Nursing Care and ECMO

Chirine Mossadegh
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Preface

Extracorporeal membrane oxygenation (ECMO) is growing rapidly and is now considered in the treatment of all patients with severe respiratory or cardiac failure. Health-care workers of all disciplines are in need of a dedicated book that will help them through the management of these patients, explaining the principles of safe and successful practice. This book is especially focused on the unique aspects of nursing care of ECMO patients. It provides a comprehensive overview of the physiopathology and indications, setting up of the device, monitoring ECMO and the patient, troubleshooting, ethical aspects, and rehabilitation. Nurses, but also physiotherapists, perfusionists, and all other key members of the ECMO team, will find herein the basics required to better understand the technology and ultimate care of the patient.

The future of this activity promises to be especially exciting.

Paris, France — Alain Combes

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Part I
Medical Aspects

Chapter 1
ECMO: Definitions and Principles

Charles-Henri David, Alicia Mirabel, Anne-Clémence Jehanno, and Guillaume Lebreton

1.1 Introduction

Directly based on the principle of cardiopulmonary bypass (CPB), short-term circulatory support was developed to supplement heart and/or respiratory failure. Circulatory support is represented by two techniques closely related in their implantation but whose objectives are different. Extracorporeal membrane oxygenation (ECMO) aims to supplement failing lungs, while extracorporeal life support (ECLS) aims to support heart failure. ECMO will primarily affect oxygenation and decarboxylation of blood, while ECLS has a circulatory and a respiratory effect. By extension, the acronym ECMO is used for all short-term circulatory support techniques (under 1 month). To distinguish the two types of assistance, cannulation sites will be identified. Venoarterial ECMO (ECMO-VA) is used to discuss about ECLS (heart failure or cardiopulmonary failure) and venovenous ECMO (ECMO-VV) to discuss about ECLS (respiratory failure only).

The main difference from the commonly used CPB is that ECMO has no cardiotomy reservoir to store the blood. ECMO is therefore a closed circuit. This detail is important because this system is more dependent on the preload and afterload than CBP. The other difference is that CBP will be used over several hours while ECMO may be used for several days or weeks.

In 1953, the first heart–lung machine was used in humans [5]. In 1972, the first successful use of ECMO outside the operating room was reported [2]. Initially developed for neonatal and paediatric use, these technologies have gradually been

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applied to adults, with disappointing initial results. A multicentre study evaluating its interest in respiratory failure found no difference from the control group [11]. Despite this, many other studies have shown that this technique could provide a benefit in terms of survival. With improvement in its components—especially the centrifugal pump with a reduction in haemolysis and the new oxygenator—a renewed interest in ECMO emerged [6, 10].

Recently, we have seen a renewed interest in ECMO in the risk of developing ARDS (acute respiratory distress syndrome) during the pandemic H_1N_1 viral pneumonia [3]. Although its use is discussed, the fact remains that ECMO saves lives where conventional treatments have failed [8].

Currently, the main indication for ECMO is cardiogenic shock with organ dysfunction (at least two organ dysfunctions in addition to the heart) and/or the need to rapidly increase doses of inotropes (especially if the patient is away from a centre with a circulatory support programme) and/or rapidly reversible cardiac dysfunction (in short, a patient who cannot wait more than a few hours or with significantly faster recovery potential: myocarditis, drug poisoning, deep hypothermia) [4, 7].

ECMO is a means and not an end. This is a bridge to one or more therapeutic orientations.

- A bridge to decision—if the diagnosis is uncertain, it can save the patient's life while investigations continue. This can eventually lead to a deadlock and a therapeutic stop.
- A bridge to functional recovery—in myocarditis, for example.
- A bridge to surgical repair of the culprit lesion.
- A bridge to heart or lung transplantation when no recovery is possible.
- A bridge to long-term mechanical support.

1.2 Principles

ECMO is currently the only emergency treatment able to support temporary cardiorespiratory failure. The basic principle of ECMO is to collect the patient's venous blood into a pump connected to an oxygenator and restore the oxygenated and decarboxylated blood to the patient. In both ECMO-VA and ECMO-VV, the patient's blood is drained via a cannula inserted into a large vein. In ECMO-VA, blood is reinjected through an arterial cannula, while in ECMO-VV, blood is reinjected through a venous cannula.

ECMO is not a cure. It can stabilise a patient in a very serious condition to allow teams to evaluate and/or make a diagnosis and to take a decision. It can provide partial or complete support, and ensures gas exchange and a satisfactory infusion to the patient to protect vital organs. One can see ECMO as a bridge to a decision.

Monitoring of ECMO is done exclusively in intensive care and close to thoracic and vascular cardiac surgery.

1.2.1 Equipment

The ECMO system is similar to that of an operating theatre CBP console, but miniaturised and simplified to enable it to be easily used outside the operating room. An ECMO circuit is composed of a pump, an oxygenator, a heat exchanger, cannulas and a set of tubes for connecting the patient to the machine. According to the patient's needs, assistance will focus on the heart and/or the lungs. In case of ECMO-VA, a venous cannula and an arterial cannula will be needed. In case of respiratory support, only two venous cannulas (or a venous cannula having an output and an input) will be used. Conventionally, the venous blood is drained from the patient from a large calibre vein such as the femoral vein through a pump and is then oxygenated and decarboxylated through a membrane (Fig. 1.1). Then the blood flows back into the patient's circulation.

1.2.1.1 Cannulas

The choice of cannulas is fundamental for the ECMO to work optimally with as little complication as possible. There are a multitude of cannulas classified according to their internal diameter (in Fr, where 1 Fr = 1/3 mm), their length (mm) and their surface treatment.

They feature a contoured tip to facilitate penetration into the vessels (especially for the percutaneous approach), metal coils to strengthen the cannula and

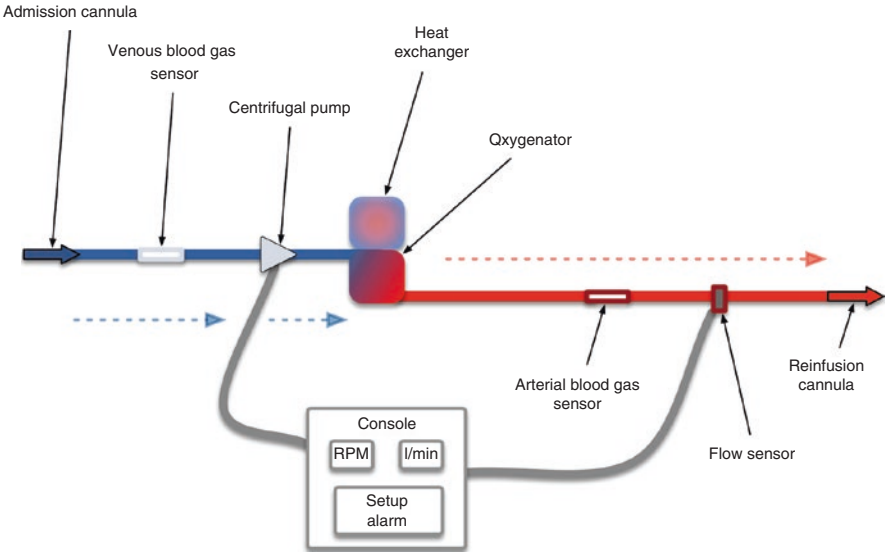

Fig. 1.1 Schematic representation of an ECMO-VA

a rigid proximal portion with a connection fitting with the tubing. The term ‘admission cannula’ is used for venous drainage cannula and ‘reinfusion cannula’ for the cannula which carries oxygenated blood from the pump to the patient (inserted either in an artery or a vein, depending on which type of ECMO is used). Venous cannulas are usually wider and longer than arterial cannulas.

1.2.1.2 Pump

In ECMO, we use centrifugal pumps. These are non-occlusive pumps which operate on the principle of entraining blood into the pump by means of a vortexing action of spinning impeller blades or rotating cones. The impellers or cones are magnetically coupled with an electric motor and, when rotated rapidly, generate a pressure differential that causes the movement of blood. The flow rate is calculated (by ultrasonic sensor) in L/min. The console allows the display and setting of various parameters of ECMO (flow, high- and low-flow alarms).

The centrifugal pump generates less haemolysis than other types of pump, and the pump stops in case of air embolism in the circuit; the rate depends mostly on input (blood volume and the choice of cannula size) and output pressure (vascular resistance). Centrifugal pumps are non-occlusive, which means that the blood can move in one direction or the other. Therefore, there can be a backflow with the patient’s blood going back to the pump. This is seen most often when the ECMO rates are low and the pressure generated by the patient’s heart is more important. There is an anti-backflow system on pumps, but regular monitoring is essential, and the golden rule is to clamp the arterial line whenever the pump is not running. All pumps are equipped with an emergency hand crank to compensate for a pump-operating failure.

1.2.1.3 Circuits

The circuit is composed of PVC tubes with an internal diameter of 3/8 inch (9.525 mm) packaged sterilely with a debubbling pocket. The circuit has a surface treatment in order to reduce clotting.

1.2.1.4 Oxygenators

The blood passes through polypropylene fibres that allow gas exchange to provide oxygenation and decarboxylation. The oxygenator reproduces the alveolar capillary function. Modern oxygenators are composed of multiple hollow fibres of <0.5 mm diameter, coated with a hydrophobic polymer (polymethylpentene), allowing the passage of gas (partial pressure gradient) but not liquid (Fig. 1.2). The gas flows

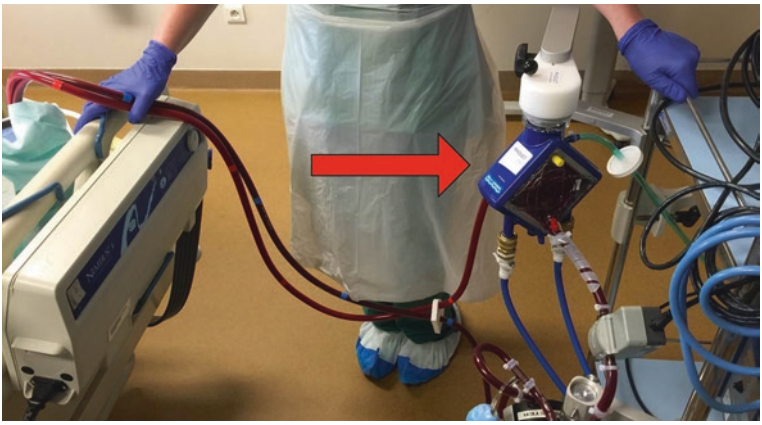

Fig. 1.2 Modern oxygenators

inside the fibres, and the liquid is on the outside. Compared with a healthy lung, transfer capacities with the membrane (artificial lung) are more than ten times lower (3000 vs. 200–250 mL/min). These transfers of O_2 and CO_2 capacity are determined by the exchange surface and the pore diameter of the fibres. These elements are not editable at the bedside to modify these exchanges; the action focuses on the flow of liquid (pump rate) and gas intake.

1.2.1.5 Heat Exchanger

This is a miniaturised thermal unit that can heat patient blood by convection. The thermal unit can heat up the patient's blood during the passage of the latter through the oxygenator: hot water circulates around the oxygenator and thus indirectly warms the patient's blood. The introduction and removal of the device is performed by the perfusionist.

1.2.2 Description of Techniques, Indications and Complications

1.2.2.1 ECMO-VA and ECLS

The most frequent indication for ECMO-VA is represented by all the causes of refractory cardiogenic shock to all medical treatments (Table 1.1). In these cases, there is an inability of the heart to pump to ensure adequate blood flow, leading to tissue hypoxia by stagnation in the absence of hypovolemia which can cause organ failure.

Table 1.1 Aetiologies of cardiogenic shock requiring ECMO

Myocardial infarction
Decompensated chronic heart failure
Valvular insufficiency (broken rope, endocarditis, aortic dissection)
Myocarditis
Refractory cardiac arrest
Post-CBP cardiogenic shock
Transplant rejection
Drug intoxication (beta-blockers)
Chest trauma
Pulmonary embolism

The femorofemoral venoarterial surgical approach is the most frequently used technique and the simplest including external cardiac massage (ECM) under local anaesthesia at the patient's bedside.

For this technique, we access the femoral triangle in the groin. After dissection of the femoral vessels (femoral artery and femoral vein), non-absorbable monofilament purse-string sutures are added at each insertion site to seal around cannulas. The patient is anticoagulated by a bolus of 5000 iu unfractionated heparin. Catheterisation of the vessels is carried out according to the Seldinger technique [9]. The venous cannula is mounted to the end of the inferior vena cava into the right atrium under echocardiographic control. Once the arterial cannula is inserted, a reperfusion catheter (5 or 7 Fr) is positioned downstream of the arterial cannula to ensure limb perfusion and reduce the risk of limb ischaemia. The cannulas are flushed with saline before being connected to their respective manifolds.

A totally percutaneous technique under ultrasound control is possible, but it will still be necessary to take a surgical approach to the removal of ECMO-VA. In this approach, vessel repair may be more complicated.

The other technique for the peripheral ECMO-VA device uses the axillary artery (VA-AF) for blood reinfusion and a femoral venous cannulation, usually percutaneously. A surgical approach to the axillary artery is made in the deltopectoral groove. Cannulation may be direct or by interposing a Dacron tube. This cannulation has a low risk of ischaemia, and anterograde perfusion reduces the risk of acute pulmonary oedema (APO).

Finally, it is possible to set up a central ECMO (VA-C) with direct cannulation of the right atrium and ascending aorta. This type of assistance is most frequent for post-CBP cardiogenic shock as, the sternum being open, implementation is easier while the complications of setting up the device are limited.

The main complications encountered following ECMO-VA establishment are summarised in Table 1.2.

Table 1.2 Complications under VA-ECMO

	Surgical FF-VA	Percutaneous FF-VA	AF-VA	C-VA
Vascular injury	+	++	+	−
Limb ischaemia	++	++	+	−
Pulmonary oedema	++	++	−	−
Haemolysis	++	++	++	+
Cannulation site infection	++	−	+	+
Harlequin syndrome	+	+	−	−
Filter thrombosis	+	+	+	+
Bleeding at cannulation sites	++	+	++	+
Bleeding ENT/VISC	+	+	+	+
Coagulopathy (HIT, thrombopoenia)	+	+	+	+
Cerebral bleeding	+	+	+	+

FF femorofemoral, *VA* venoarterial, *AF* axilofemoral, *C* central

Table 1.3 Main aetiologies of ARDS

Pulmonary	Extrapulmonary
Inhalation pneumonia	Sepsis
Infectious pneumonia	Severe trauma with shock
Drowning	Acute pancreatitis
Drug inhalation	Neurogenic ARDS
Pulmonary contusions	Overdose
	Massive transfusion
	CBP

1.2.2.2 ECMO-VV

ECMO-VV is mainly implemented in acute respiratory distress syndrome (ARDS), the main causes of which are summarised in Table 1.3. This usually involves a patient with severe ARDS who is unresponsive to conventional medical treatment [1]. These patients must have a normal heart function.

As part of ARDS, ECMO-VV will help to ensure haematosis (gas exchange), reducing the use of mechanical ventilation with small volumes (6 mL/kg), while maintaining alveolar recruitment with moderate MIP (maximum inspiratory pressure) <30 cm H_2O.

Cannulation sites of ECMO-VV are mostly femorojugular. The inflow cannula is inserted into a femoral vein and the reinfusion cannula in the internal jugular vein. These cannulations are generally done percutaneously.

ECMO-VV ensures tissue oxygenation over several weeks to put the lungs at rest and permit their healing.

1.2.2.3 ECMO-VAV

Venoarteriovenous ECMO (VAV) combines ECMO-VA with a venous reinjection. The main indication is major pulmonary dysfunction associated with heart failure.

This is ECMO-VA, usually femorofemoral, to which a cannula to jugular venous injection is added. The presence of two lines of feedback helps wean assistance based on the resumption of proper activity of the heart or lungs.

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Chapter 2
Indications and Physiopathology in Venoarterial ECMO

Nicolas Brechot

Abbreviations

CPC	Cerebral performance category score
CPR	Cardiopulmonary resuscitation
ECMO	Extracorporeal membrane oxygenation
LOE	Level of evidence
LVAD	Left ventricular assist device
LVEF	Left ventricular ejection fraction
PVA-ECMO	Peripheral venoarterial ECMO
VA-ECMO	Venoarterial ECMO

2.1 Generalities

Circulatory failure refractory to conventional treatment is a fatal condition without circulatory support. Extracorporeal membrane oxygenation (ECMO) has emerged as the first-line therapy for many centers during this condition. Peripheral venoarterial ECMO (PVA-ECMO) has indeed many advantages as salvage therapy compared to other circulatory assistance systems (Fig. 2.1): it can be implanted rapidly at patient's bedside, even in remote locations, thanks to mobile ECMO teams. It allows a biventricular assistance with a high and stable blood flow, combined with a pulmonary assistance, making it suitable for most severe patients. Lastly, it is responsible for reasonable costs compared to other devices. Among them, its suitability to mobile circulatory assistance units is a major point. Mobile ECMO units are currently emerging as a crucial aspect of circulatory assistance, as patients in cardiogenic shock can rapidly become nontransferrable to centers equipped with circulatory assistance. Mobile units allow the initiation of ECMO in hospitals

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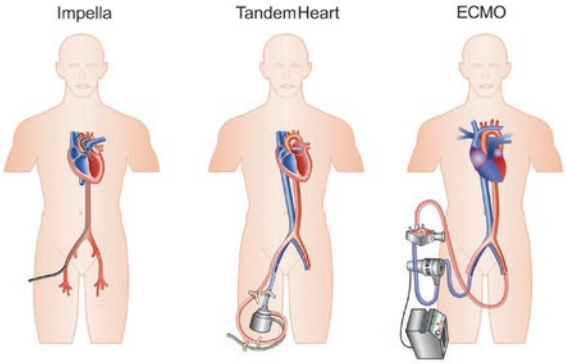

	Insertion Difficulty	Implantation at bedside/ mobile team	Flow (L/min)	RV support	Pulmonary support
PVA-ECMO	+	yes	4-6	yes	yes
impella	++	no	2.5-4	no	no
TandemHeart	+++	no	3-4	no	+/-

Fig. 2.1 Main characteristics of available short-term left ventricular assist devices (Adapted from [1])

without ECMO facilities and their transfer in tertiary care centers. In a cohort of 210 patients, ECMO-assisted patients by a mobile unit team shared the same prognosis with locally implanted patients [2].

Once implanted, ECMO will allow to buy some time to evaluate the best strategy for the patient, as a bridge to decision therapy. However, ECMO provides only a short-term support. Complications explode after 7–15 days of ECMO therapy, and the technique does not allow patient's rehabilitation, which is crucial for patient's improvement. ECMO needs therefore to be switched rapidly to another assistance, a sequence called "a bridge to"…. Patients that rapidly recover from their heart failure (myocarditis, postcardiac arrest heart dysfunction, drug poisoning, etc.) can usually be explanted from the ECMO in a bridge to recovery strategy. In patients who do not recover from multiple organ failure or are too sick to be candidate for a heart transplant or long-term assistance device (e.g., patients who developed severe brain damages), ECMO will be withdrawn with the goal of limiting the therapeutics and focusing on palliative care. Patients with intermediary myocardial or multiple organ failure recovery will be bridged to long-term mechanical assistance or to heart transplantation. An example of such kind of algorithm is presented in Fig. 2.2.

As ECMO is used at this time as a salvage therapy, no randomized study has been conducted to evaluate its true impact on mortality. However, ECMO could rescue about 40% of refractory cardiogenic shocks in large cohorts studies [3, 4]. Survivors reported a preserved quality of life, despite some limitations in physical activities and social functioning. In a before–after study in Taiwan in 70 patients

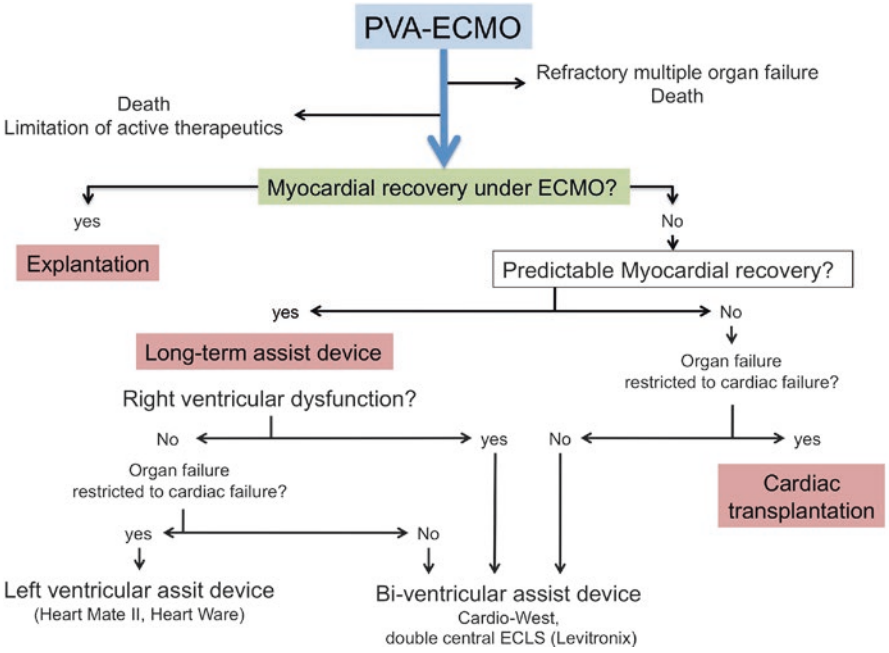

Fig. 2.2 Example of decisional algorithm after PVA-ECMO implantation

suffering from profound cardiogenic shock due to acute coronary syndrome, 30-days mortality tumbled down from 72 to 39% after implementation of an ECMO program. In a multivariable analysis, ECMO was independently associated with a better survival [5].

Contraindications to ECMO mostly contain an irreversible heart dysfunction affecting a patient who is not candidate for a left ventricular assist device or a heart transplant, and futility due to patient's condition. Other classical contraindications (anticoagulation, age, chronic organ dysfunction, compliance to medical treatment, etc.) are relative, considering the fatal course of refractory cardiogenic shock without circulatory assistance. Based on large cohorts coming from ELSO registries, Schmidt et al. could build a score predicting the expected survival for each patient, with online calculation available at www.savescore.org [6].

2.2 Optimal Timing for ECMO Implantation

ECMO assistance may be considered in case of cardiogenic shock with low cardiac output (cardiac index <2.2 L/min/m^2, or left ventricular ejection fraction (LVEF)<20% and aortic velocity time integral <8 cm assessed by echocardiography) and persistent tissue hypoxia despite administration of high doses of inotrope

and vasoconstrictors (epinephrine >0.2 μg/kg/min or dobutamine >20 μg/kg/min ± norepinephrine >0.2 μg/kg/min) and fluid volume optimization.

When first ECMO programs were built, ECMO was used as a true end-stage salvage therapy, in patients already mechanically ventilated, receiving high doses of catecholamines, and presenting a multiple organ failure worsening despite this maximal treatment. Results from those programs showed that device insertion under cardiac resuscitation as well as renal or liver failure were independent predictors of mortality under ECMO (multiplying respectively, ×21, ×7 and ×4 this risk) [3]. This indicated that ECMO should be implanted earlier during the time course of the shock, before multiple organ failure has occurred. Based on those data, ECMO centers are now more and more basing their decision to implant an ECMO on the level of cardiac output and clinical signs of tissue hypoperfusion despite catecholamine infusion. ECMO is then implanted under local anesthesia in patients spontaneously breathing and before multiple organ failure has occurred.

