene (PMP). Modern oxygenators are characterized by a low resistance to blood flow, low priming volume, easy de-airing, and rare incidents of plasma leakage (ELSO Red Book 5th Edition Ch 5). Typical ranges of prime volumes range from 80mls in the smaller neonatal pediatric specific oxygenators to 250 ml in the larger adult oxygenators.

Blood Flow

The rated blood flow must be able to transfer the amount of oxygen being consumed by the patient. (Please see table below selection of an oxygenator).

Sweep Gas

A mixture of oxygen and air administered directly to the oxygenator gas port (a blender can be used based on etiology and patient size). Increasing the sweep gas flow rate increases CO_2 clearance. Decreasing the sweep gas flow rate decreases CO_2 clearance.

Pressure gradient

The pressure gradient equals the difference between oxygenator inlet and outlet pressures. The pressure gradient reflects the internal resistance inside an oxygenator and its function of the specific oxygenator design in relation to the blood flow and internal buildup of deposits. Pressure drops across oxygenator membranes differ per the oxygenator manufacture. Calculating/documenting hourly pressure drops divided by flow is a common practice in some ECMO centers. If the pressure gradient rises gradually or suddenly independent of flow, resulting in an increasing quotient, this is a good indicator of oxygenator clot formation (**Figures 16 and 17**).

Complications Related to the Oxygenator

The ELSO registry defines a "failing oxygenator" as "requiring change due to clot formation, gas exchange failure, or blood leak".[3]

Whenever an oxygenator no longer allows sufficient blood passage, gas transfer, or becomes a potential burden to the patient (in terms of inducing consumptive coagulopathy or not providing the required gas transfer), a replacement needs to be considered and an elective change-out needs to be planned as soon as possible.

Postponing change-out can unnecessarily further burden the patient and might lead to an urgent change-out in suboptimal conditions, which always should be avoided. On the other hand, unnecessary change-outs also need to be avoided as these are invasive actions requiring a short support interruption, potentially causing iatrogenic infections, renewed blood dilution, additional platelet consumption as well as inflammation due to renewed surface contact activation. Additionally, ECMO oxygenator or circuits resources are burdened unnecessarily.[4]

Increased Pressure Gradient Over an Oxygenator

Different oxygenators on the market show a different internal resistance depending on individual design and size
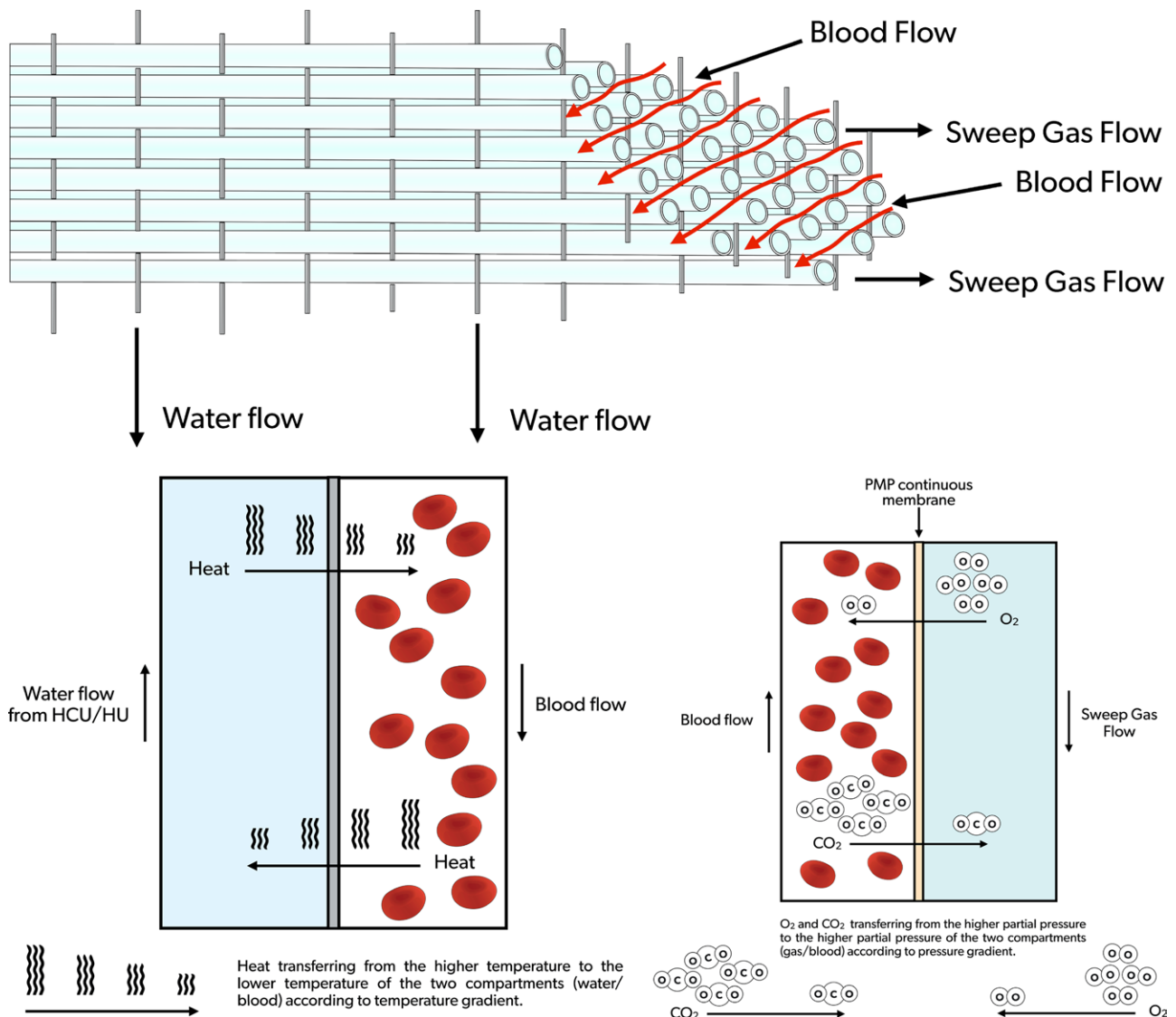
Figure 15. Extracorporeal membrane oxygenation (ECMO) oxygenator blood, gas and water flow.
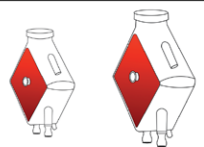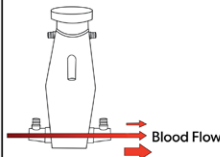
Membrane Lung selection