ANCHOR (Assessment of ECMO in acute myocardial infarction with Nonreversible Cardiogenic shock to Halt Organ dysfunction and Reduce mortality) trial, a large multicenter randomized study piloted by our center which will begin in the next few months, will compare early implantation of ECMO with implantation as a salvage therapy during profound cardiogenic shock following acute myocardial infarction. It will provide data of high level of evidence on the optimal timing for ECMO implantation and the first randomized data on the impact of ECMO during refractory cardiogenic shock.

2.3 Specific Issues by Pathology

Modalities, indications, and outcomes under ECMO are constantly evolving and strongly depend on the underlying pathology. From 2009 to 2011, 200 patients were implanted with a peripheral venoarterial ECMO in the medical ICU of la Pitié-Salpêtrière hospital, Paris. Indications, explantation, and survival rates for each pathology are represented in Fig. 2.3. Myocardial ischemia, dilated cardiomyopathy, and postcardiotomy cardiogenic shock represented the most frequent indications for ECMO and led to intermediary survival, ranging from 35 to 40%. Myocarditis, primary graft dysfunction, refractory myocardial dysfunction associated with septic shock, and poisoning appeared to be good indications for ECMO support, with a survival rate above 60%. Refractory cardiac arrest and late graft dysfunction were on the contrary associated with a very poor prognosis. The overall survival to ICU discharge was 43%. Hospital and 6-months survival rate were 40% and 33%, respectively. Mean ECMO duration was 6.3 ± 6.4 days. ECMO served as a bridge to myocardial recovery for 37% of the patients, a bridge to cardiac transplantation for 9%, and a bridge to long-term assistance for 22% of the cohort (22 central ECMO, 12 left ventricular assist device, 7 CardioWest, 3 Bi-thoratec).

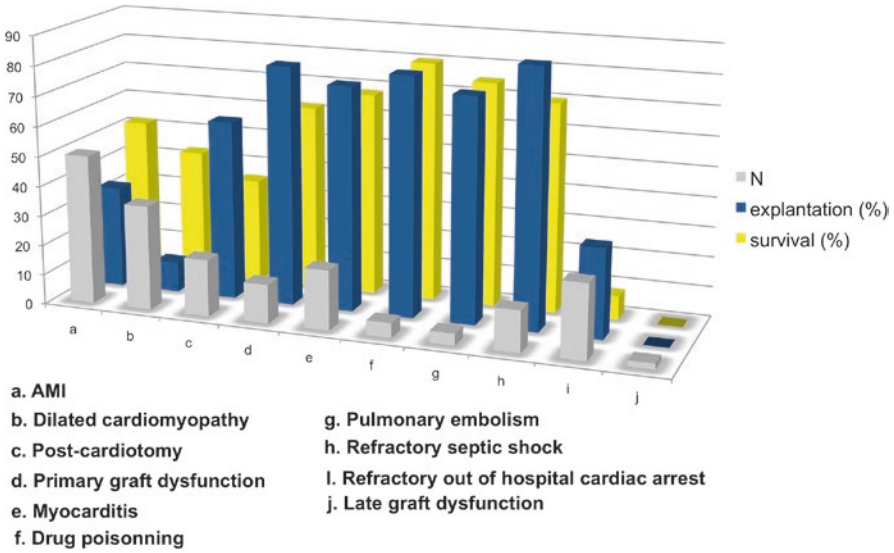

Fig. 2.3 Sample size, explantation rate, and ICU survival rate by pathology in 200 ECMO-assisted patients, from 2009 to 2011, in the medical ICU of la Pitié-Salpêtrière hospital

2.3.1 Acute Myocardial Ischemia

Acute myocardial ischemia complicated with cardiogenic shock is the leading cause for circulatory assistance. It has to date never been evaluated in randomized studies, as this condition is associated with a rapid fatal outcome. However, ECMO-assisted percutaneous coronarography was recently evaluated in a retrospective before/after study in 58 patients presenting with cardiogenic shock due to acute myocardial ischemia from 2004 to 2009 in Taiwan. Mortality at 1 year tumbled down from 76 to 37% after ECMO implementation, while patients remained unchanged regarding to demographic characteristics and disease severity [7]. This further challenges the timing for ECMO implantation in those patients. Percutaneous coronary angioplasty remains the cornerstone of the treatment in such patients, but some with profound cardiogenic shock will necessitate initiation of the ECMO first in the catheterization laboratory.

The second challenge in those patients is to predict the potential of myocardial recovery under ECMO to guide further clinical strategy. Particularly, patients with a poor potential of recovery should be rapidly switched to prolonged assistance devices such as left ventricular assist device (LVAD) or to cardiac transplantation to avoid ECMO complications.

Outcome after ECMO implantation for myocardial ischemia was recently studied in 77 patients. ECLS duration was 9.8 ± 7.1 days. Nineteen patients (24%) were finally weaned from ECMO; 40 (52%) died under ECMO; 5 (6.5%) were transplanted; 9 (11.6%) were switched to LVAD therapy; and 4 (5.2%) to biventricular mechanical assistance. Thirty-day and in-hospital survival rates were respectively

38.9% and 33.8% in this cohort. Multivariable analysis identified preimplantation serum lactate level, preimplantation serum creatinine level, and previous cardiopulmonary resuscitation as independent predictors of 30-day mortality [8].

2.3.2 ECMO Postcardiotomy

Refractory cardiogenic shock following cardiac surgery was historically the main area of development for ECMO assistance. It concerns from 0.5 to 2.9% of cardiac procedures with cardiopulmonary bypass. The rational for ECMO implantation is the potential of recovery from myocardial stunning after surgery. However, results appear quite disappointing, mainly due to age, previous medical condition, and previous cardiac damages of operated patients. In larger cohorts, patients referred for postcardiotomy ECMO had a mean age around 64 years, a mean euroscore around 21%, and a LVEF around 46% [9, 10]. More than half of the patients could be weaned from the ECMO, but only 24–33% were discharged home, and survival at 1 year varied from 17 to 29%. Age >70, diabetes, obesity, preoperative renal insufficiency, preoperative LVEF, and preimplantation acidosis were independently associated with a poor outcome, while isolated coronary artery bypass grafting appeared to be protective. Interestingly, neither cardiopulmonary bypass duration nor aortic clamping time seems to be associated with the outcome.

2.3.3 ECMO for Primary Graft Failure After Heart Transplantation

Primary graft failure is a frequent complication after heart transplantation, ranging from 4 to 24%, mostly depending on the local politics on marginal heart allografts. Several studies reported the successful use of transient mechanical support with an ECMO in this indication. Explantation rates varied from 60 to 80% and long-term survival from 50 to 82%. Interestingly, cumulative survival did not differ in patients who survived the ECMO period from non-ECMO patients [11]. Again, results appear far better when ECMO is implanted early during the time course of the disease, with a survival rate of only 14% when used as a salvage therapy [12].

2.3.4 ECMO for Acute Myocarditis

Myocarditis is a disease that may progress rapidly to refractory cardiogenic shock and death. Considering the prompt myocardial recovery in most of the patients and

its easy and rapid implantation and explantation, peripheral venoarterial ECMO has become the elective first-line assistance device for those patients.

Several large cohorts reported the favorable outcome of this otherwise fatal condition using ECMO support. In a cohort of 41 fulminant myocarditis with refractory cardiogenic shock patients assisted with VA-ECMO, survival to discharge was 70% in the ECMO group [13]. This high survival rate contrasted with the high severity of the patients before ECMO implantation, reflected by a mean SAPS-II score at 56. The median duration of assistance was quite short, 10 days, highlighting the rapid myocardial recovery in these patients. Mean LVEF was 57% at 18 months. Four patients who did not recover needed a heart transplantation and were alive at discharge. Patients needed however a high degree of healthcare resources: 88% required mechanical ventilation, 54% dialysis, and the mean hospitalization duration was 59 days. Importantly, 63% of the patients exhibited at least one major complication related to the ECMO. Ten developed hydrostatic pulmonary edema and necessitated a switch for a central assistance. Other complications comprised major bleeding at the cannulation site (46%), deep vein thrombosis (15%), arterial ischemia (15%), surgical wound infection (15%), and stroke (10%). After a mean 18 months of follow-up, patients reported a highly preserved mental health and vitality. However, they still reported physical and psychosocial difficulties, and anxiety, depression, and/or post-traumatic stress disorder symptoms were present in respectively 38, 27, and 27% of them. Ten patients presented also long-term paresthesia or neurological defect in the leg of the ECMO, and one necessitated a major amputation due to arterial ischemia. In this cohort, SAPS-II >56 and troponin >12 μg/L were the only independent predictors of poor outcome.

In another cohort of 75 pediatric and adult patients with myocarditis complicated with a refractory cardiogenic shock, PVA ECMO as first-line therapy gave comparable results. Sixty-four percent of the patients could be discharged home with a mean LVEF of 57%. Nine patients did not recover and were switched to long-term ventricular assist device (six patients) and heart transplantation (three patients). Thirty percent necessitated left ventricule drainage for refractory pulmonary edema under VAP ECMO. This condition was associated with a poorer weaning rate from the ECMO (39%) and a poorer survival (48%). Again, dialysis and a persistent elevation of troponin levels were independent predictors of a poor outcome [14].

2.3.5 ECMO and Drug Intoxication

PVA-ECMO is routinely used in daily practice during refractory cardiogenic shock following drug intoxication, and is recommended during cardiac arrest in this condition (grade IIb, level of evidence C) [15].

Interest for ECMO assistance during drug poisoning comes from the reversibility of the cardiac dysfunction observed. Experimental studies demonstrated a clear

benefit of the technique in several models, and many single case studies reported its successful use in humans [16]. The largest cohort on that subject concerned 62 patients in a single center, mean age 48, presenting a refractory cardiogenic shock following drug intoxication [17]. Ten of them deteriorated to a refractory cardiac arrest, and fourteen of the patients were implanted with a PVA ECMO, three during cardiopulmonary resuscitation. Survival was strongly increased in ECMO-implanted patients (86% vs. 48%, $p = 0.02$). Particularly, none of the refractory cardiac arrest patients survived without ECMO, whereas all of the three ECMO-implanted patients during this condition survived. It was also noticed that none of the ECMO-implanted patients died during intoxication with membrane-stabilizing agent, whereas 65% of the nonimplanted patients died. The particularity of ECMO assistance during this condition comes from the vasoplegic properties of many toxic agents, making high flow rates difficult to achieve. Thus, although PVA-ECMO seems very useful in drug intoxication, its exact timing and efficacy for each agent remains to be better determined.

2.3.6 ECMO and Deep Hypothermia

PVA ECMO has become the reference technique for rewarming patients presenting a deep hypothermia (<28 °C) complicated with a cardiac arrest after the description of several case reports and 15 survivors with favorable long-term neurological outcomes in a cohort of 32 patients [15, 18, 19]. In this last cohort, the mean temperature was 21.8 °C, and the mean interval between discovery to ECMO support was 141 min. ECMO allows indeed the fastest rewarming and assures an immediate adequate circulatory support. It also prevents the shock due to peripheral vasodilatation during rewarming, as the central body is rewarmed before its peripheral parts. As low temperatures considerably increase the ischemic tolerance of the brain, many efforts are employed by clinicians to resuscitate those hypothermic patients, with the universal idea that "nobody is dead until warm and dead." However, the mortality rate after a cardiac arrest associated with deep hypothermia is still high, even in ECMO-assisted patients, ranging from 30 to 80% [20–23]. The major problem is to determine which occurred first between hypoxia and hypothermia. Asphyxia before hypothermia developed is associated with an extremely poor survival (ranging from 0 to 6%) and a poor neurological outcome in survivors [20–22]. On the contrary, patients in whom cooling preceded the cardiac arrest have a very good survival rate (from 60 to 100%) and satisfactory long-term neurological outcome when assisted with an ECMO [19, 20, 22]. Major causes of accidental hypothermia are avalanches, drowning, drug intoxication, and exposure to cold air. In clinical settings the determination of the exact sequence of clinical events is usually very difficult, although asphyxia is usually associated with avalanches, accidents, and drowning and is more unusual in drug intoxication and exposed to cold air patients.

2.3.7 ECMO and Severe Pulmonary Embolism

Successful rescue therapy with an ECMO has been described in several cases of life-threatening pulmonary embolism [24, 25], even in patients in cardiac arrest [26]. The technique seems very promising in this indication, as it allows an immediate right ventricule and pulmonary support, whereas medical management of a severe cardiogenic shock due to right ventricular failure remains challenging. Further studies will have to precise the place of ECMO in the therapeutics available during severe pulmonary embolism, particularly regarding thrombolysis therapy. The other main challenge in this field will be to determinate whether an adjunctive treatment must be performed in ECMO-treated patients. One could advocate that a complementary treatment with catheter-guided thrombectomy or surgical embolectomy might allow a faster recovery from the right ventricule dysfunction [26, 27]. Others may argue that, once in place, ECMO allows to buy some time to ensure the natural lysis of the thrombus, as it was demonstrated in several patients [24, 28, 29]. Future studies will help us to better determinate the short-term and long-term outcomes of these different strategies.

2.3.8 ECMO and Septic Shock

The use of mechanical circulatory assistance remains controversial during refractory septic shock in adults. ECMO was shown to be highly effective as salvage therapy in children with refractory septic shock [30–32]. Most of the adult patients present a refractory vasoplegia and a preserved cardiac output during this condition, a hemodynamic profile in which the adjunction of an ECMO was shown to be quite ineffective in a cohort of 52 patients in Taiwan [33]. However, a profound myocardial dysfunction can also occur during bacterial septic shock. We recently evaluated the outcomes of 14 patients who received VA-ECMO rescue therapy for refractory cardiovascular failure during bacterial septic shock, from January 2008 to September 2011 [34]. The 14 patients, median age 45 years, were implanted with a median time of 24 h after shock onset. All exhibited severe myocardial dysfunction at ECMO implantation. Median left ventricular ejection fraction was 16% (range 10–30%), cardiac index was 1.3 L/min/m^2 (0.7–2.2), and systemic resistance vascular index was 3162 (2047–7685). All were receiving high-dose catecholamines and had signs of multiple organ failure: median pH 7.16 (range 6.68–7.39), blood lactate 9 (2–17) mmol/L, PaO_2/FiO_2 87 (28–364), Simplified Acute Physiology Score 3 84 (75–106) and Sepsis-Related Organ Failure Assessment Score 18 (8–21). Twelve patients (86%) could be weaned from the ECMO after 5.5 (2–12) days of support, and 10 patients (71%) were discharged home and were alive after a median follow-up of 13 months (3–43). All ten survivors had normal left ventricular function and reported a highly preserved quality of life. VA-ECMO might thus represent a valuable therapeutic option for adults in severe septic shock with refractory cardiac and hemodynamic failure, but this has to be confirmed in the future in larger cohorts.

2.3.9 ECMO and Refractory Cardiac Arrest

Apart from accidental hypothermia and drug intoxication in which ECMO support is recommended [15, 19, 35], its use in other forms of cardiac arrest is more controversial.

Several cohort studies, ranging from 42 to 135 patients, reported the use of ECMO during refractory cardiac arrest. ECMO could be implanted successfully in more than 90% of the patients in all studies, mostly in the emergency department and in the catheterization laboratory. Results of the technique vary largely between in-hospital and out-of-hospital cardiac arrest.

During in-hospital refractory cardiac arrest, survival rates varied from 34 to 58%, and long-term survival with good neurological outcome (cerebral performance category (CPC) score 1–2) from 24 to 38%. The patients implanted during this condition were quite old, with a median age around 65 years, had quite prolonged cardiopulmonary resuscitation (CPR) time before ECMO implantation, with median time ranging from 40 to 60 min, and had a high rate of nonshockable initial rhythm, up to 50%, in several studies [36–41]. Survival appears directly linked to CPR duration before ECMO implantation, and decreases from 30 to 17% after 60 min [37]. In 172 patients who presented an in-hospital cardiac arrest with a CPR duration >10 min, in whom an ECMO was implanted in 59, ECMO was strongly associated with a reduction in 1-year mortality (log-rank $p = 0.007$). After matching 46 patients per group on potential confounding factors (age, comorbidities, CPR duration, etc.), mortality fell from 82.6 to 67% in the ECMO group [37].

Results during out-of-hospital cardiac arrest remain more equivocal. In a cohort of 162 witnessed out-of-hospital cardiac arrest with CPR >20 min in Japan, of whom 53 received an ECMO, 3-month survival with good neurological outcome was significantly improved in the ECMO group but remained low, 15 versus 2.8% in the standard therapy group. Mean no-flow and low-flow times were 2 (0–8) min and 49 (41–59) min [39]. In another cohort of 51 patients with higher no-flow and low-flow times (3 min (1–7) and 120 min (102–149)), results were quite disappointing, as only two patients survived (4%) with a favorable neurological outcome at day 28. In this cohort, 90% of the patients died during the first 48 h from multiple organ failure and massive hemorrhage [42]. No-flow time >5 min and $ETCO_2$ <10 mmHg before ECMO implantation were associated with a 100% mortality rate. However, the low-flow time was not predictive of survival, as both survivors had prolonged low-flow time, higher than 100 min.

American Heart Association does not currently recommend routine ECMO implantation during CPR. However, ECMO may be considered when: (a) it is readily available, (b) the time of no blood flow is short, and (c) the conditions of arrest are either reversible or amenable (Class IIB, LOE C) [15]. The French Society of Intensive Care Medicine (SRLF) proposed an algorithm in which a no-flow time <5 min and an $ETCO_2$ >10 mmHg are crucial components for the decision [43]. In conclusion, implanting an ECMO seems reasonable during in-hospital refractory cardiac arrest in selected patients with good overall conditions, reasonable low-flow

time, and reversible cause of the heart failure. Its use in out-of-hospital refractory cardiac arrest seems to date more questionable and should be restricted to highly selected patients, young, with little coexisting conditions, a no-flow time <5 min, and $ETCO_2$ >10 mmHg at ECMO implantation.

Patients beyond these limits may be evaluated for potential Maastricht II organ donation, which is also an important role for the technique.

2.4 Conclusion

ECMO has emerged as the standard first-line therapy during refractory circulatory failure. It allows a prompt circulatory and pulmonary support at bedside with reasonable costs, even in remote locations, thanks to mobile ECMO units. Successful ECMO-based salvage therapy has been described to date in various cases of refractory circulatory failure, with a highly preserved quality of life in survivors. However, outcome after ECMO implantation strongly varies from one etiology to another. Myocarditis, primary graft dysfunction, refractory myocardial dysfunction associated with septic shock, deep hypothermia, and drug intoxication are associated with a prompt myocardial recovery and a high survival rate (above 70%). Myocardial infarction, dilated cardiomyopathy, and postcardiotomy refractory cardiogenic shock seem to provide intermediate survival results (from 40 to 50%). Patients are less likely to be explanted during those conditions, and a number of them will necessitate high healthcare resources, like long-term left ventricule assist devices or cardiac transplantation. Lastly, ECMO appeared to give disappointing results during out-of-hospital cardiac arrest and drowning (survival between 0 and 15%), and future research is needed in those pathologies to allow a better selection of the patients to avoid futile efforts and costs related to the technique. The other crucial progress in the field will be to better define the optimal timing of ECMO implantation during each condition, as it appears from almost all cohort studies that the shorter ECMO is implanted, the better are the chances for the patient to survive.

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Chapter 3
Indications and Physiopathology in Venovenous ECMO on Severe Acute Respiratory Distress Syndrome

Matthieu Schmidt

3.1 Introduction

Mechanical ventilation remains the cornerstone of respiratory support for acute respiratory failure (ARF) patients. However, high pressure and volume associated with tidal ventilation are known to aggravate lung injury in this setting [1]. In the most severe forms of the disease, profound gas-exchange abnormalities threatening patients' lives can occur despite using the conventional salvage therapies [2, 3]. Venovenous extracorporeal membrane oxygenation (VV-ECMO) was developed more than 40 years ago [4, 5] to rescue these dying patients. ECMO also permit "ultraprotective" mechanical ventilation with further reduction of volume and pressure that might ultimately enhance lung protection and improve clinical outcomes of ECMO [6, 7]. More recently, the successful use of ECMO for the most severe ARDS cases associated with the recent influenza A (H_1N_1) pandemic who failed on conventional ventilation [8–10] and positive results of the randomized CESAR trial [11] have been associated with a steep increase in the number of VV-ECMO procedures performed in very recent years.

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3.2 How Does It Work?

3.2.1 Settings

In recent years, major technological advances occurred, and the latest ECMO devices with polymethylpentene hollow-fiber membrane lungs and Mendler-designed centrifugal pumps offer lower resistance to blood flow, have smaller priming volumes, higher effective gas exchange properties, and are coated with more biocompatible materials. The extracorporeal system consisted of polyvinyl chloride tubing, a membrane oxygenator, and a centrifugal pump. An oxygen-air blender is used to ventilate the membrane oxygenator (2–14 $l.min^{-1}$). Venovenous ECMO provides complete extracorporeal blood oxygenation and decarboxylation using high blood flows (4–6 L/min) and large (20–30 Fr) cannulas [12–15]. Blood is usually drained from the right atrium or the inferior vena cava through a multiperforated cannula inserted percutaneously into the right femoral vein and is returned to the superior vena cava through a cannula inserted percutaneously into the right internal jugular vein (Femorojugular setting) or in the right atrium through a cannula inserted into the femoral vein (Femoral–femoral setting). During the procedure, using transthoracic or transesophageal echocardiography is fostered to properly set the position of the drainage cannula.