	Appropriate membrane lung **size**: a ML should be able to transfer the amount of O_2 consumed by the patient (VO_2 - O_2 consumption). In practice, this will be feasible as long as patient's VO_2 is below ML maximum gas transfer capacity ($MLVO_{2MAX}$).
	Every membrane lung has a **Rated Flow** = the MAX blood flow through the ML enabling the inlet blood saturation ($S_{ML-PRE}O_2$) to increase from 75% to 95% when Hb = 12g/dl (= standard to rate gas exchange devices, AAMI). Ideal flow is the flow required to increase $S_{ML-PRE}O_2$ to 99%, achievable as long as required flow is below Rated Flow.

Figure 16. Selection of an extracorporeal membrane oxygenation (ECMO) oxygenator.

Membrane Lung - schematic view

2 blood ports - IN/OUT
2 gas ports - INLET/OUTLET
2 water ports - INLET/OUTLET
0-1 deairing port with membrane
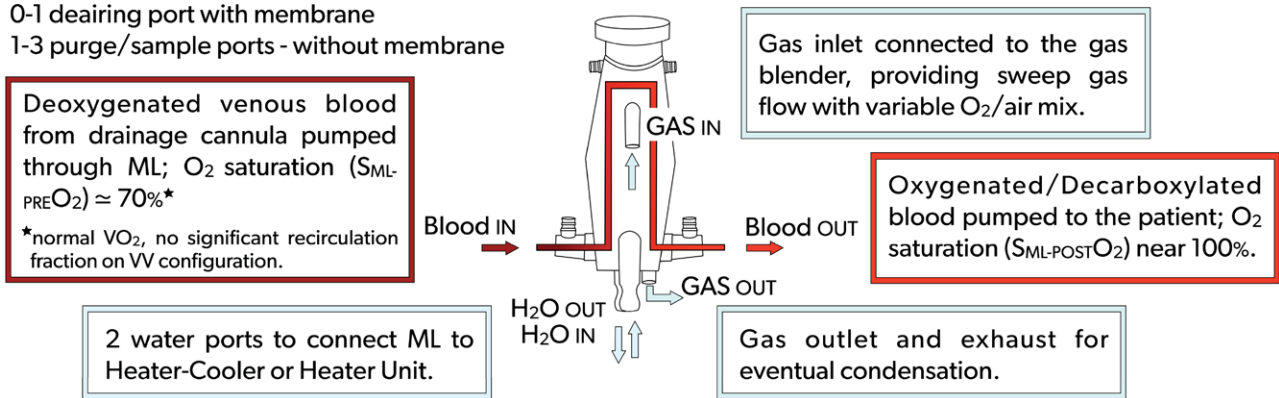1-3 purge/sample ports - without membrane

Deoxygenated venous blood from drainage cannula pumped through ML; O_2 saturation ($S_{ML-PRE}O_2$) $\simeq$ 70%*

*normal VO_2, no significant recirculation fraction on VV configuration.

Gas inlet connected to the gas blender, providing sweep gas flow with variable O_2/air mix.

Oxygenated/Decarboxylated blood pumped to the patient; O_2 saturation ($S_{ML-POST}O_2$) near 100%.

GAS IN

Blood IN   Blood OUT

GAS OUT

H_2O OUT
H_2O IN

2 water ports to connect ML to Heater-Cooler or Heater Unit.

Gas outlet and exhaust for eventual condensation.

Figure 17. Membrane lung schematic view.

properties, all allowing different flows at a certain driving pressure. A rise of the pressure drop is an indication of increased internal resistance, and if accompanied by a drop in flow for the same pump rotations, an indication of embolization inside the oxygenator. If not accompanied by flow reduction for the same pump rotations, there might be a pressure measurement error, which will then need to be resolved.