3.2.2 Determinants of Oxygenation on VV-ECMO

The main determinants of oxygen delivery (DO_2) to peripheral tissues, which is critical to preserve organ function, are hemoglobin concentration, SaO_2, and cardiac index [16]. When DO_2 falls below a critical threshold, oxygen consumption becomes dependent on DO_2 and lactate concentration may increase, reflecting activation of anaerobic metabolism. To prevent tissue hypoxia, recommended oxygenation objective is to maintain SaO_2 ≥88% using high PEEP and high FiO_2 in mechanically ventilated ARDS patients [17, 18]. However, when refractory hypoxemia develops, recourse to VV-ECMO is a reasonable therapeutic option [8, 9, 11, 19, 20]. In this circumstance, blood oxygenation may become completely dependent on membrane oxygenator oxygen transfer capability. Factors determining oxygenator oxygen transfer in this setting are blood oxygen saturation in the ECMO drainage cannula, hemoglobin concentration, blood flow in the ECMO circuit, and intrinsic membrane oxygenator properties, which depend on the exchange membrane surface and diffusibility of O_2 through hollow microfibers. O_2 transfer through recent modern oxygenator is theoretically >400 ml O_2/min when blood flow through the ECMO circuit is >6 l/min, while oxygen saturation in the ECMO drainage cannula is 70% and hemoglobin concentration is 15 g/dl [21]. However, since both drainage and return cannulae are positioned within the venous system in VV-ECMO, blood recirculation into the oxygenator occurs, that is, a proportion of returned blood is drained again into the circuit instead of passing through the right heart, thus markedly

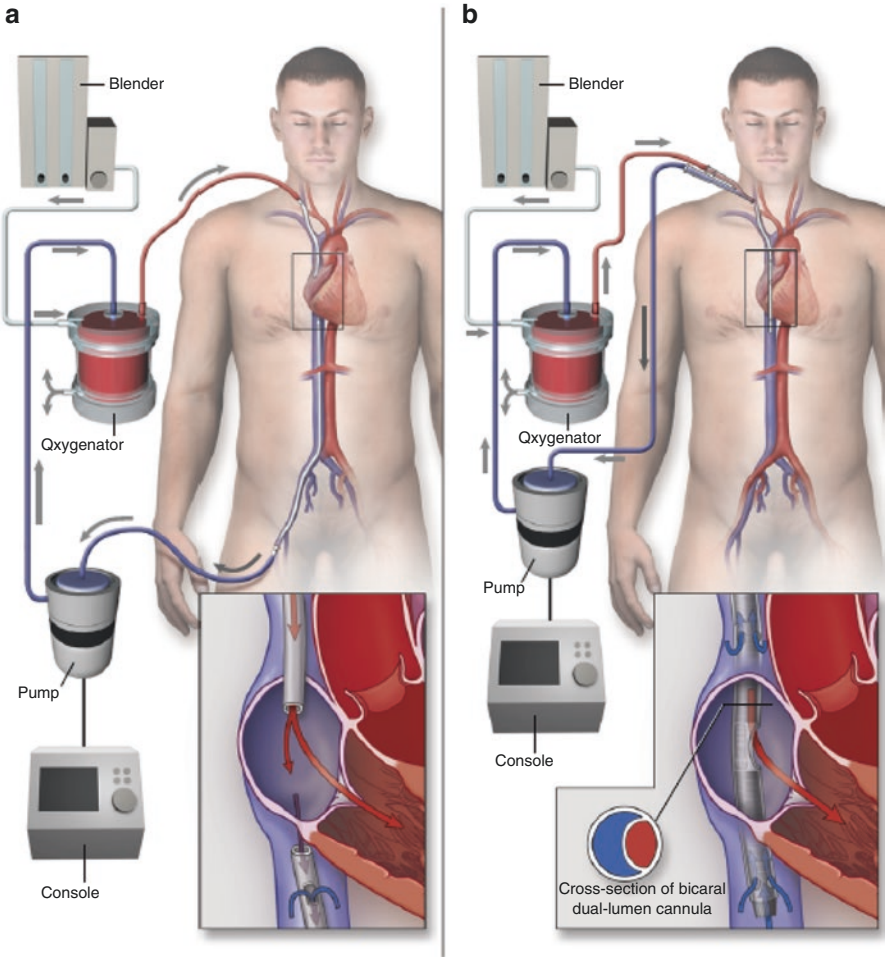

Fig. 3.1 Single-site and two-site approaches to venovenous ECMO cannulation (With permission [13] (du NEJM)). (**a**) A two-site approach to venovenous ECMO cannulation. (**b**) A single-site approach to venovenous ECMO cannulation.

reducing O_2 transfer efficiency [22]. To minimize blood recirculation into the circuit, it can be configured in several ways [19, 20]. In the bifemoral setting, drainage cannula is positioned in the inferior vena cava (IVC), and a femoral return cannula is advanced to the right atrium (see Fig. 3.1a). However, 50% of the patients who received bifemoral VV-ECMO for H_1N_1-induced ARDS in the ANZICS ICUs also needed a second (jugular) drainage cannula, because of insufficient blood drainage [8]. Alternatively, a single bicaval dual-lumen cannula (Avalon Elite®) can be inserted via the right jugular vein and positioned to allow drainage from the IVC and SVC and oxygenated blood return via a second lumen in the right atrium [23] (see Fig. 3.1b). This setting minimizes blood recirculation, but insertion of the

jugular catheter requires an experienced and skilled operator and recourse to fluoroscopy or TEE guidance for its adequate positioning. Lastly, femorojugular setting for VV-ECMO allows minimizing blood recirculation if the tip of the return cannula is positioned away from that of the inflow cannula. To achieve this goal, mean distance between both cannulae should be measured on the chest X-ray. A minimal distance of 12 cm is generally advocated. Additionally, it has been shown in a previous study that, compared to the jugulofemoral configuration, the femorojugular bypass provided higher maximal ECMO flow, higher pulmonary arterial mixed venous oxygen saturation, and required comparatively less flow to maintain an equivalent mixed venous oxygen saturation [24].

To improve oxygen blood transfer in the oxygenator and to increase oxygen transport to peripheral organs, a recent study has demonstrated that besides ECMO cannulae configuration, ECMO flow through the ECMO circuit is the major determinant of blood oxygenation. ECMO flow >60% of systemic blood flow permitted adequate peripheral oxygenation [25]. Thus, depending on the patient size, cardiac output, oxygen consumption, and lung shunt, circuit blood flow between 4–7 l/min will typically be required to achieve arterial oxygen saturations >88–90%, while maintaining safe lung ventilation. Therefore, large size (24–30 Fr) and multihole drainage cannula should be preferred to obtain high flows with reasonable negative pressure in the drainage cannula. Indeed, if small cannulae are used with high flows, the suction created by the centrifugal pump can cause excessive depression and cavitation in the inflow line resulting in massive intravascular hemolysis [19, 20]. Physiological in vivo study demonstrates that, for patients who received VV-ECMO for refractory hypoxemia and whose native lung gas exchange function was almost completely abolished, the determining factors of arterial oxygenation are VV-ECMO blood flow and FiO_{2ECMO}. Specifically, using the femorojugular ECMO setting, achieving VV-ECMO flow >60% of systemic blood flow was constantly associated with arterial blood saturation >90%.

The other important parameter that might be manipulated to enhance tissue oxygen delivery and maximize extracorporeal circuit efficiency is blood hemoglobin concentration [16] (Table 3.1). In patients under ECMO support, guidelines from the Extracorporeal Life Support Organization (ELSO) and investigators of the CESAR trial recommend maintaining normal hematocrit (40–45%) and hemoglobin concentrations at 14 g/dl, respectively [11, 26]. However, critically ill patients and specifically those already suffering from diffuse alveolar damage may be at even greater risk of transfusion-related acute lung injury [27–29]. Accordingly, a restrictive transfusion strategy with red-cell transfusion threshold set at 7–8 g/dl in most patients under ECMO is doable. Schmidt et al. demonstrated that despite mean hemoglobin concentration and DO_2 at 8.0 $g.dl^{-1}$ and 679 ml/min, respectively, every patient had adequate SaO_2, and no sign of VO_2/DO_2 mismatch was observed [25]. Lastly, transfusion of blood products increases volemia, which might also complicate the course of ARDS, since a study reported slower lung function improvement and longer mechanical ventilation duration when a liberal strategy of fluid management was used in patients with acute lung injury [30].

Table 3.1 Main determinants of oxygenation and decarboxylation on ECMO

Determinants of oxygenation on VV-ECMO
1. Intrinsic membrane oxygenator properties (size, type of microfibers, etc.)
2. Blood flow in the ECMO circuit
3. Blood oxygen saturation in the ECMO drainage cannula (i.e., recirculation)
4. Hemoglobin concentration
5. FmO_2 on the membrane
Determinants of decarboxylation on VV-ECMO
1. Size of the membrane
2. $PaCO_2$ level
3. Sweep gas flow

3.2.3 Determinants of Decarboxylation on VV-ECMO

The determining factor of blood decarboxylation is the rate of sweep gas flow ventilating the membrane lung, while $PaCO_2$ is unaffected when ECMO blood flow and FiO_{2ECMO} are reduced to <2.5 l/min and 40%, respectively.

CO_2 transfer through the membrane lung also depends on ECMO flow, with maximum transfer being >300 ml/min when ECMO flow is >6 l/min with the Quadrox® oxygenator. However, since CO_2 diffuses 20 times faster than O_2, large amount of CO_2 can be exchanged through the membrane lung even when low flow is applied through the circuit [25]. For instance, recent data showed that $PaCO_2$ remained unchanged when ECMO blood flow was reduced to <2.5 l/min. Indeed, this property is the basis for developing low-flow extracorporeal CO_2 removal devices, for which CO_2 removal is >70 ml/min at blood flows of only 450 ml/min [31, 32]. Alternatively, sweep gas flow across the oxygenator is the main determinant of CO_2 removal by ECMO [25].

3.3 Main Indications of VV-ECMO for Severe ARDS

Indications are usually based on: (1) severe hypoxemia (e.g., PaO_2 to FiO_2 ratio <80 mmHg, despite optimization of mechanical ventilation (tidal volume set at 6 ml/kg and trial of PEEP≥10 cm H_2O)) for at least 6 h in patients with potentially reversible respiratory failure and possible recourse to adjunctive therapies (NO, prone position, etc.) and/or or (2) uncompensated hypercapnia with acidemia (pH <7.15) despite the best accepted standard of care for management with a ventilator and/or

(3) excessively high end-inspiratory plateau pressure (>32 cm of water). However, considering the CESAR trial, the ongoing EOLIA trial, and the recommendations of the Extra Life Support Organization (ELSO), the thresholds of PaO_2 to FiO_2 ratio, pH, or plateau pressure may vary considerably across studies and guidelines.

Relative contraindications are usually mechanical ventilation for more than 7 days, limited vascular access, and any condition or organ dysfunction that would limit the likelihood of overall benefit from ECMO, such as malignancies with fatal prognosis within 5 years, moribund patients, or those with irreversible neurological pathologies and decisions to limit therapeutic interventions. Contraindication to the use of anticoagulation therapy is mentioned in several reviews or guidelines. However, several publications have stressed that, while using new-coated heparin circuit, anticoagulation on ECMO VV may be safely withheld for days or weeks.

3.4 Recent Data of ECMO VV in ARDS

The most recent trial (CESAR trial) which was conducted in the UK from 2001 to 2006 evaluated a strategy of transfer to a single center (Glenfield, Leicester) which had ECMO capability, while the patients randomized to the control group were treated conventionally at designated treatment centers [6]. The primary endpoint combining mortality or severe disability 6 months after randomization was lower for the 90 patients randomized to the ECMO group (37% vs. 53%, $p = 0.03$). However, results of that trial should be analyzed carefully. First, 22 patients randomized to the ECMO arm did not receive ECMO (died before or during transport, improved with conventional management at the referral center, or had a contraindication to heparin). Second, no standardized protocol for lung-protective mechanical ventilation existed in the control group, and the time spent with "protective" mechanical ventilation was significantly higher in the ECMO arm. Third, more patients received corticosteroids in the ECMO group. In the most recent series, patients benefited from the latest ECMO technology, which include a centrifugal pump, a polymethylpentene membrane oxygenator, and tubing with biocompatible surface treatment. Mortality rates ranged from 36 to 56% in the studies performed in the last 15 years and reporting outcomes of >30 ECMO patients (Table 3.1). Interestingly, ECMO was provided through a mobile ECMO rescue team in some of these studies. For example, in a series of 124 patients treated at a Danish center between 1997 and 2011 [33], survival was 71%, and 85% of these patients received ECMO via a mobile unit before being transferred to the referral hospital. Similarly, in the Regensburg cohort, 59/176 received ECMO at another hospital by a mobile unit [34]. In a multicenter French cohort of 140 patients treated between 2008 and 2012, 68% patients were retrieved via a mobile ECMO team, and their prognosis was comparable to those who received VV-ECMO support in their initial center hospital [35]. ECMO support might also cause severe and potentially life-threatening complications, such as bleeding, infections, intravascular hemolysis, thrombocytopenia, or consumption coagulopathy [35–39].

Mortality rates of ECMO for pandemic influenza A (H_1N_1)-associated ARDS ranged from 14 to 64% in the 16 studies from 11 countries reporting on the experience

of ECMO for influenza A (H_1N_1)-associated ARDS [8–10, 35, 40–50]. The Australia and New Zealand collaborative group (ANZICS) was the first to report its experience [8]. Despite extreme disease severity at the time of ECMO initiation (median PaO_2/FiO_2 ratio 56 mmHg, median positive end-expiratory pressure [PEEP] at 18 cm H_2O, and median lung injury score of 3.8), only 25% of the 68 ECMO patients died. A British collaborative cohort series [9] depicted the outcome of 80 patients transferred into ECMO referral centers in United Kingdom of whom 69 received ECMO. Mortality in this cohort was 27.5%. A propensity-matched analysis comparing survival of patients referred for consideration of ECMO to other ARDS patients showed better outcomes for referred patients. Alternatively, mortality of propensity-matched patients treated conventionally was comparable to that of ECMO patients in French ICUs of the REVA network. However, only 50% of ECMO patients were successfully matched with control ARDS patients, while unmatched ECMO patients were younger, suffered more severe respiratory failure, and had considerably lower mortality [10]. Interestingly, a higher plateau pressure under ECMO was independently associated with mortality, indicating for the first time that an ultraprotective ventilation strategy with reduction of plateau pressure to around 25 cm H_2O following ECMO installation might improve outcomes. Lastly, mortality was 29% on a cohort of 49 proven influenza A (H_1N_1) patients from the 14 ECMO centers of the ECMO-NET Italian collaborative group [51]. In this series, patients ventilated for <7 days before ECMO initiation had a significantly higher survival.

3.5 Mortality Risk Factors and Predictive Survival Models

Factors associated with poor outcomes after ECMO for acute respiratory failure include older age [34–36, 52–55], a greater number of days of mechanical ventilation before the ECMO establishment [35, 36, 52, 53, 55], a higher number of organ failure [34–36, 52–55], low pre-ECMO respiratory system compliance [55], as well as immunosuppression [35, 55, 56]. Predictive survival models have been recently developed which might help clinicians select appropriate candidates for ECMO [35, 54–57]. For instance, the RESP-score [55] constructed on data extracted from a large multicenter international population (n = 2355) computes 12 simple pre-ECMO parameters to provide a relevant and validated tool predicting survival after ECMO for acute respiratory failure. Cumulative predicted hospital survival were 92, 76, 57, 33, and 18% for five RESP-score risk class I (≥6), II (3 to 5), III (−1 to 2), IV (−5 to −2), and V (≤−6), respectively.

3.6 Conclusions

Recent technological advances have improved the safety and the simplicity of ECMO use in ARDS. In addition, mobile ECMO team has made this therapy more accessible for all patients. Actual literature has reported that early implementation of VV-ECMO in refractory and severe ARDS can strongly reduce pressures and

volumes applied on the alveoli in order to minimize ventilation-induced lung injury. However, strong evidence of its benefit and optimal timing for cannulation are still lacking. Therefore, results of next multicenter randomized trials (i.e EOLIA trial) are needed before wide spreading this promising technology.

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Part II
Nursing Care

Chapter 4
Preparing the Patient and the ECMO Device

Alicia Mirabel, Anne-Clémence Jehanno, Charles-Henri David, and Guillaume Lebreton

This chapter focuses on the different stages necessary for the safe implementation of an ECMO and the role of each in the process. We will follow a timeline similar to that used in our daily practice. Standardization of these gestures is essential, especially when the installation has to be done urgently [2].

4.1 The Team and Equipment Transportation

As the need for ECMO is established, the team is ideally composed of an anesthesiologist and the nurse responsible for the patient, a senior surgeon, a resident or an operating room nurse, and a perfusionist.

The equipment necessary for the implementation of ECMO/ECLS will be provided by the perfusionist or the surgical team. This material is checked, maintained, and conditioned by the operating room team. All the equipment (consumables and ECMO/ECLS console) must be available and ready at any time. The packaging of this material may be in a dedicated trolley and bag(s). It must include sterilized instruments, sterile drapes, surgical gowns, cannulas, introducers, radio-opaque dressings, and surgical consumables (Fig. 4.1).

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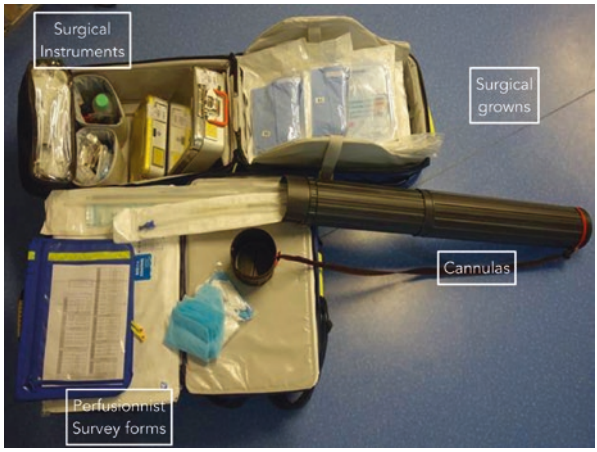

Fig. 4.1 Material packaging

4.2 Patient Installation and Preparation

The room must contain an operating light, electrocautery generator, and enough space for the surgeons to move around the patient. In order to facilitate the swiftness of the implantation, the surgeon, before arriving on site, usually asks for the equipment to be prepared and for surgical preparation of the cannulation site (depilation and sterile cleaning) to be carried out.

The patient is positioned supine with a block, usually made of rolled sheets, under the pelvis or the patient's shoulder in order to improve exposure of the surgical site. The patient must have received an operating room and a toilet depilation of the surgical site. A backup site should always be provided in case of cannulation failure. Usually, for a femoral cannulation, both sides of the groin are prepared. This will also give the advantage of varying cannulation sites (artery and vein from one side to the other to reduce the risk of ischemia). You must then install the electrocautery plate away from any metal prosthesis on healthy and fleshy skin.

This will be followed by a sterile wash according to the unit protocol, which will start from the ear and run to the patient's knees bilaterally. The right jugular site is exclusively used. If dressings are present in those areas, they must be removed first.

To avoid the risk of an electric arc between the electrocautery and the presence of alcohol vapor, do not use alcohol antiseptic, which could cause severe burns to the patient.

4.3 Surgical Approach and Preparing ECMO

Once the patient is installed and the approach sites prepared, the dressing with surgical gowns can begin. A pack of surgical drapes is positioned at the patient's foot or on a side table. The positioning of the sterile drapes must meet the standards of

Fig. 4.2 Emergency crank (*red arrow*) on a centrifugal pump (*blue arrow*)

sterility. A suction line is sterilely given to the nurse, who connects it to a strong suction connected to a collecting tray.

The nurse/resident installs the instrumentation table with all the necessary tools for the ECMO/ECLS implementation and prepares local anesthesia if necessary. In case of a mechanically ventilated patient, he ensures that sedation and analgesia are appropriate.

During this phase of installation and surgical approach, the perfusionist installs the ECMO/ECLS console in the patient's room. The console must be connected to a power supply and an air and oxygen wall supply. The entire ECMO/ECLS console must be equipped with an air/oxygen gas mixer, an emergency crank, a centrifugal pump, a membrane support, and two Vorse tube press clips (usually called Weiss clamps) (Fig. 4.2). A heat generator will warm the priming at first, and then regulate the patient's temperature. After installing the console, the perfusionist will de-air the circuit.

Before starting, the perfusionist checks the circuit's integrity and validity date. The bubble is removed by a crystalloid solution. Assembly and installation of the circuit on the console is carried out in a sterile manner. Taps, plugs, and fittings will be checked manually. Each laboratory has recommendations for de-airing that must be used (regularly updated). It is therefore essential to refer to the user manual. The priming should be done initially by gravity to expel the air from the entire circuit. Once this is complete, proceed to the removal of bubbles using a centrifugal pump, initially at

low speed and then gradually increasing the speed until no bubbles remain. The ease and speed of de-airing depends on the model of the circuit used. Once the bubble removal is complete, the circuit will be closed and secured: all valves are closed and checked for a possible leak of the circuit or oxygenator. Depending on the console used, place sensors, ultrasonic flow meter, or cream as required. It is useful to keep the de-airing lines until the initiation of assistance in case they are needed further.

4.4 Establishment of ECMO

The cannulas are inserted and purged with saline solution. Before venous cannulation, a heparin bolus must be performed to prevent cannula thrombosis. Most often, a 5000 iu standard dose of unfractionated heparin is injected. Under ECLS (ECMO-VA), a reperfusion catheter is implanted to prevent limb ischemia [1].

Once cannulation is completed, the sterile lines are given to the surgeon. The connection lines will be cleansed of residual air using a prefilled saline solution syringe.

The prestarting ECMO/ECLS checklist is set by the surgeon, anesthetist, and perfusionist trio. It includes:

- Start-up of the gas.
- Verification of the priming temperature: it must be warm to avoid rhythm disorders due to a cold shock at start-up.
- Verification that the reinjection line is clamped.
- Verification of the rotation speed of the centrifugal pump, which must be set at a minimum threshold preventing backflow when the ECMO/ECLS is begun.

In the context of an ECMO/ECLS implanted under cardiac massage, this will be stopped once the ECMO/ECLS is started and stabilized.

Surgical braided sutures fix lines and cannulas at three points. These must keep the cannula in place in the axis of the vessel and prevent any decannulation. Meanwhile, the perfusionist will manage the balance between patient hemodynamic and ECMO support with the help of the surgeon and the anesthesiologist (hypovolemia, vascular resistance, control of ventilation). Then, the surgeon closes the incision after local hemostasis verification.

The dressing is done by the surgical nurse or the resident: it must be occlusive and sterile. It can be transparent if the puncture sites are clean or opaque in case of bleeding (Tegaderm®, Cicaplaie®, Mepor®).

The member reperfusion line is covered with a transparent dressing to detect thrombosis of the tubing and prevent kinking (Fig. 4.3).

When the patient is stable on support, we can proceed to the preparation of transportation.

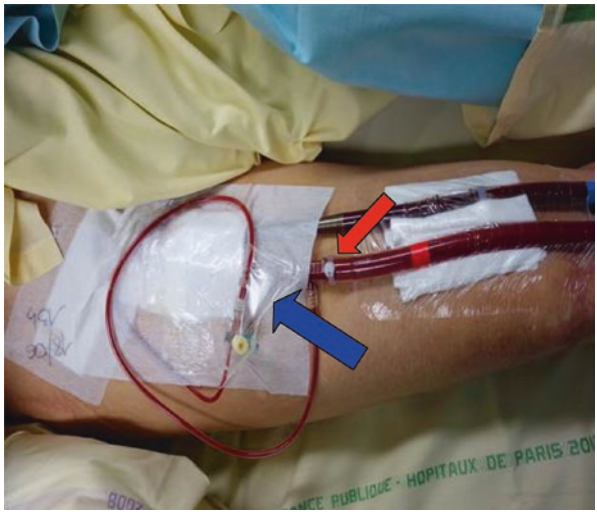

Fig. 4.3 Reperfusion line transparent dressing (*blue arrow*) and secured tubing connection (*red arrow*)

4.5 Preparation for Transportation

After the surgical dressings are removed, the perfusionist secures the tubing connection with links and a gasket-holder (Fig. 4.3).

The perfusionist performs a dissociated fixing of the lines at the thigh using a nonwoven extensible tape. Ideally, a horizontal fixing system for drains and probes (Hollister®) is used to optimize the binding of the lines on the patient.

The heat generator is set according to the patient's needs and according to the advice of the medical team.

The final and correct installation of the patient is performed by the perfusionist. It consists of a strict supine position until the removal of ECMO. The patient may have the head of the bed raised to a maximum of 30°: beyond this, there is a risk of an internal kink or bleeding from the scar. ECMO lines are in the bed and positioned along the leg: a loop can be made around the patient's foot. The lines must never be in contact with the ground.

The console is placed on a carriage (preferably with a brake system) positioned at the bedside; the control panel must be visible from the outside, as well as the scope.