Whenever the ECMO blood flow is relatively low in relation to the oxygenator capacity, pressure drop changes can be too subtle to serve as an early warning for clot formation.

In the case of a clotted CRRT, oxygenator pressure measurements can be falsely elevated if these are measured at the site of the CRRT connection. A clotted CRRT might lead to oxygenator thrombi. Therefore, clotted CRRT devices should be removed immediately and in case of repeated clotted CRRT
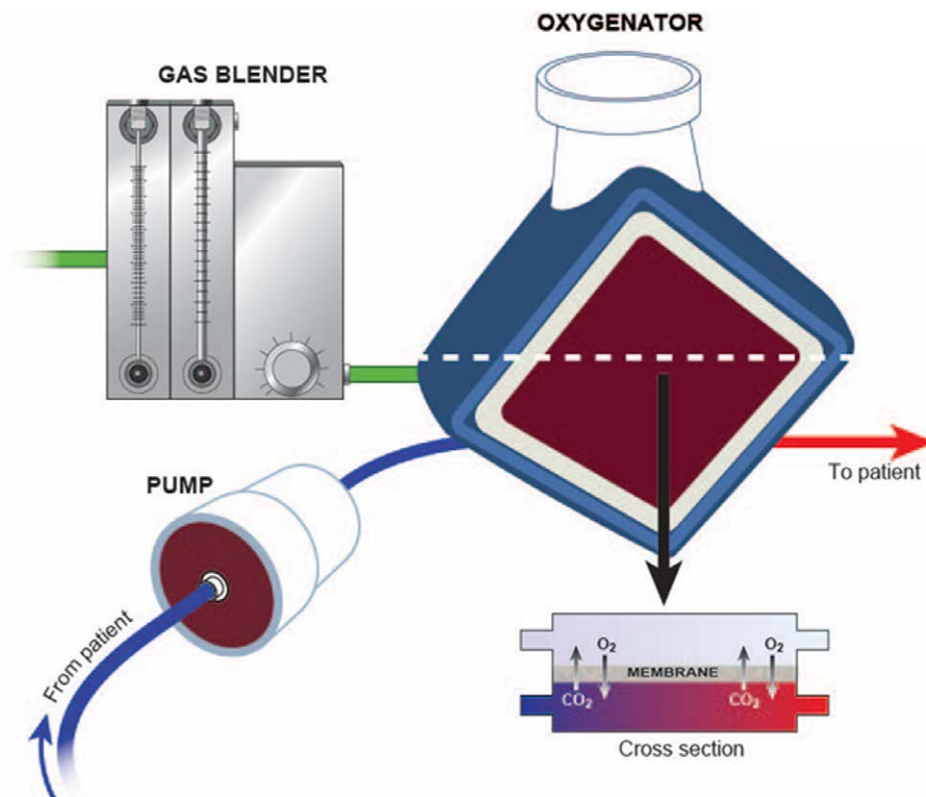
GAS BLENDER

OXYGENATOR

PUMP

From patient

To patient

O_2 O_2
MEMBRANE
CO_2 CO_2

Cross section

Figure 18. Illustration of blood-, gas and water path inside the oxygenator.

devices, an alternative access should be considered to connect the CRRT device.

Blood Tests

A change of trend in coagulation test results while on ECMO might indicate that clot formation is ongoing, such as rapid rising D-dimers and dropping platelet numbers. There always must be an exclusion of other potential reasons for changes in these parameters. D-dimers are very sensitive to circuit clots but can also suddenly rise due to other causes such as severe inflammation and intravascular thrombus.

Most patients on ECMO show some degree of thrombocytopenia from the start of ECMO, which does not necessarily indicate solid clot formation. However, platelets can form solid clots in cases of insufficient anticoagulation or heparin-induced thrombocytopenia (HITT); here an oxygenator change-out will be required. If HITT occurs, heparin needs to be substituted by alternative anticoagulation drugs.

Gas Transfer Performance

Every oxygenator has its specific O_2 transfer capacity, which can be found in the instructions for use by the manufacturer. This information gives an idea of the expected O_2 transfer with a certain blood flow and gas flow of 100% FiO_2. Oxygenation consumption requirements of patients can range in adults from 3 to 5 ml/kg/min, pediatrics 4–6 ml/kg/min, and neonatal 6–8 ml/kg/min.

Oxygen transfer during ECMO:

Oxygen transferred during ECMO ($V'O_2$) is calculated by the formula: $V'O_2 = BFR \times (CpostO_2 – CpreO_2)$ (where $V'O_2 = O_2$ transfer across the membrane lung (ML) in ml/min, BFR = blood flow rate (L/min), $C \times O_2 = O_2$ content of (pre-/post-ML) blood (ml/L)

Calculating O_2 content (CxO_2):

(CxO_2): $CxO_2 = 13.4 \times Hgb \times SxO_2 + 0.03 \times PxO_2$

(Hb = hemoglobin g/dl, $SxO_2 = O_2$ saturation of pre-/post ml blood,

$PxO_2 = PxO_2$ partial pressure of (pre/post-ML) blood (mm Hg)

Example:

(Hgb × 1.34) × (Post oxy sat – Pre oxy sat) + (PaO₂ x.003) × flow (in deciliters)

Patient with sp. Hct 35, SVO_2 (circ) 71, SaO_2 (circ) 100, Post oxygenator PO_2 365 mm Hg, Pump flow 5 LPM

To calculate oxygen transfer through the oxygenator:

(12 × 1.34) × (1.0 – 0.71) + (365 × 0.003) × 50

= [(16.08 × 0.29) + 1.095] × 50

= (4.6632 + 1.095) × 50

= 5.7582 × 50

= 287.9 ml oxygen transfer per minute through the oxygenator

CO_2 transfer can be calculated as Inlet CO_2 content – outlet content times blood flow, but it is more accurate to measure the amount of CO_2 in the exhaust gas.

CO_2 transfer is always greater than O_2 transfer if the membrane lung is functioning normally. CO_2 transfer is controlled by adjusting the sweep gas.

Membrane lung malfunction

A calculation of O_2 uptake inside the oxygenator can provide useful information with regard to the oxygenator performance.

Comparing the O_2-transfer by what is indicated on the instructions for use by the manufacturer might give us insight on the mL performance, but a daily trend is more important than absolute values. Before oxygenator blood is drawn for blood gas analysis, oxygenator gasses should be set at 100% FiO_2 to correctly compare mL transfer capacities with the IFU.

A *post-oxygenator pO2* might already be indicative of sufficient O_2 transfer; taken at a gas flow of FiO_2 of 100%, values should exceed 300 mm Hg of PaO_2. A daily blood gas control might detect deterioration of the oxygenator, and if this happens accompanied by insufficient patient support, change-out needs to be considered.[4]

Similar observations can be made to detect a decline in CO_2 removal. Here, the cause can simply be a wet membrane:

Increasing the sweep gas for a few seconds to remove condensation or clear an obstruction that is preventing gas exchange, can improve oxygenator function. This should be performed if there is a suspicion of oxygenator failure. If mL CO_2 removal rate is less than 10 mm Hg despite max gas flow an oxygenator change-out should be considered.[4]

Manufacturer DNE (do not exceed) sweep gas flow rates should be noted and observed as high gas flow rates can exceed the pressure limitation set by each oxygenator resulting in membrane rupture.

Visible clots

Clots might be visible in the oxygenator depending on the design. Most clots will be situated at the venous side of the device, where internal resistance directs the blood passage through certain paths. The areas with the lowest velocity, highest resistance, or lowest wash-out will most likely clot off first.

Clot growth needs to be observed and a component change should be considered if this accompanies a decreased blood flow with the same rpms, a burden to the coagulation profile of the patient (consumptive coagulopathy), hemolysis (increased PfHb), or insufficient patient support.

Oxygenator blood volume

Measurement of the transit time of a saline bolus passing through the oxygenator as recorded by a sensor placed pre and post oxygenator can enable a quantitative assessment of oxygenator performance (**Figure 18**).

The ECMO Blood Pump

The blood pump controls the required blood flow for the patient. There are different designs available; roller pumps and centrifugal pumps, of which centrifugal pumps are currently the most used. (ELSO Red Book 5th Edition Ch 5).

Roller pumps

Generate direct suction on the pump inlet tubing which can be limited by a bladder (reservoir) box servo-controller to prevent excessive drainage catheter suction.

The tubing can wear or rupture in the pump head or if there is an occlusion to the tubing after the pump (**Figure 19**).

Centrifugal pumps

Magnetic driven pump rotor with axis control that generates negative suction at a central hub by high rotational speed; blood is expelled *via* lateral hole.

All centrifugal pumps have their specific control consoles which ensure pump operation, and each have certain monitoring and safety features (flow, air bubbles, pressures, visual, and auditory alarms). Most have backup batteries. There should
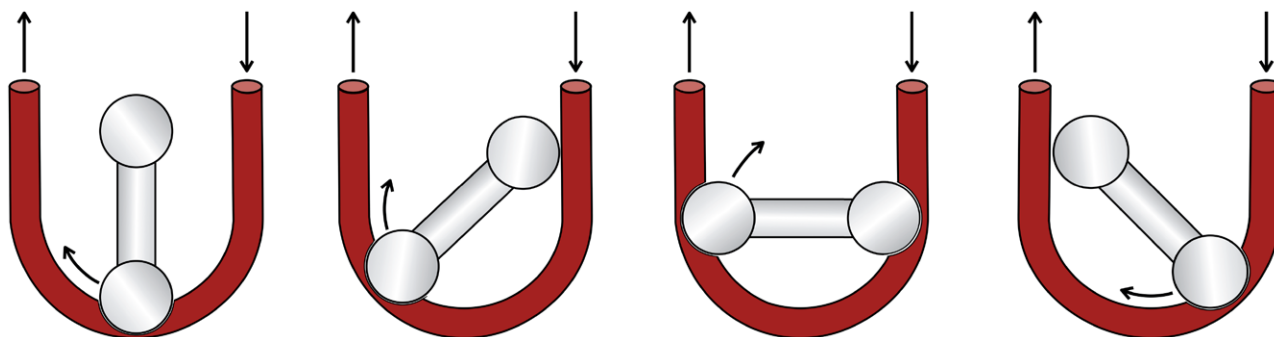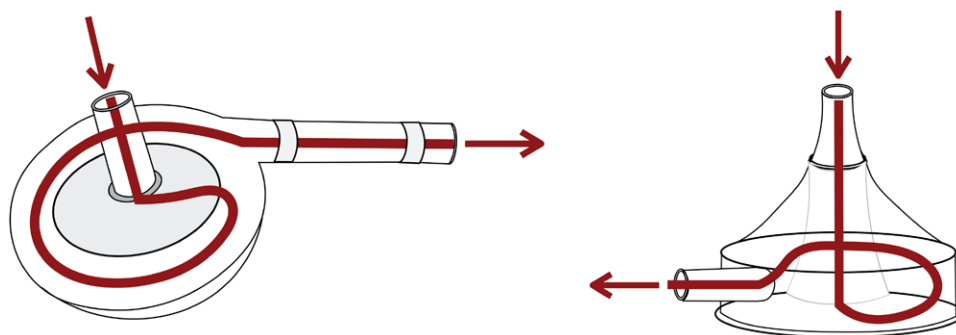
Figure 19. Roller pump example.

Figure 20. Centrifugal Pump examples.

DESIGN	IMPACT OF DESIGN ON PERFORMANCE
1. Small CP & designs without impellers	Higher rpms to produce flows
2. Fixed shaft CP	More thrombolytic & hemolytic
3. CP with impellers	Fractionizes & forward bubbels faster than CP with cones
4. Small designs	Easier blocked by thrombus
5. Levitated impellers	Can tilt due to disruption magnetic field (by air/thombus) creating turbulence, hemolysis & potential pump failure
5. High flow CP	Potential hemolytic in low flow/high P conditions
6. Failing CP	Handcrank or back-up motor

Figure 21. There are different centrifugal pump designs clinically available; all containing different features which has an impact on performance. They all behave differently towards clots and air and need different protocols with regards to troubleshooting and in case of technical failure.

Figure 22. Causes of pump failure and how to intervene.

always be a backup available (hand crank, backup motor, or spare console). If ECMO transport needs to be performed, a safely transportable system needs to be available.

Performance is related to rpms and is dependent on preload and afterload (**Figures 20–22**).

Priming the Circuit

Circuits are primed with crystalloid solutions and/or blood products based on center preference under sterile conditions. (ELSO Red Book 5th Edition Ch 5).

Blood Prime

Infants and small pediatric patients approximately <10–15 kg should have the circuit primed with blood (packet red blood cells + hemodilution) before initiation of ECMO support, unless cardiopulmonary resuscitation is in progress, whereas the goal is to establish ECMO support as soon as possible.

Blood prime additives may include NaHCO3, CaCl, Heparin, FFP, and 25% albumin. It is advisable to check the electrolyte composition of the blood prime before initiating ECMO.

Crystalloid prime

Patients >10–15 kg can be primed with a crystalloid solution, but this is also dependent on the circuit to patient volume or hemodilution.

ECMO Circuit In-Line and Online Monitoring

ECMO circuit monitors either connected in or placed on the circuit are intended to measure the ongoing function of the circuit and alert the operator of any undesirable conditions. Each institution should examine if pressure monitoring is appropriate for their ECLS patient population (**Figure 23**). (ELSO Red Book 5th Edition Ch 5).

Flow monitors

Blood flow is typically monitored directly with ultrasonic flow meters on the circuits with centrifugal pumps or calculated from tubing capacity and revolutions per minutes for roller pumps. Direct monitoring should be considered with roller pumps to ensure proper occlusion and accurate blood flow.

Circuit pressures monitoring

Inlet pressure (P1): the amount of negative pressure produced from pulling blood from the patient toward the pump.

For roller pumps, servo inlet pump regulators should be utilized to ensure that gravity siphon does not result in cavitation from excessive negative pressure or air entrainment from various connectors or stopcocks.

For centrifugal pumps, monitoring inlet pressure can be achieved by a circuit pressure monitoring device, which in
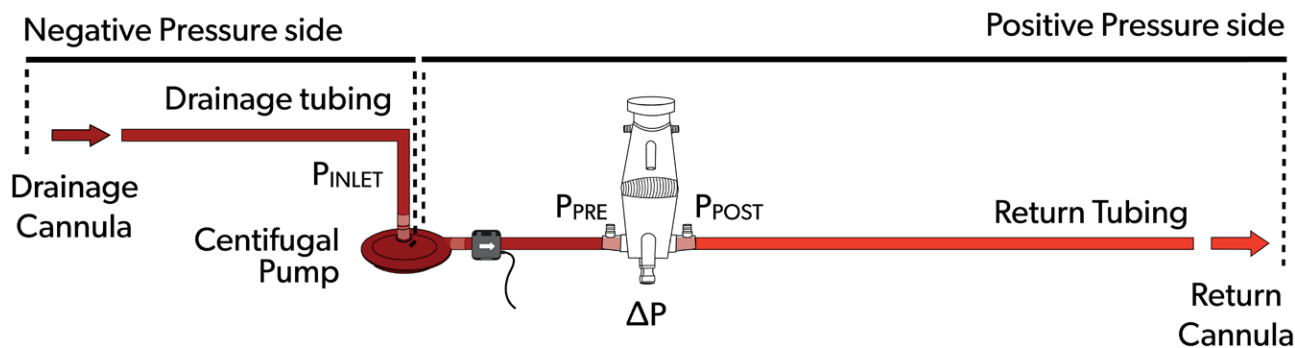
Figure 23. Extracorporeal circuit pressures.

some pumps can serve as an automatic rpm's regulator in case of exceeding negative pressure limits (**Figure 24**).