The crank handle is positioned proximate to the centrifugal head to facilitate any manual relay.

A panel with the crank handle explaining the emergency procedure is left for every person who will take care of the patient. The 24/7 phone number of the ECMO team is written on one side of the console.

4.6 Conclusions

The establishment of ECMO is a team effort that must be standardized and organized. Each key player must have a place and a well-defined role. The different stages must always be the same and are the guarantee of effectiveness and of the safety of the patient.

References

1. Allen S et al. A review of the fundamental principles and evidence base in the use of extracorporeal membrane oxygenation (ECMO) in critically ill adult patients. J Intensive Care Med. 2011;26(1):13–26.
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Chapter 5
Monitoring the ECMO

Chirine Mossadegh

As we saw in the previous chapter, the ECMO device is complex and requires a precise, thorough, and constant management.

The aim of this chapter is to describe and explain the different aspects of managing ECMO patients at bedside after implantation. We will be discussing here only about centrifugal pumps. The monitoring of an ECMO patient starts first like the surveillance of any ICU patient starting with a head-to-toe assessment of the patient:

- Vital signs: heart rate, mean arterial blood pressure (MAP), temperature, saturation, central venous pressure (CVP)
- Physical assessment noting: hypoperfusion signs, sweating, moisture level
- Neurological status: consciousness, pupillary reaction
- Check of all the devices: IV lines, dressings, ventilator, infusion pumps

In addition to these regular rounds will be added the monitoring of the ECMO device itself and the surveillance of all the potential risks linked to the ECMO.

5.1 Monitoring the Circuit

5.1.1 The Circuit Check

It is a complete check up of the ECMO: plugs, fluid connectors, alarms, the integrity of the whole circuit:

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- *The position of the device*: The ECMO cart should be placed on brake position, with the controller facing the entrance of the patient's room. It allows any caregiver to have a visual on the parameters immediately as he enters the room.
- *Power supply*: Check that the ECMO is correctly plugged, if possible, to a secure plug (a red power outlet). Every ECMO device, whatever the brand, has a power and a battery light on the controller; make sure the battery light is off and the power light is on.

  On some device, there is an additional on/off switch next to the plug itself.

  Finally, make sure the power supply alarm is switched on which alerts you in case of an accidental unplugging or an electrical dysfunction.
- *Fluid connections*: Fluids (air and oxygen) are connected to a blender which ensures gas exchanges. This blender is then connected to the oxygenator of the ECMO via a simple tubing. Check the absence of kinks, tensions, and the right connection of the fluid tubing to the oxygenator and gas hoses.
- *The cannulas and tubing*:
  - For the ECMO to run properly, there must be no kinks on the full length of your cannulas. The sutures of the cannulas have to be in place. The presence of tie-bands in the appropriate places and the safety of all connectors should be checked. The entire circuit (tubing and oxygenator) must be inspected with a flashlight, looking for clots and/or fibrin , and more specifically the connectors, pigtails, or stopcocks that may be on the circuit. Every center has its own tubing configuration, from a simple loop getting in and out the patient through the pump and the oxygenator, to more complex circuits with bridges, multiple pigtails, stopcocks to allow monitoring pressures, use as IV access to infuse volume or medication. The more connections that are present on the circuit, the more stagnation of blood is created. It enhances the risk of clot formation. That is why complex circuits must be watched with much more caution.
  - The ECMO (VV or VA) allows blood oxygenation. Hence, there is a color difference between cannulas: the admission cannula is dark red, deoxygenated blood, and the reinfusion cannula (starting after the oxygenator) is light red, oxygenated blood. The nurse should check this color difference between the cannulas (Fig. 5.1).

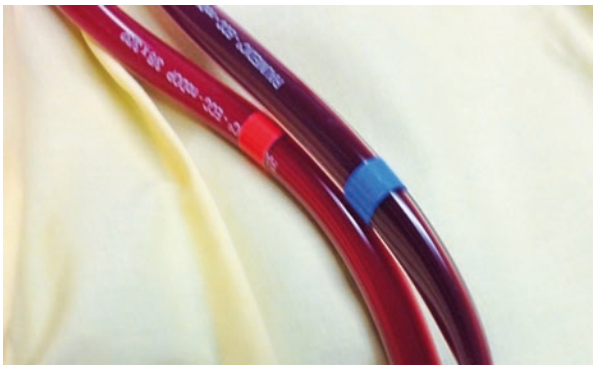

Fig. 5.1 Color differenciation of the tubings

- *The circulatory parameters of the pump*: Circulatory support is the essence of the ECMO, to ensure a correct support or replacement of the cardiac function for VA ECMO or to ensure an adequate gas exchange for VV ECMO.

  The pump being nonocclusive, the flow rate must always be above 2 L/min. Under that flow rate, there is a risk of backflow, leading to an inefficient ECMO run.

  The ECMO flow depends on a few parameters:

  – The preload: determined by volemia, venous tone, the position, and the size and length of the admission cannula.
  – The afterload: determined by vascular resistance, the position, size and length of the reinfusion cannula, and the length of the tubing between the pump and the oxygenator.
  – Cannulae sizes: 17–19 Fr for reinfusion cannuale, 21–23 Fr for admission cannulae, and 5 Fr for the reperfusion line for PVA ECMO.

The parameters are the rotations per minute (RPM) and the blood flow. The therapeutical goal set by the team is the blood flow. For the nurse, writing down these two parameters has no relevance. The correlation of the RPM and blood flow and its evolution through time will allow an effective management of the ECMO run. For example, at 2 pm, the RPM is set up at 4500 L/min for a blood flow at 4 L/min. At 5 pm, for a similar RPM, the blood flow went down to 2.5 L/min. It can be a sign of hypovolemia maybe due to blood loss or the patient may have moved and kinked partially part of the tubing.

- *The setting of the gas blender*: The blender ensures gas exchanges through the oxygenator—oxygen supply is adjusted via the FiO_2 and the CO_2 removal via the gas flow. It is essential to write down at each round the gas blender settings. In addition to patient's saturation, ventilator's settings, and blood gases results, it enables a timely decision-making.
- *The alarms*: They must be set regarding the therapeutic goal. The pump being nonocclusive, it is recommended to maintain the blood flow above 2 L/min to avoid any backflow.

  It is also crucial to know on which mode your ECMO is working.

  In a free mode, when an alarm is activated, the ECMO will keep working, but when the ECMO is on intervention mode, as soon as an alarm is set on, the ECMO stops working, and an immediate action must be set to resolve the problem. The choice of the mode depends on the human resources; if a nurse, ECMO specialist, or a perfusionist is constantly present at the patient's bedside, the intervention mode is possible, but if a nurse is taking care of more than one ECMO patients and cannot intervene immediately when the pump stops, the free mode will be safer.
- *The emergency kit:* It should be available at the bedside or in the unit, allowing an immediate response to any adverse events—clamps, emergency hand crank, emergency supplies (appropriate-sized connectors/shears/tubing/rapid access line, fluid, tie-gun and tie-straps/sterile gloves, preprimed pump, etc.)

5.1.2 The Pressure Monitoring

Monitoring pressures is not essential, but it is an additional tool to help the team detect a potential and/or immediate dysfunction of the ECMO. There are no exact target numbers to refer to. Pressures vary depending of the size of the cannulas, the ECMO flow, the patient volemia, etc.

Like explained sooner for circulatory parameters, it is not the number but the evolution of pressures through time that will help the team prevent dysfunctions. Again, it is crucial to write down at each ECMO rounds the pressure numbers in the patient's chart.

Three pressures are commonly measured (Fig. 5.2).

P_{vein} or Venous Pressure

It is the prepump pressure. It measures the pressure in the admission cannula. So, it is a negative pressure. It should not excced 100 mmHg.

A quick and significant rise of P_{vein} means the ECMO has difficulty to drain blood from the patient. It can be caused by a hypovolemia or by a kinked and/or occluded admission cannula.

P_{art} or Arterial Pressure

It is the post-oxygenator pressure. It measures the pressure in the reinfusion cannula. It is a positive pressure that should not exceed 200–250 mmHg.

A quick and significant rise in P_{art} may be caused by an increase of the patient's preload or a sign of a kinked and/or occluded reinfusion cannula.

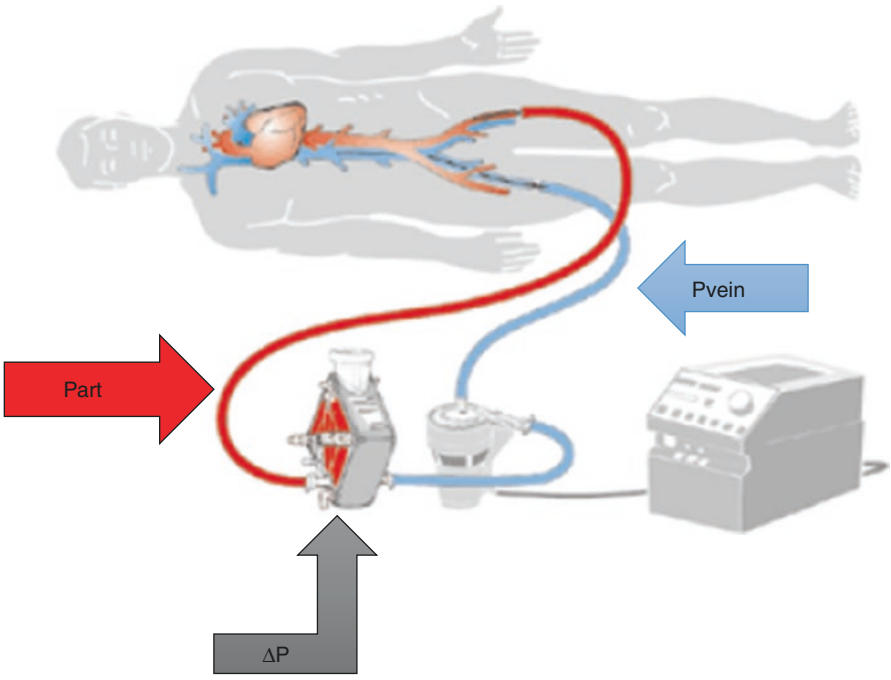

Fig. 5.2 Pressure monitoring (Courtesy of Maquet®)

Δp

It is the pressure difference through the oxygenator. It changes during the ECMO run. The speed of the rise depends mostly on the flow and on a good management of coagulation. It is an indicator of the level of saturation of the membrane of the oxygenator.

Any significant rise of Δp (+20 mmHg/h) must be reported immediately to the medical team. It can be a sign of clotting inside the oxygenator. This could evolve towards a pump failure.

These pressures can be monitored by:

- Adding pigtails to the circuit in the appropriate places and connecting them to a pressure monitoring system (similar to the ones used for arterial lines or CVP).
- New ECMO consoles have added the pressure monitoring function to their controllers, without the need to add any connectors to the ECMO circuit.

A pressure number alone is not a significant element; it is a tool that can help the team manage and assess the patient's ECMO run in addition to clinical exam, circuit control, and patient's blood panel. For example, a rise of 60 mmHg in the Δp in an hour could be a sign of clotting in the oxygenator, but this number alone cannot justify the replacement of the oxygenator. It has to be completed by blood gases to assess the ability of the oxygenator to perform gas exchanges efficiently.

5.2 Adapting the Specifics of ECLS to the Regular Monitoring of the Patient in a Critical Care Unit

5.2.1 Pain and Sedation

ECMO patients are now more commonly awake and even extubated sooner [1]. It is mostly the case for VA ECMO patients: they can be awakened just after ECMO implantation; some teams even implant the ECMO on nonsedated and extubated patients with local anesthetics. For VV ECMO patients, they are always deeply sedated the first few days due to the major lung damage.

The ECMO membrane lung is trapping medications, altering pharmacokinetics and pharmacodynamics of analgesics and sedatives such as propofol, midazolam, or opioids [2]. Higher doses of sedatives and analgesics must then be administered to obtain an appropriate sedation and comfort of the patient. Hence, protocols of management of pain and sedation should be reassessed for ECMO patients.

5.2.2 Infection

Like any other device inserted inside the patient, the cannulas can be a source of infection. ECMO cannulas, being of large diameters, enhanced the risk. The site of cannulation worsens this potential complication: drowning can soil jugular

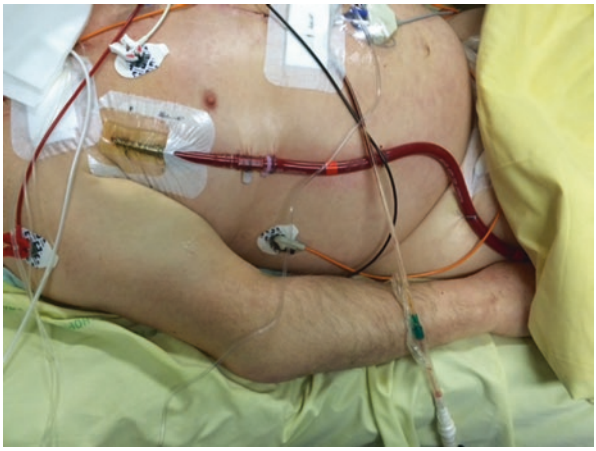

Fig. 5.3 Transparent chlorhexidinie gluconate impregnated dressing

cannulas, stool contaminates femoral cannulation, and central cannulation is directly inside the heart of the patient.

Early detection is of paramount importance; the nurse should check:

- Daily white blood count and cell blood culture
- At each round, the integrity of the cannula dressing
- A daily assessment of the insertion point of the cannulas, looking for redness, swelling, bleeding, or potential infection

In central lines, the use of chlorhexidine gluconate-impregnated sponge reduces the infection rate, diminishes the frequency of dressings up to 7 days, and allows a visual on the insertion point [3]. It can be done with the ECMO cannulas (Fig. 5.3).

5.2.3 Skin Care

Skin care is a constant challenge for ICU nurses. ICU patients have always been good candidates for developing pressure sores: they are lying in bed most of the day, often sedated; infection and heparin infusion can provoke skin abrasion or hematoma; and edemas are unavoidable, specially for patients with heart failure.

ECMO patients, in addition to these preexisting skin alterations, must face other potential skin damages: cannula's sutures are tight and through time lesions can appear. Edema plus the pressure of the cannula on the skin can lead to unavoidable pressure sores.

Protecting the skin from the cannulas can be done with foam dressings or hydrocolloids already used for regular patients. To fix the cannulas without damaging more skin, some attachment devices like the horizontal tube attachment are composed of hydrocolloid, allowing skin protection and an additional fixation (Figs. 5.4 and 5.5).

Fig. 5.4 Horizontal tubing attachement device (Courtesy of Hollister®)

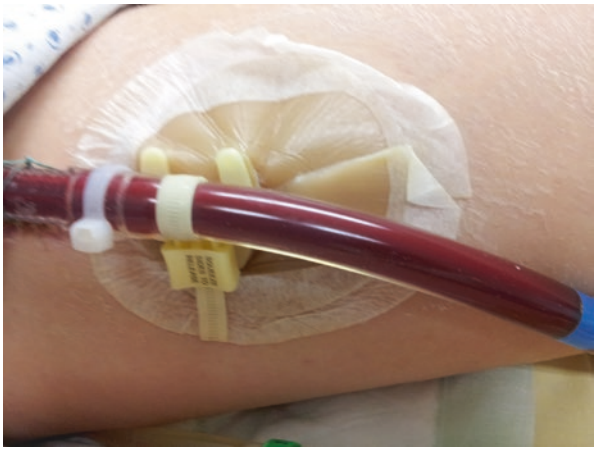

Fig. 5.5 Horizontal tubing attachement device on an ECMO patient

5.3 Preventing Complications

ECMO is a miniaturized version of the extracorporeal circuits used in the operating room for thoracic surgery. An ECMO run is therefore the source of minor to major complications, endangering the patients.

One of the key points of ECMO management is to prevent and make an early detection of these complications. All the ICU caregivers (doctors, nurses, perfusionists, physiotherapists, respiratory therapists, help nurses) must be trained to acknowledge the signs of an early bleed, an infection, and a dysfunction of the ECMO.

5.3.1 Bleeding

Bleeding is frequent and can be massive during any ECMO run. The blood of the patient is in contact with an inert and nonbiological material, so continuous systemic anticoagulation by nonfractionated heparin infusion is necessary to prevent fibrin and

clot formation in the ECMO circuit. During implantation, a bolus of 5000 UI of heparin is most commonly injected to the patient, enhancing the risk of bleeding. In the immediate postimplantation phase, the challenge is to be able to balance the control of postoperative bleeding as well as minimizing the formation of clots in the ECMO circuit. Bleeding can also be worsened after an open heart surgery or transplant.

5.3.1.1 Prevention

To prevent bleedings, a very strict control of the hemostasis is necessary: the heparin infusion rates have to be titrated to obtain an aPPT ratio between:

- 1.8 and 2 times normal level for VA ECMO patients depending on their cardiac condition; the antifactor Xa can also be a better indicator of the heparin management
- 1.5 and 1.8 times normal level for VV ECMO patients
- 2 and 2.2 times normal level for ECMO circuits with more than two cannulas like VAV, central cannulation

5.3.1.2 Clinical Signs and Treatment

Bleeding on ECMO can be local or generalized:

- *The Ear, Nose, and Throat (ENT) area*: Bleedings in this area are almost unavoidable. Mouth care is then difficult, and sometimes ineffective. With a nose bleed, the nurse can start by digitally pressuring the nostrils for a 5-min period. If the bleeding persists, insert a resorbable hemostatic wick in each nostril. If this technique fails too, the last resort is to insert a nasal compression probe (it is possible to use a urinary catheter). By inflating the balloon of the probe, a compression is made in the posterior fossa, stopping the bleeding.

  For the mouth, oral care stays crucial even if it seems ineffective. The mouth of the patient should still be gently suctioned to remove drooling, blood, and clots, and cleaned with smooth mouth sticks but only with water. Mouthwashes usually contain alcohol, which can maintain the bleeding and provoke a burning sensation to the patient. In the most severe bleedings, ENT specialist can perform a packing of the mouth: the entire oral cavity and throat will be then packed with hemostatic wicks. Oral care is then impossible, but to avoid pressure ulcer on the palate and tongue, the "packing" must be humidified with saline every 4–6 h and completely removed after 48 h.
- *The dressings:* Bleedings can occur on all the patient's dressing, insertion point of IV lines, suction drains, and ECMO insertion point. The use of hemostatic dressings can avoid redoing the dressings several times a day.
- *The neurological status of the patient:* Look for any signs of intracranial hemorrhage—bilateral pupillary response, level of consciousness, patient's reaction to the decrease of sedatives [4].
- *The aspect of the lung secretions*: Intra-alveolar hemorrhage can occur. Bleeds can be related to the disease itself, especially for patients on VV ECMO with

severe ARDS, but it can also be caused by a disseminated intravascular coagulation (DIC) for patients on VA ECMO. It is recommended for patients on VV ECMO to use a humidifier on the ventilation tubing. Warming and humidifying the bronchial tree could minimize clot formation.

- *The aspect of the urine:* Although rare, presence of blood in urine can occur. The urine color is then bright red. Be careful not to cofound it with the "dark reddish" color of the urine in case of hemolysis.
- *The digestive tract*: Presence of blood in stools can be seen. If there is a doubt, use hydrogen peroxide on a stool sample. If foam appears, it means there is blood. In the absence of external bleeds or in severe DIC cases, a gastric lavage should be performed to check the presence or absence of blood.
- *General treatment*: It is essential that the team understands and finds the right balance between pro- and anticoagulants to manage the patient properly. The daily blood count can assess the blood loss and the need to transfuse the patients with packed red blood cells or platelets. It is still a debate in the ECMO community to determine the cutoff for red blood cells transfusion; some teams (La Pitié Salpêtrière is part of them) recommend to transfuse only when the hemoglobin is under 7 g/dL; others argue that an ECMO patient should have a normal hemoglobin to allow an optimized oxygenation, so that the transfusion limit will be 12 g/dL.

  For long, ECMO teams have been reluctant to discontinue heparin during ECMO runs. Experiences from several teams and data show that in case of severe hemorrhage and if the patient is nonresponsive to transfusion and a decrease rate of the heparin infusion, the discontinuation of the heparin is possible [5] for hours and even days, with a strict control of the aPPT and a thorough check of the oxygenator and cannulas looking for clots and thrombin. In a worst case scenario, using recombinant factor VIIa has been done safely by several teams with a major decrease of bleedings, but must be a last resort therapy with an extreme caution and surveillance of the ECMO circuit [6–8]

5.3.2 Thromboembolic Risk

Good and effective anticoagulation treatment not only avoids bleeding but also prevents formation of clots and thrombin. They are the results of cells lysed by the turbulence of the ECMO pump and the stagnation of blood. They are easily visible with a flashlight within the tubing and connectors: dark clots and white fibrin strands can be easily observed.

Meticulous surveillance is of paramount importance: detection, documentation, and the evolution of clots and fibrin can prevent major adverse events like brain damage or ECMO failure due to pump or oxygenator thrombosis (Figs. 5.6, 5.7, and 5.8).

At each round, the nurse must inspect the entire ECMO circuit with a flashlight: the cannulas, the connectors, the pigtails, stopcocks, the pump, and the oxygenator. The challenge for the nurse is to differentiate "normal" clots and "bad clots." "Normal clots" are small and have no risk to harm the circuit or the patient. They are frequently seen at the top of the oxygenators, where the blood stagnation is not preventable. The "bad" clots are the ones becoming an obstacle to the blood flow,

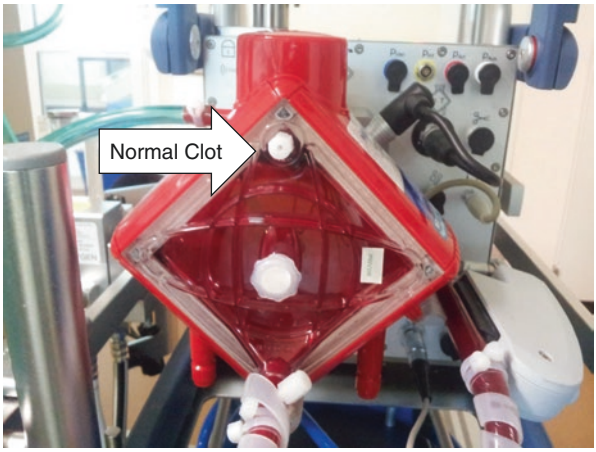

Fig. 5.6 Normal clot on the arterial side of the ECMO oxygenator

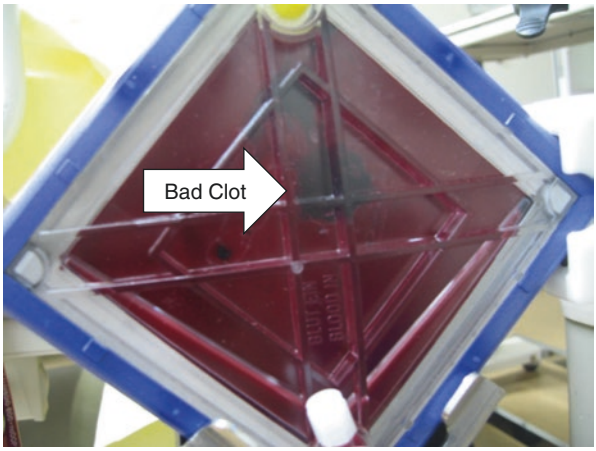

Fig. 5.7 Abnormal clot on the ECMO oxygenator

the gas outlet, and causing pressure changes through the membrane. Also, the clots formed on the "arterial" side of the oxygenator, from which the blood goes back directly to the patient. If a clot detaches and goes back to the patient's bloodstream, it can cause cerebrovascular accident.