Pre-oxygenator pressure (P2): the pressure between the pump and oxygenator.

Post-oxygenator pressure (P3): the pressure in the circuit after the oxygenator.

Transmembrane pressure gradient or pressure drop (ΔP) is determined by the difference between the pre-oxygenator and post-oxygenator pressure and reflects the internal resistance within an oxygenator (**Figures 25–27**).

Peripheral arterial O$_2$ saturation monitoring

Arterial O$_2$ saturation (SaO$_2$) is the fraction of oxygen-saturated hemoglobin relative to total hemoglobin in the blood.

Bubble detection

Bubbles can be detected using a noninvasive ultrasonic sensor placed on the circuit or visual recognition. A bubble detector is preferably placed postoxygenator to ensure gross air is not administered to the patient. This can be turned off during circuit maintenance to avoid confusion of air detection. The bubble detector should be in use during routine care, especially if the postoxygenator side of the circuit will be accessed routinely.

Battery indication

The console should always be plugged into an electrical outlet which is designated for emergency backup electricity.

Pre-primed ECMO Circuits on Standby

Due to the time it takes to assemble and prime the ECMO circuit, many centers keep circuits assembled and filled with a crystalloid solution and will administer additives when ECMO is needed (see *Priming the Circuit* above). Due to the time and meticulousness that is required to not contaminate the circuit, it is best to assemble, and crystalloid primes the circuit in a controlled situation *versus* an emergent circumstance. Using the sterile technique and a solution that does not have substrates for bacterial growth, the circuit is unlikely to grow bacteria over time if contamination is prevented during standby times. Per ELSO's Infection Control Guidelines, "it is safe to maintain preprimed circuits for up to 30 days, and possibly beyond 30 days,
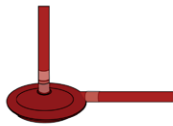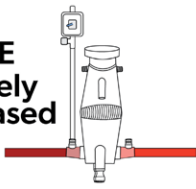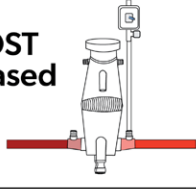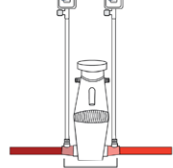

Centrifugal Pump Circuit Pressures	
Acronym	**Definition & Determinants**
P$_{INLET}$ decreased	**Pump inlet** or **pre-pump pressure** is the negative pressure in the blood phase from drainage cannula to the pump. Affected by: drainage cannula size & length, drainage tubing size & length, patient volume status/ venous return, patient's venous resistances, site of pressure monitoring, relative position of pump vs patient. Be careful! P$_{INLET}$ monitoring could be associated to the risk of air embolism if requiring circuit manipulation: consider pre-pump side as NO-touch
P$_{PRE}$ severely increased	**Pre-membrane pressure** is the positive pressure in the blood phase from the pump to the membrane lung inlet. Affected by: membrane lung internal resistances, return cannula size & length, return tubing size & length, patient afterload (depending from ECLS configuration), relative position of pump vs patient.
P$_{POST}$ increased	**Post-membrane pressure** is the positive pressure in the blood phase at the membrane lung outlet. Affected by: return cannula size & length, return tubing size & length, patient afterload (depending from ECLS configuration), relative position of pump vs patient.
ΔP	**ΔP** or **Delta P** or **Pressure Drop** is the pressure gradient between the inlet and outlet of the membrane lung, calculated as P$_{PRE}$ - P$_{POST}$. Affected by: extracorporeal blood flow, membrane lung internal resistances, return cannula size & length, return tubing size & length, patient afterload (depending from ECLS configuration).

Figure 24. Centrifugal pump circuit pressures.

Be aware of ≠ pressures within the centrifugal pump circuit

Drainage canula → pump
: P1 = -ve
Avoid chattering of lines
& peak negative
pressures
= 'No touch' zone (air!)!!