If clots and/or fibrin are jeopardizing the efficiency of the ECMO therapy or expose patients to brain damages, the ECMO circuit should be changed. Depending on the team's strategy, we can either change the component or change the whole circuit. But, the assessment of changing an oxygenator must not depend solely on the presence of clots. Clots are one parameter; the efficiency of the membrane to complete the gas exchange properly stays the most important parameter.

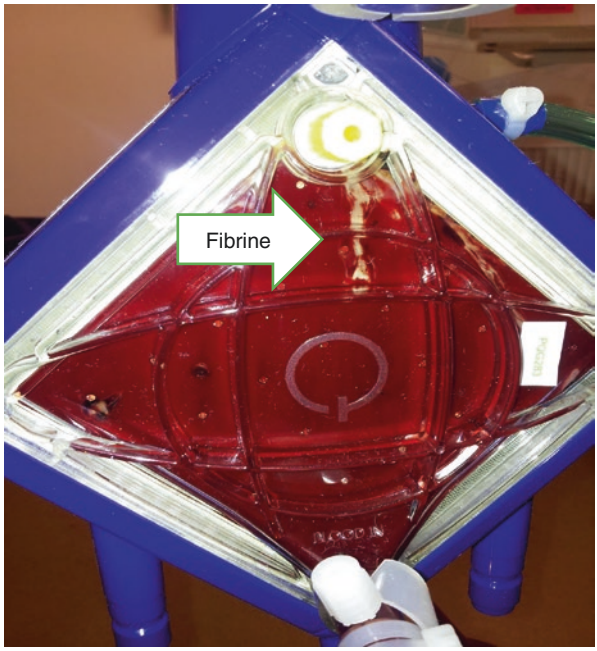

Fig. 5.8 Fibrine strand on the ECMO oxygenator

5.3.3 Hemolysis

The ECMO flow is generating spins and trauma to blood cells causing them to break and causebleeding. Hemolysis may occur due to

- Membrane failure (causing fibrin and clot formation)
- Pump with highly turbulent flow
- Clotting in the cannulas
- High-energy blood suction: hypovolemia, flow competition between the pulmonary artery and the left atrium admission cannula when the native heart function recovers

Prior to clinical signs, on the patient's daily blood panel, a rise of the free plasma hemoglobin above 50 mg/L, associated with a drop of platelets and red cell counts, can be seen. Clinically, the hemolysis shows with a characteristic bloodyish color of the urine or the effluent bag if the patient has no urine output (Figs. 5.9 and 5.10).

In uncontrolled cases, other external or internal bleedings can occur; ultimately, with no adequate treatment, the patient will develop DIC.

There are two sides to treat hemolysis:

- The symptomatic treatment: replacing the blood loss with packed red blood cells, platelets, and minor the bleeding with frozen plasmas
- The curative treatment: changing the ECMO circuit

Fig. 5.9 Typical aspect of the urine in case of hemolysis

Fig. 5.10 Typical aspect of the CRRT urine bag in case of hemolysis

5.3.4 Decannulation

It is a rare but feared complication. Inadvertent decannulation can be avoided by respecting simple but very strict guidelines before mobilizing a patient in and/or out of bed:

- The caregiver (nurse, ECMO specialist, perfusionist) must have a complete visual of the circuit (cannula, tubing, pump, oxygenator, controller).
- Check all fixations: tie-bands placed at all connectors, presence of sutures in appropriate places such as the insertion point and more importantly on the first connector (between the cannula and the ECMO circuit (Fig. 5.11).
- Additional fixations can be placed on the leg or torso using basic dressings, but it can generate pressure sores. Some horizontal drain fixation devices exist. They allow a good fixation and are made of hydrocolloids, which protect the skin of the patient (Fig. 5.12).

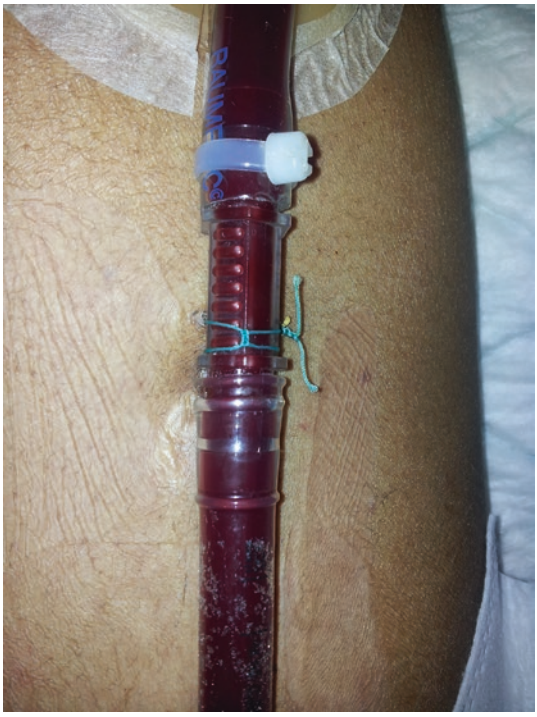

Fig. 5.11 Secured suture on the first connector between the cannula and the ECMO tubing

Fig. 5.12 Horizontal tubing attachement device (Courtesy of Hollister®)

5.4 Specifics of VA ECMO Patients

5.4.1 Hemodynamic Monitoring

The ECMO is a nonpulsatile device and generates a laminar flow. Right after implantation, most VA ECMO patients have a poor or no heart pulsatility.

Hence, the arterial blood pressure is delivered mostly by the ECMO. The patient's arterial line can look dampened or even flat with identical systolic, mean, and diastolic arterial pressure numbers, sometimes only with the mean arterial pressure. Inexperienced staff can think that the arterial line is deficient (Fig. 5.13).

When monitoring these patients, the aim is to maintain the mean arterial pressure above 65 mmHg.

The recovery of a pulsatile blood pressure is one of the signs of left ventricular function improvement.

As we will see later in 4.4, a balloon pump can be inserted to prevent pulmonary edema. In that case, the arterial line will regain a pulsatility caused by the balloon. To assess if the pulsatility is due to the balloon pump or the heart of the patient, pause the balloon for a few seconds and watch the arterial line: if it flats, then the native heart has not yet recovered.

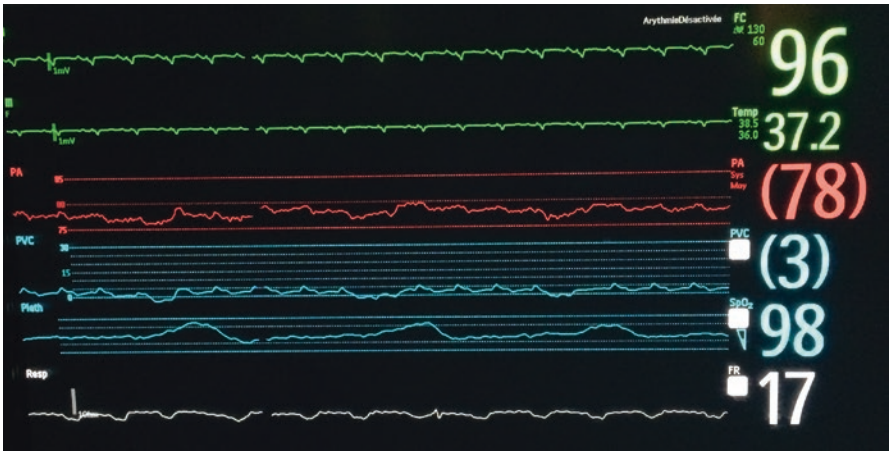

Fig. 5.13 Flat arterial line due to the laminar flow of the ECMO pump and the absence of heart contraction

5.4.2 *Limb Ischemia*

The femoral arteria is partially or totally occluded by the reinfusion cannula of the ECMO. Blood flow to the leg is then low or inexistent. To prevent limb ischemia, it is recommended to insert a reperfusion line in the superficial femoral arteria and connect it to the reinjection cannula to allow leg perfusion [9–11] (Fig. 5.14).

The nurse will monitor the leg by

- Comparing the temperature of both legs by touching or using oxymetrie or NIRS
- Checking the aspect of the leg: its stiffness, color: first white, then blisters, and, in the most extreme cases, foot necrosis (Figs. 5.15, 5.16, and 5.17)

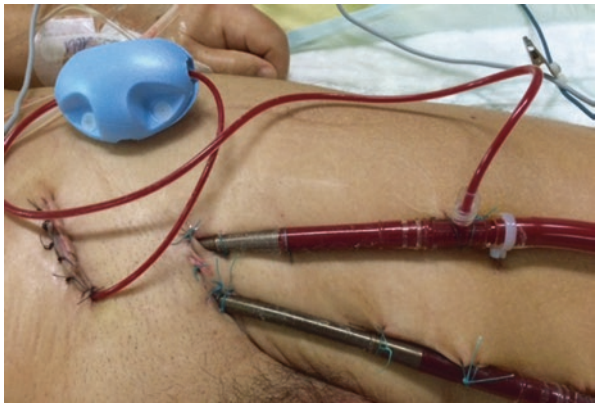

Fig. 5.14 Reperfusion line on a femoral peripheral VA ECMO

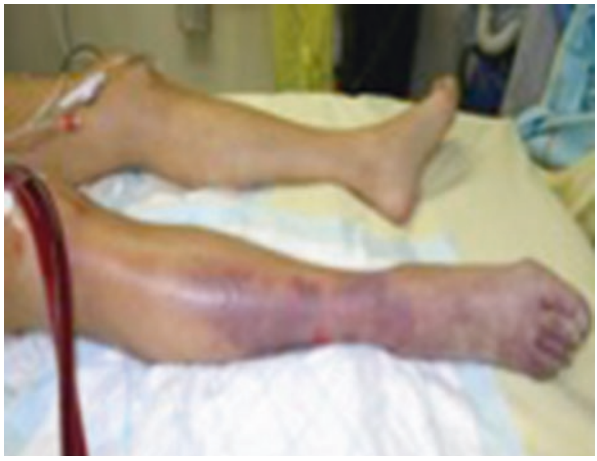

Fig. 5.15 Limb malperfusion on a patient with femoral peripheral VA ECMO

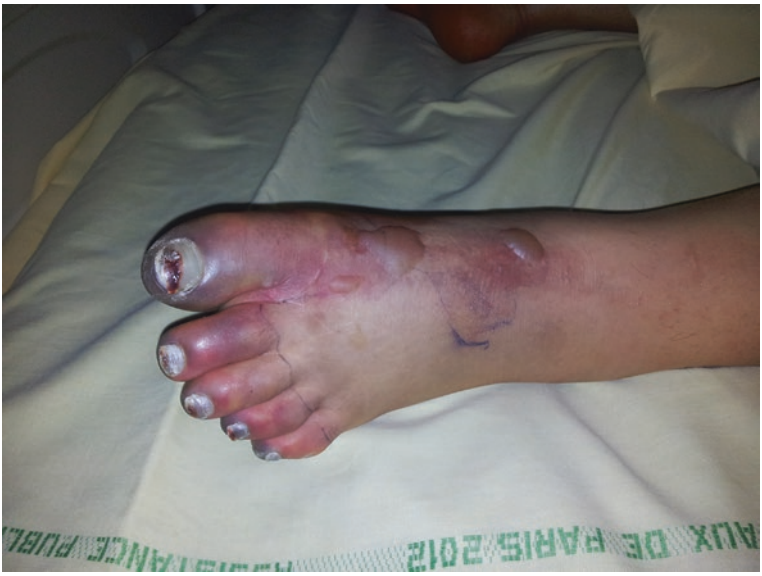

Fig. 5.16 Feet malperfusion on a patient with femoral peripheral VA ECMO

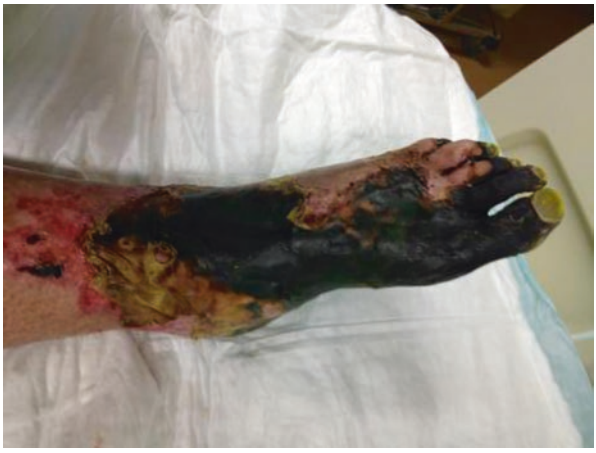

Fig. 5.17 Foot ischemia on a patient with femoral peripheral VA ECMO

The reperfusion line must always be visible through a translucide dressing, so that the nurse can check the absence of kinks, clots, and/or fibrin. On this picture you can see clots and fibrin on an occluded reperfusion line (Fig. 5.18).

The same ischemia can occur with axillary cannulation. A reperfusion line can be inserted to allow perfusion in the arm.

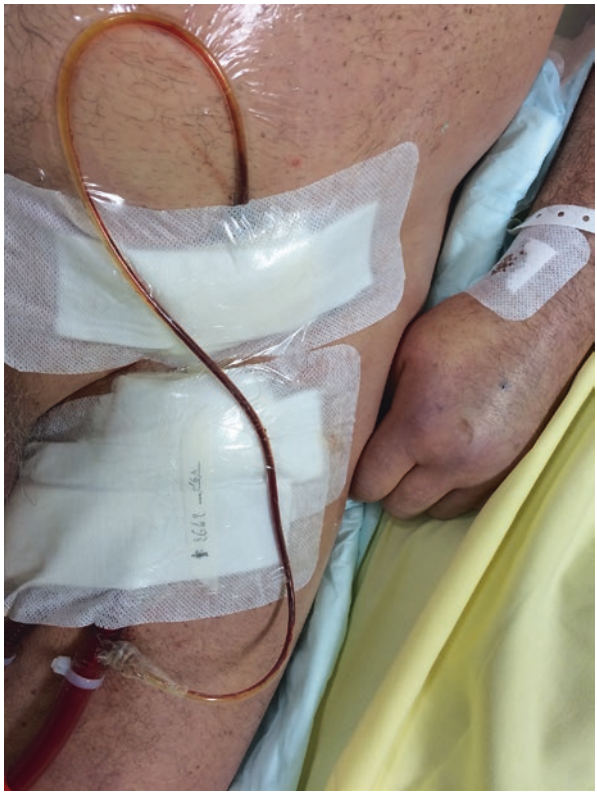

Fig. 5.18 Clotted reperfusion line

5.4.3 Differential Hypoxia

It only concerns patients on peripheral VA ECMO. It is also called the Harlequin syndrome, two circulations syndrome, or north/south syndrome.

In extreme cardiac dysfunction, if the heart is not beating and the aortic valve is not opening, the ECMO is providing 100% of the patient blood flow and oxygenation. The ECMO blood flow infused into the femoral artery is in a direction that is retrograde to the native blood flow. When the heart recovers a pulsatility and the aortic valve begins to open, fully saturated blood from the ECMO mixes with the blood ejected from the native ventricle in the aorta and create a mixing cloud. The location of this mixing cloud depends on the amount of ECMO support provided and the degree of left ventricular ejection. The mixing cloud moves proximally in the aorta when there is poor left ventricular ejection function and/or when the ECMO flow is increased. On the contrary, the mixing cloud moves distally in the aorta when the ventricle recovers and/or the ECMO flow is decreased. If the pulmonary function is impaired, the typical VA ECMO flow rate (80% of full cardiac output) can result in desaturated blood from the left ventricle perfusing the aortic arch, the brain, and coronary arteries, and fully saturated infusion blood perfusing the lower body. The patient's head appears blue, whereas the lower extremities appear pink.

To detect and/or diagnose differential hypoxia, the pulse oximeter must be placed on a finger of the right hand, and blood gases should be measured in the right radial artery, which reflects the patient's cardiac output.

To correct and treat this hypoxia, most teams add a jugular cannula to deliver oxygen to the brain.

5.4.4 Fluid Management

Finding the right balance between hypovolemia and fluid overload is more complex for patients undergoing VA ECMO, especially after cardiac surgery.

Massive blood losses are frequent after heart surgery, and the ECMO itself can worsen this loss.

At the bedside, the nurse can suspect hypovolemia with a chattering of the lines associated with sudden variations of the ECMO flow resulting in hypotension. The nurse must then administer enough volume to maintain an efficient ECMO flow (MAP >65 mmHg). Hypovolemia induces hypotension and an unstable and low ECMO flow. The variation of flow increases also fibrin and clot formation.

But, giving large volumes in association with muscle relaxants and venodilators can contribute to extraordinary amounts of unavoidable peripheral edema. Diuretics can treat this fluid overload. For patients not responsive (urine output <0.5 mL/kg/h, positive fluid balance >500 mL in the past 24 h), renal replacement therapy should be started.

Also, inefficient fluid management often results in pulmonary edema. The ECMO reinjects blood cross-current from the native blood flow. In VA ECMO patients with poor or no cardiac function, this generates an increased afterload, causing pulmonary edema.

Implanting a CPIAB at ECMO initiation could prevent it by unloading partially the left ventricle [11, 12].

To treat pulmonary edema, the aim is to unload the left ventricle. If conventional treatments like the use of diuretics are inefficient, several approaches are then possible:

- The atrioseptostomy [13, 14]
- Implanting an Impella®: it is a pump implanted percutaneously, taking blood from the left ventricle and reinjecting it in the aorta [15, 16]
- Unloading both ventricles by implanting a central double ECLS

5.5 Specifics of VV ECMO Patients

5.5.1 The Avalon® Cannula

This double-lumen cannula placed in the right atrium through the jugular vein must be placed correctly, so that the blood gets out of the cannula in front of the tricuspid valve. To make sure the tip of the cannula is toward the valve, the writing on the cannula must be visible by the nurse. If the writings are toward the patient's neck, then the tip of the Avalon is not in the right direction (Fig. 5.19).

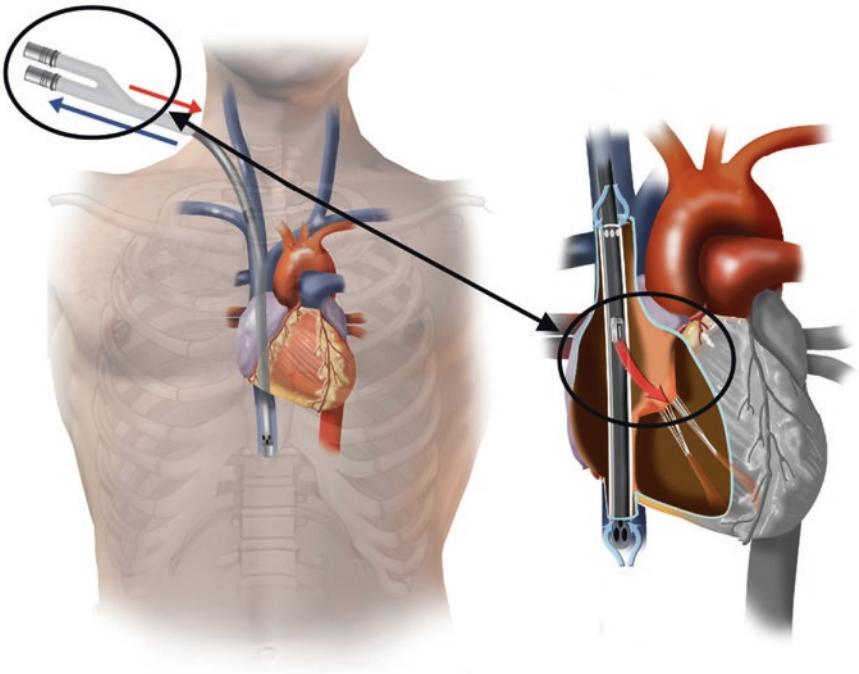

Fig. 5.19 Placement of the Avalon® cannula (Courtesy of Maquet®)

5.5.2 Monitoring of the Patient

For VV ECMO patients, the saturation target is rarely 100%. A saturation of 91% is enough. Most pratients are ventilated on pressure mode, allowing a low and controlled pressure in the lungs. In severe ARDS cases, most patients are completely dependent on the ECMO support and take very low or no volume on the ventilator. Despite these minor volumes, it is of paramount importance that the nurse or respiratory therapist writes down in the patient's chart the volume numbers. If the patient is taking more volume, it could be a sign of lung recovery.

5.5.3 Recirculation

5.5.3.1 Definition

It is a specific phenomenon to VV ECMO implanted in femorojugular and results in an inefficient ECMO run. Oxygenated blood delivered by the ECMO is immediately suctioned by the admission cannula without passing through general circulation. In that case, organs are not efficiently oxygenated, and the patient's status can decline.

It can be caused by:

- Tips of the femoral and jugular cannulas being too close
- Very high flows
- Intrathoracic pressure variations (tamponade or pneumothorax)

5.5.3.2 Monitoring

There is always some recirculation, but it can be diminished by:

- The direction of the ECMO flow: drain from the femoral vein and reinject in the jugular vein.
- A daily monitoring of the cannulas' placement on the X-ray.
- Cannulas of big diameters allow very high flows, but minimize the negative pressure in the leg.
- Strict control of the ventilator settings to avoid variations of intrathoracic pressures

5.5.3.3 « Treating » Recirculation

If, despite taking all the precautions listed earlier, the patient's oxygenation does not improve, several options are still available to bring more oxygen:

- Mobilizing the cannulas
- Switching to a dual lumen cannula (Avalon®): but be careful as these cannulas can be smaller and not allow an ECMO flow above 5 L/min
- Adding a cannula in the other femoral vein

5.6 Specifics of VAV ECMO

VAV ECMO allows a combination of the standard support of a VA and VV ECMO. VAV ECMO is implanted in patients with major lung damage associated with cardiac dysfunction. There is one admission cannula and two reinfusion cannulas: one femoral or jugular for the "VV ECMO" and one femoral for the "VA ECMO". Hence, an additional flow meter must be placed, so that flows in both reinfusion cannulas can be monitored (Fig. 5.20).

Depending on which organ recovers first (the lung or the heart), a clamp is positioned on the appropriate reinfusion cannula to diminish the flow and start weaning.

For example, on the picture below, the patient's heart starts to recover, so that the clamp is placed on the « VA »femoral cannula (Fig. 5.21).

Extreme caution is advised: adjusting the flow with the clamp provokes a partial occlusion of the cannula. If the cannula is completely occluded by the clamp or if

clots and/or fibrin appear on the tubing, do not remove the clampas it may cause major ischemic strokes. The only option then is to remove the thrombosed cannula.

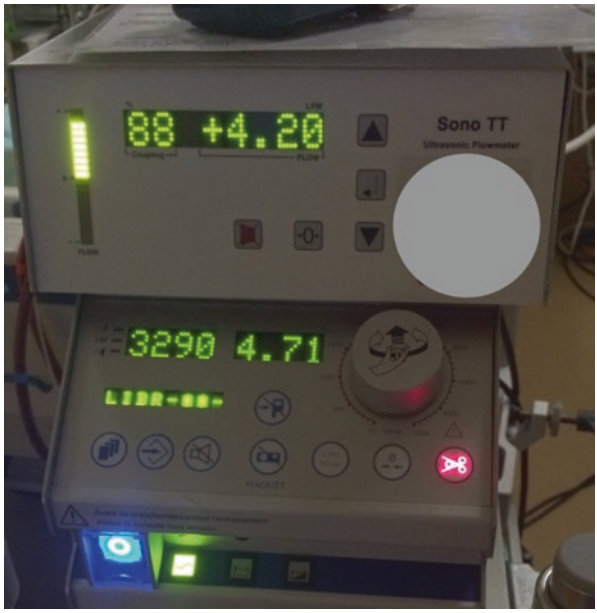

Fig. 5.20 ECMO controller with additionnal flow controller for VAV ECMO patients

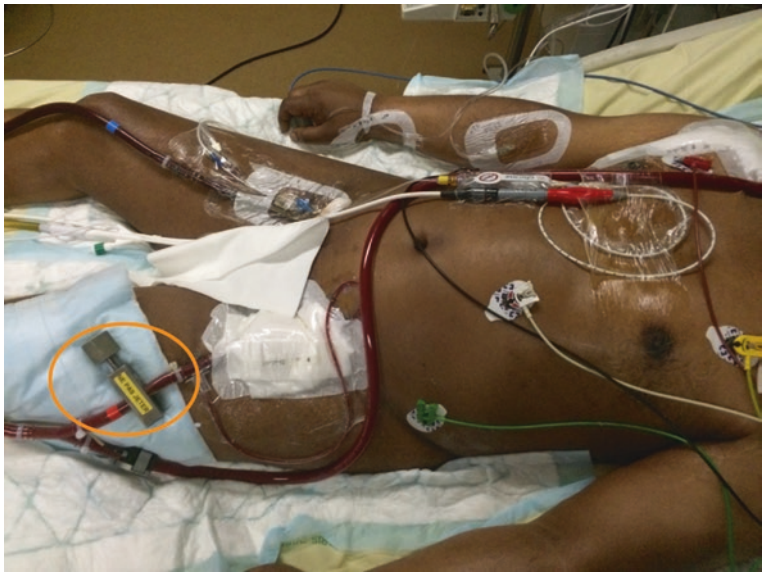

Fig. 5.21 VAV ECMO with partial clamp positionned to adjust the preferential flow

5.7 Troubleshooting

5.7.1 Flow Variations

During an ECMO run, the flow can suddenly vary (e.g., the ECMO flow can pass from 5 L/min to 1.5 L/min in a second). For patients very dependent on their ECMO, this can have major consequences, with an inefficient flow, and the MAP can drop to 45 mmHg and/or the saturation to 75%.

Before assessing the cause and trying to treat appropriately, the nurse should try to stabilize the ECMO flow to avoid clot formation and big hemodynamics changes: the RPM should be lowered until a stable flow is achieved.

For example, if your ECMO had a 5 L/min flow for a RPM of 4500, the nurse may have to turn down the RPM to 3200 to get a stable 4 L/min, even if your MAP is only of 55 mmHg.

Then the nurse should call the doctors, do a complete circuit check to make sure there are no kinks or bleeding. Most probably, these flow variations are due to hypovolemia, and a chattering of the line can be observed: we can see a suctioning phenomenon with a dancing movement of the ECMO tubing. If ECMO pressures are monitored, there also will be a major increase of the PVein.

Be careful, a chattering of line can also be seen:

- When the heart recovers a pulsatility for VA ECMO patients, the ECMO tubings can chatter at the rhythm of the patient's heart.
- If a patient has a balloon pump, the ECMO tubing will chatter at the rhythm of the balloon pump.

In these two cases, the chattering of the line is regular and normal. Chattering becomes a problem when it is associated with flow variations and unstable vital signs.

5.7.2 Decannulation

We saw earlier how to try to prevent inadvertent decannulation, but when it happens, the ICU team must react quickly and efficiently. Unfortunately, any delay even of a few seconds can be lethal to the patient.

Action to be taken: *the 3C rule: CLAMP, Call for help, and Compress.*

1. *Clamp:* It is the first thing to do. In nursing school, nurses are always taught to check the patient first and the machines after. This is one case where this rule does not apply; the priority in case of decannulation is to avoid more blood loss and air embolism. Use the clamps available on the ECMO cart. If unfortunately there is only one clamp available, clamp the reinfusion line to avoid air embolism. And if there are no clamps, clamp the line manually.

2. *Call for help*: It is impossible to manage this situation alone. The quicker you call for help, the safer it is for the patient. All ICU members must know where to find the emergency material or the number to call for the perfusion team to come.
3. *Compress:* The patient can bleed out from insertion point; so, once the lines are clamped, compress firmly.

Of course, after these three steps, all measures to stabilize the patient (CPR, transfusion, setting up a new ECMO) must be taken.

5.7.3 Pump Failure

Pump failure is like decannulation a life-threatening emergency.

Actions to be taken:

- Clamp the cannulas.
- Turn the RPM speed down to zero.
- Take out the pump head out of the motor and place it in the backup pump.
- Start the backup pump (electrically or manually).
- Take off the clamp on the admission cannula first and then on the reinfusion cannula.

Depending on the manufacturer, the backup pumps are manual or electrical. Make sure that all team members know how to transfer the pump head and start the emergency backup pump. Not only initial training but continuous education is also crucial. At least once a year, a training for all team members should be organized.

Usually manual backup pumps have a hand crank. Like we saw in the circuit check, the crank must be placed somewhere near the original pump head, and the nurse must be able to crank "fluently" without any obstacle.

5.7.4 Oxygenator Failure

We discussed throughout the chapter about the different parameters that will allow the team to try to detect early an oxygenator failure:

- Alteration of blood gases without any changes in the ECMO parameters and patient's general status
- Significant rise in the Δp (>20 mmHg/h)
- Presence of numerous clots or an increase of clots and fibrin

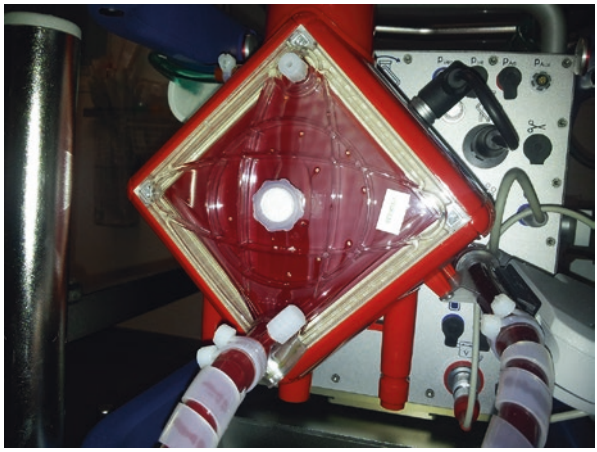

Fig. 5.22 White Veil on the oxygenator of a VV ECMO

In our experience in La Pitié, in some VV ECMO patients infected with the H1N1 virus, a white veil can appear in less than an hour and be also a sign of oxygenator clotting (Fig. 5.22).

When an oxygenator is failing, it has to be replaced. Depending on the team's strategy, two options are possible:

- Change only the oxygenator.
- Change the entire ECMO circuit. We recommend a complete circuit change, especially if one uses circuits with multiple pigtails and stopcocks. In this case, there are probably clots in those connectors too, and a complete circuit change will be safer.

5.8 Psychological Support

Being on ECMO support or having a loved one being implanted with an ECMO is difficult to understand. This device is not well known, and it is a last resort therapy when conventional treatment has failed. Families (and patient if possible) need to be guided: they must understand why the ECMO has been implanted, the adverse events and complications that can occur, and the concept that the ECMO is an emergency device set up to give time to the medical team to assess the options. "The bridge" therapy has to be explained:

- Bridge to recovery: the heart recovers and the ECMO can be withdrawn.
- Bridge to bridge therapy: the patients will be implanted with a VAD. This is considered for patients with a possibility of long-term recovery. It allows the patient to go back home.
- Bridge to transplant.
- A destination therapy: when ECMO is the last resort and is ineffective. A procedure of end-of-life care must then be set up.

An effective, honest, and clear communication has to established, and regular meetings set up to explain the evolution of the patient's medical status. It can be very difficult for the patients or families to understand right away that the device that is saving their loved one's life can also be a source of major complications or lead to death.

Also, staff are exposed to additional stress. ECMO gives an extra workload, and support of patient and family can be time-consuming. Some long or difficult ECMO runs with negative outcomes can discourage team members. An open communication inside the ICU team is of paramount importance, so that everyone accepts the patient's plan of care.

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Chapter 6
Mobilizing the ECMO Patients in Everyday Care and Ambulation

Chirine Mossadegh

Mobilizing an ECMO patient is more difficult than mobilizing a usual ICU patient. Any tensions, kinks, or dislodgment of cannulas can be fatal for the patient. A good preparation, team communication, and extreme caution are the key to mobilize and even ambulate an ECMO patient safely [1–3].

6.1 Mobilizing in the Bed

It has been explained in the previous chapter that before mobilizing any ECMO patient, the nurse should

- *Have a complete visual of the circuit:* Insertion points, cannulas, tubings, controller, etc.
- *Check the fixations of the cannulas*: Sutures and eventual additional fixation devices.
- *Assess the length of the tubing*: It does not always facilitate mobilization in the bed. To prevent any adverse events, move the ECMO cart if necessary to avoid any kinks or tension while turning the patient to prevent bed sores or wash him.
- *Evaluate the level of consciousness of the patient*: If the patient is responsive, the nurse should explain how he or she is going to be mobilized, what is expected of him or her, and assess if he or she needs analgesics before starting the process. If the patient is sedated but reacts during care, make sure to anticipate the need for extra sedatives or analgesics.
- *Have enough caregivers to help*: For a "normal" ICU patient, usually two or three people are needed. When a patient on ECMO is mobilized, an additional

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person (at least) is necessary to check tubings and the pump controller. If the patient is overweight or very unstable, more caregivers can be involved. The key is to assign a specific task to each team member, for example, one person is in charge of the head, another will be in charge of washing the back of the patient, a third one will hold the ECMO tubing and check the controller.

- *Prepare all materials necessary*: If the patient is being mobilized to be washed, make sure all materials necessary are in the patient room before you start, so that there are no delay or need for a team member to leave the room during the process.

6.2 Ambulating an ECMO Patient

6.2.1 Prerequisites

For the past 48 h, the patient should:

- Be conscious, oriented, responsive to simple orders
- Have enough muscle strength to stand on his feet
- Have stable hemodynamic parameters (Pam >70 mmHg) with no or very low dosage of vasopressors
- Be stable on ventilation parameters
- Have encountered no major adverse events: flow variations, bleedings, septic shock, etc.
- Not be on futile indications for ECMO

Also check some logistical aspects:

- Availability of team members: to help out, to be able to monitor the other patients of the unit.
- Availability of ECMO specialists or perfusionists: in case of an emergency (pump failure, decannulation, etc.), the caregivers in charge of emergency situations should be reachable and available.

6.2.2 Practical Aspects

- The same as mobilizing a patient in his bed: check fixations, have the patient's consent and cooperation, have a full visual of the ECMO circuit, and each team member must be assigned with a specific task.
- Check the patient's strength.
- Check the alarms: blood flow and battery.
- Bring two full oxygen tanks dedicated to the ECMO.
- Have a chair as a backup for the patient if he gets tired.

- Clear the hallways: no obstacle should be in the way of the patient while he walks in the unit.
- At least four caregivers: one for the pump, one to hold the ECMO tubing, one with the backup chair, and at least one to help the patient. If the patient is ventilated and/or has a lot of infusion pumps, additional team members are needed.

6.2.3 How to Proceed

When everything and everyone is ready, the actual mobilization and ambulation can start:

- Explain to the patient the different steps: always wait for the caregiver instructions; first seat on the edge of the bed; then stand and go for the walk afterwards. Reassure the patient that there are a lot of caregivers to ensure his safety. Encourage the patient to express any needs, fear, or difficulties during the ambulation.
- Reconfirm everyone's duty during ambulation.
- Disconnect the ECMO from the fluids on the wall and connect it instead to the oxygen tank.
- The power supply must be the last element to unplug: ECMO devices have internal batteries with an autonomy of 1–6 h depending on the manufacturers and on the age of your device. Each time the battery is used, and with time, this internal battery will lose some of its autonomy (from 1 h, the battery will last only 45 min). Hence, make sure to check at least three times a year the batteries with the technical platform of your institution.
- Ambulate the patient.

When the patient is back in his bed, reconnect power and fluids and do a complete monitoring of the patient's vitals and a circuit check. Also, report in the patient chart the ambulation and eventual adverse events.

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Chapter 7
Mobilizing the ECMO Patients: Prone Positioning During Venovenous Extracorporeal Membrane Oxygenation (vvECMO)

Sabine Valera

This chapter deals with adult venovenous extracorporeal membrane oxygenation (vvECMO) patients who will benefit from proning sessions.

A combination of these therapeutic techniques is used for patients presenting the most severe ARDS, who are particularly frail.

This section describes specificities of these combined therapeutic strategies and presents the nurse's role for optimized quality care.

Nurses have a decisive part to play in the security and comfort of patients; effectiveness in nursing care is usually associated with training and procedures, so the purpose of this section is to give you an orientation for creating your own protocols.

7.1 Background

- Prone positioning (PP)

Prone positioning (PP) for trying to improve oxygenation in patients with acute respiratory failure has been done for a long time (1970s).

During PP, an increase of the posterior pulmonary alveolar recruitment is described, as well as a decrease of inflation in ventral regions [1]; moreover, a homogeneization of ventilation and ventilation/perfusion ratio are also observed.

In addition, there is a reduction in lesions associated with ventilation (VILI), and proning position is effective in 70% of cases.

It is a simple and inexpensive procedure, but little practiced because of the workload and possible complications.

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- vvECMO

vvECMO for adult pulmonary failure was controversial because of negative results with regard to mortality in several large studies [2, 3].

- But, times change and techniques evolve
  - In 2007, the CESAR [4] study showed a real benefit, in terms of survival, for patients with severe ARDS supported by ECMO.
    This study has also shown the benefit of being transferred to referral centers, where an "ECMO-specialized team" is present.
  - In 2009, the H1N1 pandemic caused a renewed interest in the use of extracorporeal membrane oxygenation (ECMO) for extremely severe ARDS [5].
  - In 2012, Consensus conférence organized by the French Intensive Care Society [6] concluded: ECMO should be considered in patients with PaO_2 to FiO_2 ratio lower than 50 mmHg during at least 3 h despite the use of a protective lung strategy including prone positioning.
  - Very recently, systematic PP performed in ARDS patients with PF ratio lower than 150 has been shown to decrease mortality [7].

Usually, PP is considered before vvECMO.

Some studies have evaluated the effect of PP on lung function for patients under vvECMO [8–12], and they all come to the same conclusions:

PP and vvECMO are probably complementary, because ultraprotective ventilation allowed by vvECMO may reduce overinflation, but probably does not permit ventilation redistribution allowed by PP.

PP can be associated with vvECMO with an improvement in arterial oxygénation, and thereafter facilitation of weaning from vvECMO.

PP during vvECMO can be proposed without compromising the safety of selected patients, and can be implemented by centers experienced in both techniques.

ECMO probably makes PP safer in the most severe patients, because the risk of hemodynamic compromise or of sudden respiratory worsening, while turning the patient, is much less in vvECMO patients.

7.2 Nursing Care Related to vvECMO and Proning

Contraindications for PP under vvECMO are the same as those without ECMO:

- Intracranial pressure >30 mmHg
- Massive hemoptysis requiring an immediate procedure
- Serious facial trauma or facial surgery
- Cardiac pacemaker inserted in the last 2 days
- Unstable spine, femur, or pelvic fractures
- Mean arterial pressure lower than 65 mmHg
- Pregnant women
- Single anterior chest tube with air leaks

Safety and complications:

The nurse's main role is to coordinate and organize the procedure, and to avoid complications.
To be performant, nurses have to know the possible side effects.
Most of the time, the proning session last 12–16 h.
Concerning PP position, studies have shown that the main side effects are:

- Pressure ulcers
- Endo Tracheal Tube (ETT) obstruction
- Thoracostomy tube dislodgment

The team also has to keep in mind the side effects of vvECMO:

- Bleedings
- Thromboembolic risk
- Hemolysis
- Air embolism
- Mechanical complications
- Cannula dislodgment

Because of all these side effects, one efficient way to avoid them is to have standardized procedures and checklists (annexe).

It is necessary to think about the patient himself and the ECMO machine.

The environment in the room has to be particularly tidy.

The process is not difficult, but every detail has to be thought of.

The team has to be prepared, informed, and trained.

One more person than that in the usual PP procedure is needed.

This person will be totally dedicated to the ECMO machine and cannulas, which means checking the flow monitoring, checking all the tubing, and maintaining cannulas.

This person will be the referent for mobilization, associated with the one who is in charge of the endotracheal tube (ETT).

Usually, seven people are needed:

- One for ETT
- One for vvECMO and cannulas
- Two on each side
- And one for cleaning the mattress, positioning the sheet, helmet and mirror (if needed), and gel supports

7.2.1 Material

Intubated patient:

- A gel half-pipe-shaped headrest or small gel pad for the head. Depending on the anatomy, a special helmet can be used.

- Thoracic gel pad (or two gel squares according to the patient's morphology).

Tracheotomized patient:

- Helmet with mirror and foam to be unwrapped 1 h before PP to allow time for expansion.
- Thoracic gel log-shaped pad for thorax.

According to the patient size, the bed may have to be shortened, and anti-equine foams must be positioned to avoid legs' wrong positions.

Provide electrodes, clean sheets, wipes and surface decontaminant for bed, and protection pad.

Hydrocolloid dressings may be needed to protect the skin from medical devices, ECMO cannulas.

7.2.2 Patient

- Hygiene
  - Proceed to the toilet before the patient PP.
  - Wash the back after PP.
- Digestive
  - Check the permeability and the mark of the nasogastric tube.
  - Fix the nasogastric tube on the nose.
  - Stop the enteral nutrition during the procedure and occlude the nasogastric tube.
  - Maintain slow but enteral feeding 500–1000 ml/day.
- Eye
  - Usual care.
  - Add plenty of vitamin A cream.
  - Position an adhesive strip horizontally on the upper eyelid.
- ENT
  - Nose and mouth secretions suctioning.
  - Mouth care.
  - Position the ETT lace node on the cheek which will not be in contact with the mattress.
  - Check the hold of the tube lace and plaster (the complementary fixation with tape will release the lace to avoid skin damage, especially in the mouth corner due to edema).
- Bronchial
  - Protected suctioning system.

  - Perform bronchial aspiration before the maneuver.
  - Check the pressure of the balloon (30–35 cmH_2O).
- Skin
  - Preprocedure skin condition evaluation; fill in the lesions form.
  - Hydrocellular dressings to avoid contact between the tubing and the skin and between the bladder catheter and testes.
  - Do not use hydrocolloid dressings systematically. Reserve them for damaged skin and prominent body parts if required.
- Equipment
  - Identify the line of catecholamines.
  - If necessary, extend the perfusion lines. No lines or tubes should be under the patient.
  - Check dressings.
  - ECMO cannulae dressings need to have been done <24 h previously.
  - Start relay of catecholamines before PP maneuver.
  - Position infusions so that lines do not interfere with the maneuver.
  - Check the length of every tube and be sure that the chest fluid drainage is not interrupted. Check the vacuity of bowls, and put them at the foot of the bed.
  - Position the artery line at the foot of the bed.
- Urinary
  - Proceed to urogenital toilet.
  - Check the urinary catheter position to be sure that it is not twisted or will not injure the patient.
  - The diuresis collector system has to be positioned in the right place for PP.
- Medical
  - Arterial blood gases before FiO_2 level modification.
  - FiO_2 100% before mobilization.
  - Ensure that sedation is correct (RASS – 5). Curare is often prescribed.

7.2.3 PP Maneuver

- Plastic apron, nonsterile gloves, compliance with isolation precautions for patient.
- "Maximum pressure" bed position.
- Remove the electrodes and cables except the artery one.
- If foam and/or helmet is necessary, pass the gastric tube and the endotracheal tube through the opening.
- Do not forget to clamp off ETT if ventilator tubes have to be disconnected (e.g., to put the helmet in the right position).

- Position the patient on the edge of the bed, on the opposite side of the ventilator.
- Put the patient in a lateral position.
- Clean the mattress and put on a clean sheet. Add a protective drawsheet under the mouth.
- Prone the patient. Move his arm carefully (risk of dislocation, specially with curare).
- Position the gel log-shaped chest support.
- Remove the "maximum pressure" of the bed.
- Check the position of the head in the helmet, position the mirror, or place the head block.

7.2.4 Checklist for Proned Patients

- No support at eye level.
- No folding ears.
- Positioning of the gastric tube and the endotracheal tube or tracheostomy tube.
- Balloon and aspiration subglottic accessibility.
- Perform bronchial suction to check the airway permeability.
- Replace the monitoring (saturation and ECG).
- Check the positioning of the arms along the body, palms up.
- Readjust the length of the bed or move the anti-equine equipment.
- Position the tubes and drains and check the permeability of vascular access. Attach the ECMO cannulas to the bed.
- Place a hydrocellular on the genitals for men.
- Replace the initial FiO_2.
- Check for objects that can induce skin lesions.
- Place the bed 20° Reverse Trendelenburg.
- Start prescribed enteral feeding.

7.2.5 Nurse's Monitoring During PP Session

- Respiratory monitoring:
  - Arterial blood gases h + 1, then every 6 hours.
  - Permeability of the endotracheal tube or tracheostomy tube.
  - Tracheal suctioning if necessary.
- Skin condition
  - Check the tension of the ETT fixation every 2 h. If facial edema, loosen.
  - Check the lid closure.
  - Check the absence of ear folding.

  - Massage on support points every 2h (elbows, knees, face, iliac crests).
  - If occurrence of persistent redness, protect with a hydrocolloid.
  - Removal of folds in sheets. Limit the use of absorbent pads under the patient as they favor maceration.
- Checking of digestive tolerance
  - No vomiting, no regurgitation.
  - Transit.
- Equipment
  - Checking permeability and fixation of the drainage, tubes, and vascular access.
  - Checking ECMO parameter.

7.3 Traceability

Traceability is part of the nurse's mission.

Prone positioning session has to appear on the patient record with:

- Vital signs before and during PP
- Number of the session
- Begin time and ending session scheduled time
- Problems encountered during the maneuver
- Ventilator settings
- ECMO settings
- Lesions form carefully filled out

7.4 Conclusion

Prone positioning patients with vvECMO has a considerable impact on the number of caregivers and their workload: a large team is needed.

Teams have to be experienced, and they have to use standard procedures.

It takes a lot of practice to use the procedures optimally.

Key Points

- Training and procedures
- Organization and coordination
- Knowledge of side effects for avoiding them
- Skin protection reflection: the best protection is frequent massage and checking cutaneous pressure point

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Chapter 8
Transport Under ECMO

Anne-Clémence Jehanno, Charles-Henri David, Alicia Mirabel, and Guillaume Lebreton

Transporting a patient on ECMO requires organisation and specific support. Mobilisation of a patient on ECMO could be hazardous and must remain exceptional. The perfusionist is the guarantor of the proper conduct of this movement and of safety for the patient and his machine to prevent any risk of accident. Anticipation and compliance with appropriate procedures and logistics are the conditions that ensure maximum safety for the patient.