DRAINAGE/RETURN CANULA

Oxygenator → return canula :
P3 =++ve

ΔP : P3 – P2 = Cte

pump

oxygenator

Pump → lung : P2 = +++ve
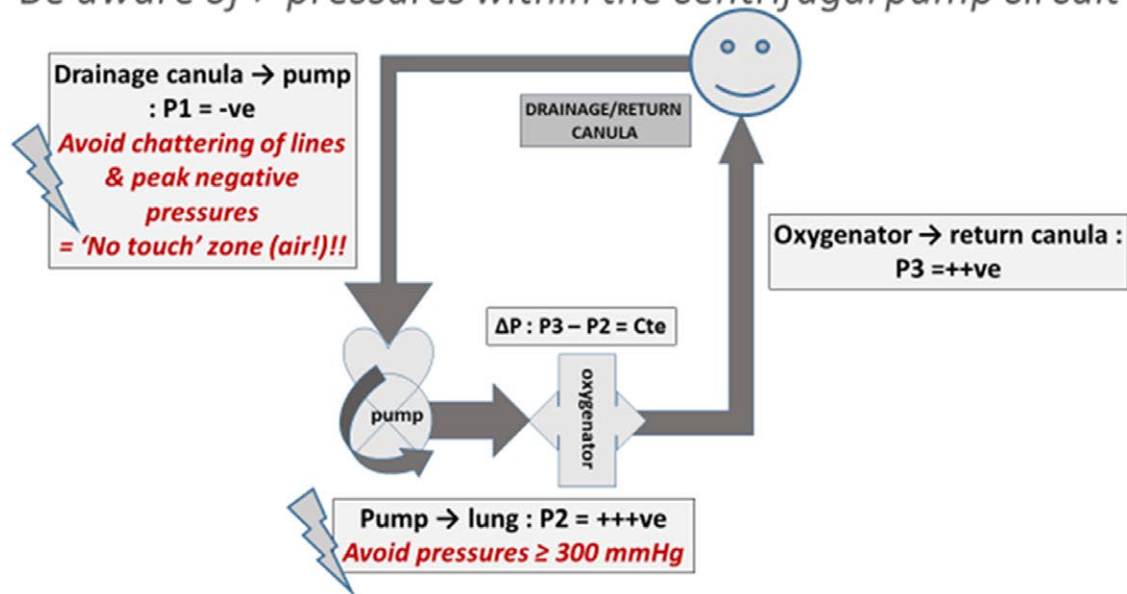*Avoid pressures ≥ 300 mmHg*

Figure 25. The 3 different pressure zones in a centrifugal pump extracorporeal membrane oxygenation (ECMO) circuit, Pressure zones in centrifugal pump ECMO circuit are relative values and are in relation to certain variables.

Be aware of ≠ pressures within the centrifugal pump circuit

P1 : Drainage canula → Pump =
negative (-)
P1 is in relation to :
size & length canula & tubing, volume
status patient, location P1 transducer,
position pump versus patient
P1↓↓ = resistance to inflow
(hypovolaemia, tamponade,
pneumothorax, inflow obstruction,
kinking)

DRAINAGE CANULA

RETURN CANULA

P3 : Oxygenator → Return canula =
positive (++)
P3 is in relation to :
Patient afterload, size & length of canula
& tubing, height pump
P3↑↑ = resistance/obstruction distal
from oxygenator (kinked or obstructed
return line or canula, increased patient
afterload)

ΔP : P2 – P3 = Cte
ΔP is in relation to flow
ΔP ↑↑ = obstruction
inside oxygenator

Pump

Oxygenator

P2 : Pump → Oxygenator = positive (+++)
P3 is in relation to : height pump, internal resistance oxygenator, size & length of tubing & canula, patient afterload)
P2↑↑ = resistance/obstruction distal from pump (clotted oxygenator, kinked or obstructed return line or canula, increased
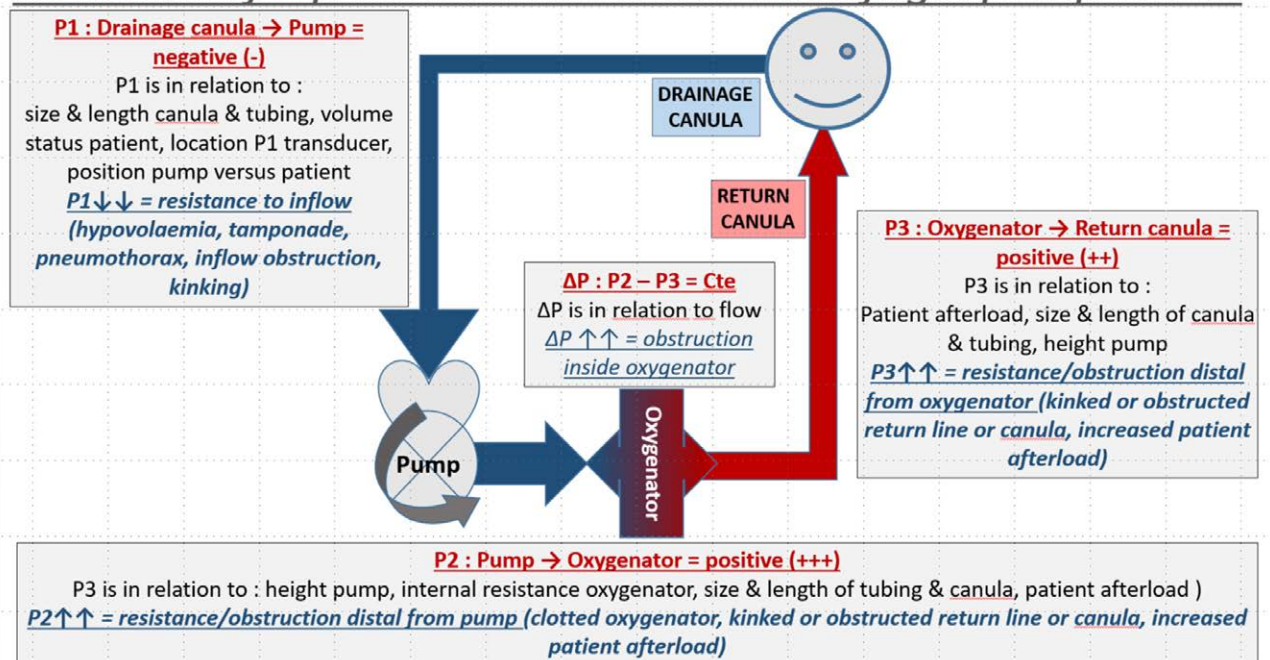*patient afterload)*