8.1 Considerations Common to All Transportation

Transferring a patient on ECMO is risky and must therefore be performed by a specialised team with at least three people, including at least a doctor and a perfusionist.

Before transferring a patient on ECMO, the method of cannulation and the type of pump used must be known. The fixation of the ECMO cannula stitches on the patient must also be assured, and if necessary they should be reattached. It is then necessary to ensure adequate oxygen and electricity autonomy during the transportation.

The procedure for passing the ECMO on an oxygen bottle is identical to any type of ECMO. The oxygen tank should be dedicated to the ECMO and not shared with the transport ventilator. First of all, the oxygen tank flow rate should be set to the gas air–oxygen mixer flow (e.g. gas mixer: 60% FiO_2; air 4 L/min; the oxygen tank will be set to 4 L/min; the FiO_2 of the bottle is 100%). The oxygen supply tube of the oxygenator is then disconnected from the gas mixer and connected to the oxygen

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cylinder. It is essential to check that there is no kink in the oxygen line and to ensure that the ECMO circuit is well supplied with oxygen. The air/oxygen wall lines can then be disconnected. For the transfer, it is important to hold the oxygen tank on the ECMO trolley, on the stretcher or on the bed so as not to separate the membrane from its oxygen supply.

Most ECMO consoles have a pretty good electric supply (30 min to several hours). However, over time, the electrical supply of these batteries can sometimes be reduced. Thus, the power supply must be disconnected at the last moment in order to preserve the battery. It may be useful to provide a sufficiently long power cable to plug into the examination room or the ambulance. Finally, a backup pump should always be available during transport. For pumps with an electromagnet (most ECMO pumps), this pump is a hand pump handle; for other pumps (electromagnetic levitation pump), a backup pump or a battery must be available during transport.

Transportation of every patient on ECMO requires continuous haemodynamic monitoring, especially for blood pressure and oxygen saturation. Indeed, the parameters of ECMO are not sufficient to ensure haemodynamic patient monitoring. The patient's vital parameters must always be visible—pulse, mean arterial pressure (MAP) and oxygen saturation—as well as the parameters of ECMO (speed, blood flow).

Finally, to be prepared for any incident in the ECMO circuit and to be able to support a complication (backflow, defusing, decannulation)—as for any patient receiving ECMO in intensive care—it is necessary to have two available pipe clamps during any transfer.

8.2 Intrahospital Transport

The care of a patient on ECMO often requires several complementary examinations (CT, angiography) on transfer to the operating room. Those transfers are often trivialised and could cause many complications or incidents if rules are not respected.

If the ECMO pump is a pump designed for transportation, it can be done more easily. In all cases, the perfusionist is positioned between the patient's bed and carriage to secure the ECMO circuit and pump and to avoid any tension on ECMO lines. The travel speed is slow, and the staff accompanying the patient must remain attentive to the perfusionist and can stop at any time. The communication between the perfusionist and the anaesthesiologist must be the *primum movens*. When moving, it is important to anticipate elevator calls and doors opening, and the route must be cleared of any object (cart, stretcher) which could impede the progress of the move.

On arrival in the operating room or in the examination room, the ECMO console power must be reconnected to the oxygen line (check the oxygen supply tank if there is no wall supply). The transfer of the patient to an operating table or examination table should be in 'one piece': the perfusionist secures cannulas and ECMO lines and gives the departure signal in agreement with 'the head', which involves securing the endotracheal tube. Lines and cannulas should be visible to

avoid kinking, tension or decannulation. When removing the transport bed, everybody must remain vigilant to avoid any incident.

During the examination or intervention, it is essential that the console and the ECMO circuit follow the movement of the patient (if the machine allows, it may be useful to place it on the examination table), preferably in the presence of the perfusionist. The patient-monitoring parameters and ECMO will remain visible for the duration of the examination/intervention, and it must be possible to act at any time on the ECMO machine or on the patient cannulation sites.

The return will take the same precautions as described above. Back in the room, the power supply is reconnected (ensure that no battery circuit breaker is activated), and the oxygen supply to the air/oxygen mixer is connected to the wall plugs and adjusted as described before. It is also necessary to ensure after each patient mobilisation that the cannulas have not been displaced, are properly fixed and that transportation did not cause any bleeding.

8.3 Extrahospital Transport

Extrahospital transport must respect the aforementioned rules. The main features of these transfers reside first in the fact that the duration will be longer and therefore requires greater autonomy (electricity, oxygen, monitoring, team, drugs) and then in the limited space in which adjustments are made. Transfers must therefore only be carried out by specialised teams who are trained to avoid any risk of incident.

Concerning the power supply, it is important to consider several things. First, the electrical characteristics of the ECMO pump and its power source (ambulance, aeroplane, helicopter, generator, battery) must be clearly defined and verified. Some ECMO pumps are designed to accept different voltages, but not all. The power output can also vary according to the vehicle and transport phase (stop, taxi, take-off). Thus, the power supply may not be available when the vehicle is stopped, or will only ensure the power supply but not the loading. The type of plug must also be considered.

In terms of monitoring, it is important to emphasise the need for continuous monitoring of invasive blood pressure, oxygen saturation and electrocardiogram.

Depending on the vehicle used, some specific features need to be considered.

8.3.1 Ambulance

Space is limited, and each device (electric syringe, respirator, ECMO console, scope) must be installed, stable and accessible to everyone. In the case of a jugular cannulation for a large or obese patient, it may be appropriate to extend the reinjection line for a few centimetres (30–40 cm). In this way, it is ensured that there is no

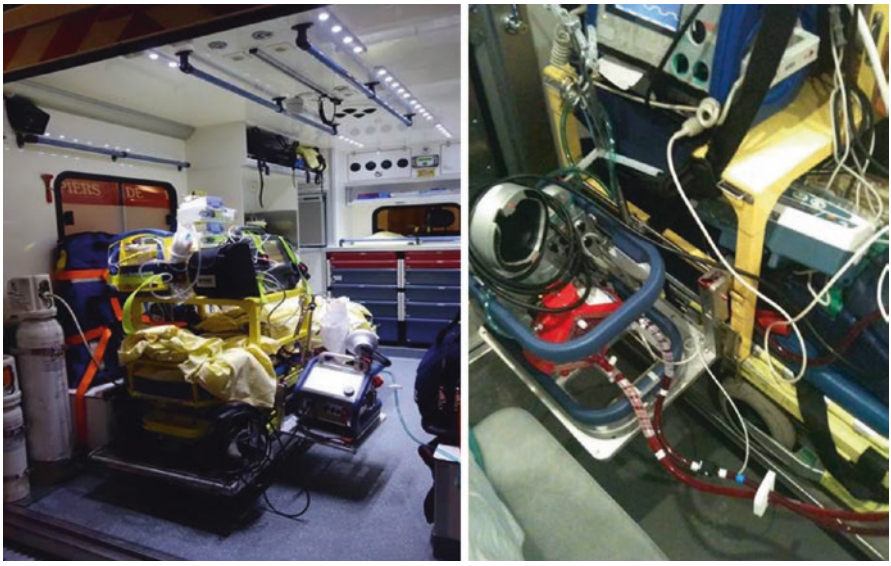

Fig. 8.1 ECMO transport on ambulance

tension or risk of tearing the reinjection line. This will be more comfortable and safer for the installation of the ECMO console.

In terms of installation, two configurations are considered according to the device used. The console can be positioned between the patient's legs (Fig. 8.1) or on a transport shelf in cases where the pump and oxygenator are compact (CARDIOHELP®). In other cases, one will consider an offset attachment of the oxygenator and the engine to the stretcher by means of an articulated arm (Fig. 8.1). In the latter configuration, the console may be positioned on the ground or on a shelf. In all cases, the ECMO console will be securely attached and will remain visible (supervision parameters) and reachable during the whole transportation, as well as ECMO lines, cannulas and the entire circuit [2].

The installation of the patient in the vehicle is slow and under the control of each stakeholder. Once the stretcher is in the ambulance, the power supply must be reconnected as soon as possible. Most often, a power supply is available during transport, but not always at the stop of the vehicle. The equipment required for patient resuscitation (respirator, syringe pumps) can be reconnected electrically and reinstalled on board. However, one must ensure that the power output of the vehicle is sufficient to supply the outlet of all these devices and ECMO. It is sometimes necessary to use different sockets.

To prevent any falling during transport, including shocks to the ECMO equipment, it is necessary to perform such transportation with soft and smooth driving. Being a risky transfer, it is better not to be delayed during transportation and to make it as safe and smooth as possible. In this regard, in our experience, it is always better to call a police motorcycle escort.

8.3.2 Helicopter

Transporting a patient on ECMO by helicopter necessitates a compact, stable and organised installation. The space available on a helicopter is indeed very limited and often allows the accompaniment of only two or three caregivers, depending on the load weight and the size of the helicopter.

The material used must be approved for air transfer. An aviation-type power outlet may be available and supplied with the ECMO machine. If the devices are not approved, it will not be possible to connect the console on the helicopter electrically, and the proper functioning of the console and its engine during the flight cannot be guaranteed. Intra-aortic balloon pumps are not approved for air transfer.

On board, security constraints must be respected. The pilot is there to help and support teams and must respect their instructions. The space on board is very limited, and so it is necessary to transport only the equipment strictly necessary for the intervention.

8.3.2.1 Transfer on the Stretcher of the Helicopter

Unlike an ambulance transfer, not all devices accompanying the patient and which are required for his resuscitation will be reinstalled on board. Installation must be thorough and rigorous. The ECMO console is placed between the patient's legs, the emergency hand crank is attached to it and Weiss clamps will remain with the perfusionist.

ECMO lines need to be fixed along the patient's legs and will be installed and secured in such a way to take up as little space as possible (Fig. 8.2).

The perfusionist must remain vigilant that no device disturbs the smooth function of the ECMO. Nothing must be put on the ECMO lines. One must check that there is no compression on cannulas that would prevent good drainage or bad reinfusion of blood to the patient.

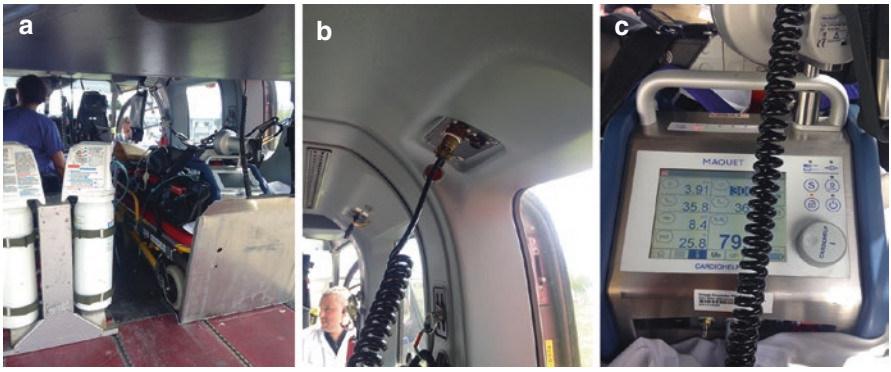

Fig. 8.2 ECMO transport on helicopter. (**a**) Oxygen support; (**b**) Power supply; (**c**) ECMO console between patient legs

All interhospital transport must be under surveillance, following the same vital signs as during other types of transport. These parameters must be visible and controllable at all times during patient transport. The syringe must remain accessible, and the amount of medication needed during transport should be sufficient.

Any device placed on the stretcher must be secured so as not to fall on the patient or on the ECMO console during transport.

The perfusionist must also anticipate the oxygen needs and provide assistance accordingly; the correct number of oxygen bottles must be transported.

The power supply of the ECMO console will be disconnected at the last moment before leaving the patient's room.

8.3.2.2 Before Take-Off

The hospital team to which the patient is being transferred is notified of the arrival of the team, and if necessary an ambulance team comes to welcome the incoming team on the runway. It is important to anticipate the arrival of the helicopter during the flight, because the team on board is unreachable.

The perfusionist checks that no bleeding has occurred during installation on board and checks the assistance settings.

8.3.2.3 During the Flight

The radio headset allows communication between the pilot and the medical team on board.

Oxygen consumption is increased during the flight, so it is important to monitor the level of the oxygen tank. The surrounding noise can prevent hearing alarms; it is therefore necessary to monitor visually each device. One must remain vigilant.

8.3.2.4 Descent from the Helicopter

One must first recheck all the parameters of the resuscitation devices and the ECMO console. Always disconnect the aircraft ECMO power plug and set aside. The descent from the helicopter is slow and under the control of each professional. The patient is taken to the resuscitation unit where he will be reinstalled. The stretcher should be returned as quickly as possible to the helicopter, so as not to monopolise it unnecessarily.

8.3.3 Plane

Transferring a patient under ECMO by plane requires careful preparation and organisation [1].

Before any transfer by plane, it is necessary to be aware of the aeronautical requirements, such as aeronautical approvals, the safety instructions on board and the technical requirements such as weight and the maximum volume allowed on board.

A briefing is given to pilots and the flight crew before boarding to identify everybody in case of need. It is important to be aware of the flight time and altitudes to better prepare coordination on arrival and for needs during the flight.

One must anticipate the oxygen and electricity needs on the plane and on arrival (at a civil airport, military, freight or drop zone).

The space on board is very limited, so only those materials essential to the success of the flight should be taken.

8.3.3.1 Before the Flight

It is important to check the compatibility between different devices.

Electricity on board may differ from one model to another (US socket, aeronautical socket). The voltage and power outputs can also vary. It is therefore important to anticipate these needs prior to installation on board. During take-off and landing, it may happen that electricity is cut. Electrical autonomy during the installation phases of take-off and landing must be anticipated. To ensure sufficient autonomy, one can take extension cords and an external battery.

The oxygen supply during the flight must be performed by means of aeronautic oxygen.

For a better calculation of the autonomy, two separate oxygen supplies for the ECMO and the respirator should be used.

8.3.3.2 Installing the Patient on Board the Aircraft

Initially, the ECMO console must be secured with straps, and the screen control must always remain visible to doctors and the perfusionist. Tubes, clamps, the emergency hand crank and the pump must remain permanently accessible.

The patient must also be strapped to his stretcher; a survival blanket can cover the patient and the tubes. The cannulation sites should always be visible and accessible in order to monitor the occurrence of bleeding, pressure or kinks in the tubes.

Medications for the flight must be sufficient in number and syringes full (sedation, catecholamines). Installation of venous access should be simple and accessible, and each venous access must be identified.

The monitoring required for the transfer of the patient should include electrocardiogram scope, invasive arterial blood pressure and oxygen saturation.

The doctor is positioned at the patient's head along with monitoring, venous routes and drugs.

The ECMO team (perfusionist/surgeon) is positioned at the patient's foot with the ECMO console, the clamps, the emergency hand crank and emergency kit.

Once the patient and his team are installed, the ECMO team gives the green light for take-off.

We must consider that, once in flight, nothing can be done: actions are very limited.

8.3.3.3 During the Flight

The landing and take-off phases are critical and necessitate maximum vigilance. There is a risk of backflow due to the plane's high speed. Falling objects may also impede the proper functioning of equipment or cause patient injury. Travel and interventions with the patient must remain limited so as not to destabilize the devices or the patient himself.

The cuff of the endotracheal tube should be inflated with a saline solution to reduce pressure changes inside the balloon which might cause spontaneous extubation. It should be checked regularly during the flight.

During the flight, all monitoring parameters must be entered into the records.

Take-offs and landings must be as long and smooth as possible.

The altitude has little impact on the patient. It can induce temperature variation: the higher you go, the cooler the temperature, and vice versa. To control the patient's temperature during the flight, one can cover or uncover the ECMO tubes.

8.3.3.4 After the Flight

Once a power source is available (extension, external battery), it is possible to disconnect it from the aircraft.

The remaining oxygen tank supply must be ascertained.

Keep in mind that vigilance is especially necessary following the descent and arrival of the aircraft, as it is at this point that the risk of accidents increases.

The transport of the patient is complete when the patient is in intensive care.

8.4 Installation in Intensive Care

The transfer to the patient's bed is carried out from the stretcher to the ambulance (as opposed to transfer to the stretcher).

It is important to check that during travel the ECMO cannulas and lines have remained attached to the patient and no bleeding has occurred.

After installing the patient in the intensive care bed, the ECMO console and its membrane must be installed on a dedicated, stable, strong and mobile trolley. The crank handle and Weiss clamps are also installed on the carriage. The power assistance is reconnected. The oxygen supply is plugged into the wall connections and is set up using a Sechrist® air/oxygen gas mixer (Fig. 8.3).

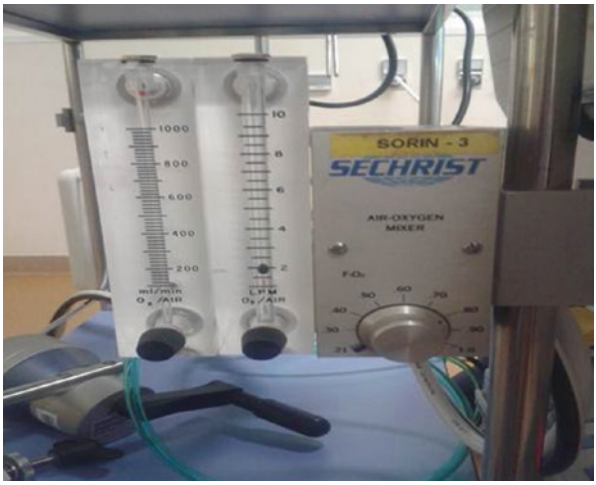

Fig. 8.3 Sechrist® air/oxygen gas mixer

The perfusionist ensures proper positioning of the ECMO carriage with the nurse and the doctor in charge of the patient. Finally, he sets up all the desired alarm rates.

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Chapter 9
Weaning Process from Venoarterial ECMO

Nicolas Brechot

There is no consensus among ECMO centers regarding the way to manage weaning from VA-ECMO. Decrease in doses of catecholamine infusion, recovery of a pulse arterial pressure, and improvement of myocardial function assessed with echocardiography are indicating that the patient might be weaned from ECMO. A weaning test has then to be conducted. The only published test at this time consists in a daily transient decrease in ECMO blood flow at 1 L/min during 15 min. Hemodynamic stability and echocardiography parameters, aortic velocity time integral (reflecting cardiac output)>12 cm, left ventricular ejection fraction>20%, and S′ wave at mitral annulus >6 cm/s are predictive of weaning success under this regimen [1]. ECMO explantation is then performed at the patient's bedside or in the operating room depending on local practice.

Success of weaning from right ventricular dysfunction remains less predictable. Indeed, right ventricular failure can be masked, even during low ECMO blood flow regimens, making the criteria previously described not suitable to predict weaning success or failure, and can occur several hours after ECMO removal. In that case, weaning process consists in a gradual decrease in ECMO blood flow during approximately 10 days, until reaching 1.5–2 L/min. ECMO explantation will be mostly guided by (1) the predictive clinical course of right ventricular dysfunction considering the underlying pathology (usually several days in case of primary graft dysfunction, more progressive and uncertain in case of ischemia); (2) right ventricular aspect and contractility during the 15-min weaning test at 1 L/min; and (3) right ventricular aspect and contractility during a real clamp test during 20 min.

Respiratory function must also be assessed before explantation. A high proportion of patients assisted with venoarterial ECMO exhibits indeed an ARDS, due to

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initial multiple organ failure. Switching off the sweep gas flow cannot be done during venoarterial ECMO (as it is during venovenous ECMO), as it would create a venoarterial shunt. Weaning test consists in reimplementing a standard mechanical ventilation (tidal volume 6 ml/kg of ideal body weight) and decreasing the pulmonary assistance on ECMO: decrease sweep gas flow to approximately 2 L/min and decrease FiO_2 on ECMO to <50%. Pulmonary compliance and oxygenation are then checked. Patients not stable under this regimen (increase in the plateau pressure, lack of oxygenation) will necessitate a switch from venoarterial to venovenous ECMO. Drainage cannula is left in place, and an additional return cannula is placed in the right jugular vein while arterial cannula is removed.

An algorithm to guide venoarterial ECMO explantation is presented hereafter:
Criteria for readiness to wean venoarterial ECMO

- Adequate cardiac function with acceptable levels of vasoactive agents

Weaning from circulatory support (step 1) and pulmonary support (step 2) are conducted concomitantly.

Step 1: Weaning from circulatory support

Two main approaches can be used:

1. Incrementally reduce extracorporeal blood flow
   (a) Monitor hemodynamics, vasopressor requirements, cardiac function and output (by echocardiography), ABGs, laboratory markers of end-organ perfusion (e.g. B-type natriuretic peptide, creatinine), as blood flow is reduced. Frequency of echocardiographic and serologic assessments is dictated by clinical scenario. Minimum blood flow that may be achieved safely will vary by cannula size and level of anticoagulation; recommend maintaining ≥1 L/min within each cannula.
   (b) If hemodynamics, vasopressor requirements, cardiac function, end-organ perfusion are acceptable at the minimally acceptable blood flow, check for readiness to be weaned from pulmonary support (step 3).
   (c) If hemodynamics are inadequate, resume previous blood flow rate and further optimize hemodynamics.
2. Daily transient reduction in ECMO blood flow
   (a) Reduce ECMO blood flow to 1 L/min for 10–15 min, and monitor hemodynamics and echocardiographic settings. Hemodynamic stability under this regimen combined with LVEF>20%, aortic TVI>12 cm, and S′ wave at mitral annulus>6 cm/s are strongly associated with weaning success [1, 2].
   (b) If clinical and echocardiographic criteria are met, check for patient's ability to be weaned from lung support (step 3).
   (c) If criteria are not met, reincrease blood flow rate to the lowest possible level according to aortic TVI, maintaining a blood flow higher than 2.5 L/min to prevent from circuit clotting.

Approach #2 may accelerate weaning process. However, it is *not suitable for weaning from right ventricular failure,* as RV failure can be delayed from blood flow reduction and masked by low blood flow rates.

Step 2: Weaning from lung support

Incrementally reduce FDO_2 and sweep gas flow

1. Reduce FiO_2 delivered on the membrane (FDO_2) in stepwise fashion (e.g. 20% increments), as needed to maintain oxygenation.
2. Reduce sweep incrementally while increasing tidal volume and/or respiratory rate as needed to maintain ventilation. *Sweep gas flow should never be completely discontinued when weaning venoarterial ECMO* because of the creation of a deoxygenated right-to-left shunt.
3. Arterial blood gas analysis after each reduction in FDO_2 and sweep gas flow are taken at the right arm to be as far as possible from the ECMO blood flow.
4. If gas exchange is inadequate, revert to previous ECMO settings and optimize respiratory status further.

Step 3: Criteria for readiness to wean pulmonary support

If the patient remains stable under usual protective mechanical ventilation ($PaO_2/FiO_2 > 150$ and plateau pressure <26 cmH_2O, with tidal volume 6 ml/kg of ideal body weight) and adequate oxygenation and decarboxylation using minimal pulmonary support with the ECMO ($FiO_2 < 50\%$ and sweep gas flow at 2 L/min), patients can be weaned from ECMO pulmonary support. *Sweep gas flow should never be completely discontinued when weaning venoarterial ECMO* because of the creation of a deoxygenated right-to-left shunt.

Step 4:Decannulation

- If criteria are met to wean from circulatory support (step 1) and pulmonary support (step 3), decannulation is recommended.
- If criteria are met to wean from circulatory support (step 1) but not for pulmonary support (step 3), consider switching for a VV-ECMO.