Figure 26. Pressure zones in centrifugal pump extracorporeal membrane oxygenation (ECMO) circuit are relative values and are in relation to certain variables.

P1 -50/-100	P2 250/350	P3 200/300	ΔP (P3-P2)	Flow	Rpms	Possible causes	Corrective actions
↓	↓	↓	↓	↓	=	Hypovolemia, Tamponade, Pneumothorax Venous cannula malposition or venous line kinking, venous canula clot	Improve patient fluid status, Check for tamponade and pneumothorax Check patency and position of lines & canula
↑	↓	↓	↓	↓	↓ =	Pump failure Clot or air in pump	Hand crank or use back-up pump Remove clotted pump or air
↑	↑	↓	↑	↓	=	Oxygenator failure (thrombosis)	Exchange failing oxygenator
↑	↑	↑	↓	↓	=	Increased pump afterload (hypertension in VA ECMO, arterial line kinking, arterial canula kink or clot)	Check patency and positon of return line & canula

P1 = drainage pressure / P2 = pre oxygenator pressure / P3 = post oxygenator pressure / ΔP = pressure drop over oxygenator

Figure 27. Relation between pressures, flow, and rpms – possible causes and corrective actions.

if: 1) the circuit is constructed and primed using standard sterile techniques and 2) the prime is electrolyte solution-based, and no glucose-containing solutions or albumin are used within the prime." (ELSO Red Book 5th Edition Ch 5).

Special ECMO Configuration

An additional cannula may be configured into the circuit because of lack of drainage (adding a [venous] drainage catheter) or the need of additional oxygen delivery (adding an additional return catheter). The use of flow-controlling maneuvers (Hoffman clamp) may be needed in these configurations to deliver desired blood flows to certain areas of the patient. Additional flowmeters can be used to determine accurate flows going to each location.

When and where to clamp off the ECMO circuit?

Weaning from ECMO

Decreasing the amount of support to the patient to determine the patient's readiness to come off ECMO support (**Figure 28**).

When weaning, one must be cognizant of the minimum flow required through the oxygenator as recommended by the manufacturer. To achieve the minimal flow indicated by the manufacturer, the bridge can be opened (if applicable) or a shunt can be added to the circuit, which will increase the blood flow through the oxygenator while maintaining low blood flows to the patient. (ELSO Red Book 5th Edition Ch 51).
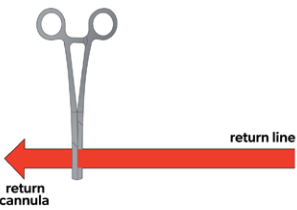
Clamp ECMO		Required	NOT Required
(forceps image) return line return cannula	**VV**	disconnected circuit or cannula circuit rupture (place 2 clamps pre/post leak)	pump failure/sudden pump stop resuscitation with external chest compressions but properly secure cannulae/tubings and monitor BF to eventually adjust RPM
Clamp return tubing first	**VA**	pump failure/sudden pump stop to prevent back-flow; if LV vent present, also clamp venting tubing disconnected circuit or cannula circuit rupture (place 2 clamps pre/post leak)	resuscitation with external chest compressions, and ventricular fibrillation (providing shock as needed), but properly secure cannulae/tubings and monitor BF to eventually adjust RPM

Figure 28. Where to clamp the extracorporeal membrane oxygenation (ECMO) circuit.

VA ECMO

Low flow trial

Consider additional anticoagulation or increase anticoagulation levels, to prevent clot formation during low flow trials with a VA ECMO wean.

Wean gradually during a low flow trial according to institutional protocol. Do not leave blood flow under recommended low blood flow limits longer than necessary.

Pump controlled retrograde flow can also be used.[5]

Clamp trial

Consider brief clamp trials in neonatal and pediatric patients before decannulation.

VV ECMO

Turning off the sweep gas to the oxygenator: the gas line can be disconnected to ensure there is no gas exchange occurring. A VV clamp trial does not require clamping off blood flow because there is no cardiac support being provided to the patient. Capping off is usually done for a minimum of several hours to assure patient's tolerance of decannulation.

Terminology

For nomenclature terminology for different types of ECMO, please refer to the extracorporeal life support organization maastricht treaty for nomenclature in extracorporeal life support, a position paper of the extracorporeal life support organization.[6]

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