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Chapter 10
Weaning of Venovenous Extracorporeal Membrane Oxygenation

Matthieu Schmidt

In the context of severe acute respiratory distress syndrome, the duration of venovenous extracorporeal membrane oxygenation (VV-ECMO) is frequently long. The process of VV-ECMO weaning is very simple, which easily allows clinicians to perform trial at bedside as soon as possible.

10.1 Duration of VV-ECMO for Severe ARDS

In a recent multicenter retrospective study of 140 patients, Schmidt et al. reported that 90 (64%) patients survived to ICU discharge [1]. In-ICU deaths were attributed to multiple organ failure for 28, septic shock for 18, hemorrhagic shock for 6, intracranial bleeding for 4, and brain hypoxia sequelae for 4. It is interesting to notice that respective median duration of ECMO and mechanical ventilation support were 15 (8–30) and 40 (23–68) days, and median hospital length of stay was 65 (39–111) days. In addition, 25% survivors had more than 1 month ECMO. Similarly, in the Conventional Ventilation or ECMO for Severe Adult Respiratory Failure (CESAR) trial which was conducted in the UK from 2001 to 2006 to evaluate a strategy of transfer to a single center (Glenfield, Leicester) which had ECMO capability while the patients randomized to the control group were treated conventionally at designated treatment centers, duration of ECMO was 10 (4.8–22.8) days [2]. Lastly, in 2355 patients with respiratory failure treated with ECMO reported to ELSO during a 13-year period, a total of 1338 patients (57%) were alive at hospital discharge after a median of 170 (105–280) hours on ECMO [3]. During the influenza A (H_1N_1) pandemic, the Australia and New Zealand Collaborative Group (ANZICS) was the

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first to report its experience on ECMO [4]. Despite extreme disease severity at the time of ECMO initiation (median PaO_2/FiO_2 ratio 56 mmHg, median positive end-expiratory pressure [PEEP] at 18 cm H_2O, and median lung injury score of 3.8), only 25% of the 68 ECMO patients died. Their duration of ECMO was 10 (7–15) days. In the context of drowning, successful longer ECMO run has been reported with late recovery after 117 days on ECMO support [5].

10.2 When Should Clinician Think About VV-ECMO Weaning?

Select patients with respiratory failure receiving ECMO may be safely and successfully managed without invasive mechanical ventilation. It must be emphasized that not all respiratory failure patients receiving ECMO will be appropriate for endotracheal extubation, even if gas exchange is adequate. In fact, in current practice, only a minority of patients would even be eligible at experienced centers [6]. Most of the time, especially in the context of severe ARDS, ECMO is withdrawn before mechanical ventilation.

Based on the ELSO Guidelines from 2013, when ECMO support is <30% of total, lung function may be adequate to allow coming off ECMO, and a trial off is indicated [6]. However, such evaluation of the participation of the ECMO support might be difficult to appreciate at beside. Signs of pulmonary recovery are generally indicated by reduced ECMO and sweep gas flows to maintain SaO_2 and $PaCO_2$, improvement of the chest radiograph, and increased tidal volumes. In others words, when pulmonary function has recovered sufficiently to allow adequate ventilation on modest amounts of positive-pressure ventilation, a weaning ECMO should be performed.

10.3 How to Perform VV-ECMO Weaning Trial?

The complete procedure is described in Table 10.1. Fortunately, weaning trial of VV-ECMO is very simple. Indeed, with this configuration, cardiac function is adequate, and only native gas exchange is tested. After maintaining blood flow and stopping the sweep gas, the patient SaO_2 and $PaCO_2$ have to be followed.

The ventilator is generally set to moderate levels of mechanical support (e.g. tidal volume 6 mL/kg, plateau pressure <30 cmH_2O, PEEP 5–12 cmH_2O, FiO_2<0.6) [7]. Similarly, in the CESAR trial, a peak pressure <30 cmH_2O and FiO_2 <60% were required [2]. In the EOLIA (ECMO to rescue lung injury in severe ARDS) trial, patients were ventilated in BIPAP/APRV mode under ECMO with a PEEP >12 cmH_2O and upper pressure limited to 23–24 cmH_2O [8]. Weaning trial was indicated when the tidal volume generated by the driving pressure was >200 mL. The device may be withdrawn if (1) PaO_2 was >60 mmHg with SaO_2 >90% with FiO_2 on

Table 10.1 ECMO-VV weaning trial

ECMO and mechanical ventilation settings
Set the ventilator with moderate levels of mechanical support (e.g., tidal volume 6 mL/kg, plateau pressure <30 cmH_2O, PEEP 5–12 cmH_2O, FiO_2<0.6)
Maintain ECMO flows of >2 L/min
Turn off the sweep gas flow
Follow SaO_2 and $PaCO_2$
During more than 6 h
Successful criteria
PaO_2 was >60 mmHg with SaO_2 >90%, with FiO_2 on the ventilator <60% and inspiratory plateau pressure <30 cmH_2O
Echocardiography reveals no signs of acute cor pulmonale
During 1–12 h
Procedure for decannulation
Stop anticoagulation for 1 h
Patient in Trendelenburg position with a short-term pharmacological paralysis
Remove ECMO cannulas and apply topical pressure for 30 min
Routine venous Doppler ultrasound of the cannulated vessel after decannulation

the ventilator <60% and inspiratory plateau pressure < 30 cmH_2O and (2) echocardiography reveals no signs of acute cor pulmonale for at least 1–12 h.

During the trial, ECMO flows of <2 L/min should be avoided to reduce the risk of thrombus forming in the circuit. However, maintaining normal circuit flow with the sweep gas turned off prevents thrombus forming in the circuit but allows the patient to be tested off extracorporeal support. In most instances, after stopping systemic anticoagulation for 1 h, the ECMO cannulas can be removed without surgical repair of the vessel, but simply by a topical pressure pulling for 30 min. As the cannula is removed, the patient should be on Trendelenburg position and have received a short-term pharmacological paralysis or perform a Valsava maneuver to reduce the risk of air embolism. Routine venous Doppler ultrasound following decannulation is warranted to detect deep vein thrombosis in the cannulated vessel. Its prevalence following ECMO was estimated to 8.1/1000 cannula days [9].

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Chapter 11
Initial Training of Nurses

Jo Anne Fowles

11.1 Introduction

The nursing team caring for the patient supported on ECMO requires specialist training to ensure safe, effective care. All training must be supported by a robust assessment and regular reassessment. ELSO provides invaluable guidance and resources to meet training and assessment requirements.

11.2 The Nursing Team

Within the nursing team, different roles will require specific training. Most ECMO nursing models are based around four levels of nurses:

- ECMO coordinators
- ECMO specialist
- Bedside nurse
- Healthcare support worker

In addition, many ECMO services also include a retrieval service so will have nurses fulfilling roles as transfer nurses (Fig. 11.1).

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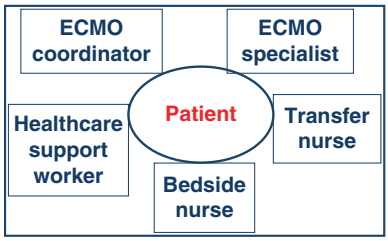

Fig. 11.1 Nursing roles in the ECMO Team

11.3 ECMO Coordinator

The ECMO coordinator is a senior ECMO specialist who, with the ECMO director, is responsible for developing and maintaining guidelines and standards for the multidisciplinary team. Their responsibilities also include the supervision, training, and assessment of the ECMO team.

11.4 The ECMO Specialist

ELSO defines the ECMO specialist as "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 red book – Ref. [1]).

The ECMO specialist can come from a number of different clinical backgrounds, including nursing, perfusionists, and respiratory therapists. For the purpose of this chapter, only the training of nurses to achieve and maintain the qualification of ECMO specialist will be discussed.

The ECMO specialists are usually nurses with more than 2 years of experience at a senior level of working in an intensive care unit (ICU). They will have shown themselves to be able to work in stressful conditions, be decisive, and have excellent communication skills. The latter is of utmost importance, as they are central to all patient care and must maintain effective communication with not only the multidisciplinary clinical team but also the patient and his family.

Each center should have written guidelines and protocols defining the specific responsibilities of the ECMO specialist. These responsibilities will cover managing the extracorporeal circuit, including regular circuit surveillance, troubleshooting, accessing the circuit (e.g., CRRT), monitoring pre- and post-oxygenator gases to ensure optimal function, ensure cannula and circuit are safe during any mobilization or movement of the patient, and manage circuit emergencies. In some centers, the ECMO specialist's role has expanded to include management of anticoagulation and weaning using defined guidelines. Such developments have improved the timeliness of interventions and thus improved patient care. The training of the ECMO specialist is built around providing them with the skills and knowledge to fulfill this role.

Table 11.1 ECMO Specialist course – aims and objectives

ECMO specialist course
Course aim
On completion of training and successful assessment, the candidate will be qualified to practice as an ECMO specialist in Papworth Hospital NHS Foundation Trust.
Course objectives
Upon successful completion of this course, the student will be able to:
Understand and demonstrate the importance of multidisciplinary teamwork in the care of the patient on ECMO
Demonstrate an in-depth understanding of the 'extracorporeal membrane oxygenation (ECMO) Papworth ICU guidelines'
Be able to define the different types of ECMO and clinical indications for each
Demonstrate competence in practical skills including troubleshooting, routine surveillance, and emergency management

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11.4.1 ECMO Specialist Training

Although centers may have differing approaches to the training and assessment of ECMO specialists due to differing equipment, patient type, and local practice, most will follow recommendations set out by ELSO, using the ECMO Specialist Training Manual published by ELSO (Ref. [2]) as a guidance to compliment their own written guidelines and protocols.

As previously acknowledged, ECMO specialists can have differing professional backgrounds; each group will have specific needs and in this chapter, training and assessment of those with a nursing background will be discussed.

The ideal ECMO specialist course will combine didactic and practical sessions supported by supervised practice in the clinical area alongside experienced ECMO specialists. The course will have a clearly defined aim and objectives (Table 11.1). An example of a course outline based on ELSO recommendations is shown in Table 11.2.

The majority of sessions will be taught by senior ECMO clinicians, the ECMO coordinator, and senior ECMO perfusionist. Senior clinicians from other specialties should be involved in the training program, for example, radiologists, hematologists, and microbiologists. Involving other specialties ensures a broad understanding of the complex needs of the ECMO patient.

On completion of the course, the ECMO specialist will have developed the skills and understanding to practice as an expert. Benner (Ref. [3]) defines the expert nurse as one that has accumulated the knowledge and experience to have an intuitive grasp of clinical situations and is able to respond in a highly proficient manner. They operate with a deep understanding of the total situation allowing them to perform in a fluid and flexible manner. The management of the patient supported on ECMO is complex and can change rapidly, requiring the ECMO specialist to have developed to this level.

Table 11.2 ECMO Specialist course – course outline

ECMO specialist course
Components of training program
30-h classroom teaching
Minimum of 32 h practical training in clinical area or in simulated sessions – maintain a log book detailing practical training
Identify an experienced ECMO specialist to act as mentor
Complete three reflective accounts of patient episodes
VIVA assessment by senior ECMO doctor and ECMO coordinator
Assessment of practical skills by ECMO coordinator and senior ECMO perfusionist
Learning outcomes
The student will achieve an understanding and be able to discuss:
Didactic sessions:
Introduction to ECMO – history, types and indications, risks and benefits, provision of ECMO, and current research
Physiology of diseases/indications
Criteria and contraindications for ECMO including patient selection
Physiology of coagulation including management of anticoagulation
ECMO equipment including circuit and membrane physiology
Physiology of VV-ECMO and VA-ECMO, including cannulation, indications, and complications
Safe mobilizing of the ECMO patient
Weaning from ECMO, including decannulation
Post-ECMO complications
Ethical and social issues including withdrawal of support
Day-to-day circuit and patient management
Emergencies and complications during ECMO support, including patient and circuit emergencies
Practical sessions:
Be familiar with standard ECMO circuit
Identify key components of the circuit and potential risks
Identify essential equipment on standard ECMO trolley
Understand when circuit blood gas analysis is required, demonstrate obtaining samples safely, and interpreting results
Identify location of pressure monitoring and recognize normal limits
Interpret pressure readings and treat appropriately
Know procedure and indications for changing circuit components
Understand and demonstrate troubleshooting the circuit
Be aware of regular maintenance requirements of the circuit
Demonstrate connection and disconnection of CRRT

11.4.2 ECMO Specialist Assessment

Assessing competency can be achieved using a variety of methods, either in the clinical area, classroom, or simulation area.

Three skills that need to be considered when assessing are:

1. Critical thinking (knowledge)
2. Practical skills
3. Behavioral skills

Assessment criteria are included in the center's protocols and guidelines and provide a framework for objective assessment of the ECMO specialist.

A written or oral exam can be used to assess the ECMO specialist's knowledge. An oral exam is often preferred, as by challenging with developing scenarios, the specialist's ability to understand a situation and prioritize appropriately, be decisive, and respond accordingly can be assessed. The assessors are usually a senior ECMO clinician and the ECMO coordinator.

Practical skills can be assessed in the clinical area but are often assessed in simulation labs. In this way, not only routine skills can be assessed but common problems requiring troubleshooting can also be simulated, allowing assessment of these vital skills.

Behavioral skills encompass leadership qualities, ability to work within a team, excellent communication, and professionalism. Feedback from other members of the multidisciplinary team is sought to evaluate the ECMO specialist. Simulation of scenarios involving the whole team can be used to assess and develop effective communication and essential behavioral skills.

Regular updating including attendance at multidisciplinary meetings and annual reassessment of skills is mandatory.

11.5 Bedside Nurse

Although the bedside nurse may also be an ECMO specialist, in many centers, the ECMO specialist will oversee two or more patients supported on ECMO with a bedside nurse allocated to each patient. The bedside nurse, although not qualified as an ECMO specialist, requires training to ensure they can do bedside monitoring and interpret patient observations and communicate any concerns to the ECMO specialist. They do not have skills to troubleshoot or access the extracorporeal circuit. Education covering these vital aspects will ensure safe care.

11.5.1 Bedside Nurse Training and Assessment

ECMO centers vary in the approaches to training bedside nurses, some reliant on practical experience-based learning and others having a more structured approach. An example of a structured approach to training is outlined in Table 11.3.

Whatever the approach, the bedside nurse requires the following:

Table 11.3 Bedside nurse training – program outline

Bedside nurse training program
Classroom learning – 1 day program. Topics to include:
Indications
Types
Risks
Role definition – bedside nurse and ECMO specialist
Circuit surveillance – what to look for, when to alert the ECMO specialist
Patient monitoring
Completion of workbook
Supervised practice in the clinical area
Formal assessment completed by senior ECMO specialist in the clinical area
Annual reassessment mandatory

- Knowledge of the indications and risks associated with ECMO
- Knowledge of the different types of ECMO – VV, VA, etc., and the specific risks associated with different cannulations
- Basic circuit surveillance
- Safe moving and handling of the patient
- Point-of-care monitoring where used, that is, ACT monitoring
- Cannula site care and dressings
- Understand limitations of their own role and the responsibilities of the ECMO specialist

11.6 Healthcare Support Worker

The healthcare support workers are unqualified members of the team who assist with basic nursing care and ensure all equipment is available. Although training is not necessary, an overview of the risks associated with ECMO should be discussed with them before they assist with any nursing care.

11.7 ECMO Transfer Nurses

In centers that provide a service which encompasses going to other centers, instigating ECMO support, and transfer of the patient back to the ECMO center, a team is trained to do this safely. Centers vary, but many include an ECMO doctor, ECMO specialist, and a perfusionist in the team sent to retrieve patients. These ECMO specialists require further training to ensure they have the skills necessary.

11.7.1 ECMO Transfer Nurse Training

Training for the transfer nurse will provide skills and knowledge to:

- Assist the ECMO doctor in cannulating the patient
- Use transfer monitors, ventilators, and other equipment required in the safe transfer of patients being supported on ECMO
- Respond and assist in any patient or circuit emergency
- Monitoring of the patient during transfer

How this training is provided is center-dependent, with many using team simulation training and a program of training nurses accompanying experienced teams.

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Chapter 12
Training of Nurses and Continuing Education in ECMO

Marc A. Priest, Chris Beaty, and Mark Ogino

ECMO is a low-volume, high-risk procedure and therapy. After completion of an initial education program, it is important to provide ongoing continuing education and clinical competence assessment. In order for continuing ECMO education to be successful, the proper infrastructure for continuing education in ECMO is essential. This chapter will discuss:

1. Essential hospital support
2. Staffing models
3. Assessment of ECMO clinical competence and quality assurance

12.1 Essential Hospital Support

Organizational hospital support is necessary to provide high-quality ECMO care. It takes a collaborative multidisciplinary approach to be successful in the development of a comprehensive ECMO program. Both initial and continuing education standards should be identified for the multidisciplinary care teams. Key hospital support positions would include, but is not limited to:

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1. Hospital Administration Representative
2. ECMO Steering Committee
3. ECMO Program Director
4. ECMO Physician
5. ECMO Program Coordinator
6. ECMO Specialist or Nurse
7. Multidisciplinary Support Staff

12.1.1 Hospital Administration Representative

Hospital administration will be involved in allocating the necessary resources to support continuing education. Administrative approval of nonproductive time is a key factor in supporting continuing education. Resources and a designated training environment are a part of the organizational operating and capital budget review process. Institutions must embrace and invest in continuing education to ensure efficiency and competency of ECMO teams.

12.1.2 ECMO Steering Committee

The institutional ECMO Steering Committee may include an ECMO Program Director, ECMO Program Coordinator, and delegated members of the multidisciplinary team. Responsibilities of the Steering Committee would include the formulation of guidelines and policies which outline the indications and contraindications for ECMO, clinical management of the ECMO patient, maintenance of equipment, termination of ECMO therapy, follow-up of the ECMO patient, initial and continuing education of the ECMO staff [1]. The Steering Committee will need to define the quality assurance review procedures for annual internal ECMO program evaluation. Obtaining membership to the Extracorporeal Life Support Organization (ELSO) is highly recommended as it is the world's largest extracorporeal support organization registry with over 61,000 extracorporeal support patients to date and currently over 300 ECMO center members around the world [2]. Institutions can use the ELSO registry and its reports as a benchmark for their annual quality assurance reviews.

12.1.3 ECMO Program Director

The ECMO program director is an ECMO physician that is responsible for the overall operation of the center's ECMO program [1]. The program director ensures appropriate training and performance, quality improvement, and

ELSO data validation and submission. Currently, ELSO recommends each institution's ECMO program director define the credentialing qualifications of an ECMO physician. Each institution's medical staff office is responsible for implementing and monitoring compliance of credentialing guidelines for their ECMO physicians [1]. See Appendix 12.1 for a sample of credentialing guidelines.

12.1.4 ECMO Physician

The ECMO physician may be a critical care physician or surgeon that has had specific ECMO training as outlined by their institutional credentialing guidelines. An ECMO physician should be available to provide 24 h on-call coverage to support the ECMO patient. The responsibility of the ECMO program director and ECMO physician is to support and participate in the continuing education of the multidisciplinary ECMO staff.

12.1.5 ECMO Coordinator

The ECMO coordinator may be an experienced intensive care nurse, respiratory therapist with a strong ICU background, or clinical perfusionist with ECMO experience [3]. The ECMO coordinator will have the ultimate responsibility for the supervision and training of the ECMO nonphysician staff. Continuing education of the ECMO staff will depend on the care model of the institution.

12.1.6 ECMO Specialist

An ECMO specialist is any nurse, respiratory therapist, clinical perfusionist, physician, biomedical engineer, or technician who has received ECMO training as an ECMO care provider. The initial training for the ECMO specialist includes a mix of didactic and "hands-on" education. See Appendix 12.2 for a sample training guideline. The ECMO specialist has the primary responsibility for maintaining extracorporeal support as outlined in their institutional protocols. These responsibilities include instituting ECMO setting adjustments under the direction of an ECMO physician, troubleshooting equipment, assessing the ECMO circuit, and responding appropriately to ECMO emergencies [1]. An ECMO specialist will have more intensive continuing education requirements than an ECMO nurse due to the specialist's increased level of responsibility in monitoring the ECMO circuit and patient.

12.1.7 ECMO Nurse

An ECMO nurse is a bedside nurse that cares for ECMO patients and has a modified responsibility for assessing and managing the ECMO system. It is recommended that an ECMO specialist team be available, either on site or on call, to manage advanced circuit issues and ECMO emergencies. The multidisciplinary care model described in the Sect. 12.2 "Staffing Models" section outlines the roles and responsibilities of the ECMO nurse. The continuing education requirements are modified for the ECMO nurse compared to the ECMO specialist, depending on the care model of the institution.

12.1.8 Multidisciplinary Support Staff

The management of the ECMO patient requires a comprehensive multidisciplinary healthcare team and resources from all areas of the organization to optimize care and minimize potential complications associated with extracorporeal life support. Other specialty services outside of the critical care environment may be called upon to provide care to a complex ECMO patient. Rehabilitation specialists including occupational, physical, and speech and language therapies are essential to meet the multidisciplinary needs of the ECMO patient [1]. The support services of blood bank, radiology, and clinical laboratories are required to provide adequate clinical care of the ECMO patient.

12.2 Staffing Models

12.2.1 Traditional Staffing Model

The plan for continuing education will be determined by the designated staffing model used within a given organization. Traditionally, many neonatal and pediatric ECMO centers have used a 2:1 care model with an ECMO specialist to manage the ECMO pump and a bedside nurse for patient care.

12.2.1.1 Recommendations

1. Equipment
   (a) Centrifugal or roller pump technology
   (b) Multiple areas of pressure monitoring to assess drainage, return, and oxygenator pressures
   (c) Infusion ports as determined by the team

2. The ECMO specialist's primary responsibility is to monitor the pump and perform ECMO-associated tasks
   (a) Performs comprehensive circuit check every 4 h
   (b) Titrates sweep gas flow and FiO_2 per-protocol
   (c) Titrates blood pump flow by adjusting rpm per-protocol
   (d) Administers volume to patient in response to patient and circuit hemodynamics per-protocol
3. ECMO specialists need to identify emergency situations and perform ECMO pump emergency procedures in the following situations:
   (a) Arterial and venous air
   (b) Accidental decannulation
   (c) Circuit-related complications requiring component changes (pigtails, connectors, tubing, raceway, centrifugal head, oxygenator, circuit change)
      (i) This may need to be performed with an ECMO specialist
   (d) Pump failure requiring hand crank or switch to back up pump
4. ECMO resources to support the bedside ECMO team will need to be available with 24/7 coverage, and if the resource is outside the hospital, a defined response time will need to be defined.
   (a) ECMO specialist with advanced training in all aspects of ECMO pump management including: circuit priming, cannulation, decannulation, ECMO circuit troubleshooting, and component/circuit changes. This role is often supported by an ECMO coordinator and/or the perfusion team.
   (b) ECMO physician.
5. The bedside nurse caring for the ECMO patient has the primary responsibility to care for the patient and not the ECMO system.
   (a) Requirements
      (i) Basic understanding of ECMO physiology and emergency procedures
      (ii) ECMO system emergencies are managed by the ECMO specialist

12.2.2 Multidisciplinary Care Model

The advancements in ECMO technology and increase in adult ECMO cases have led to a new staffing model for ECMO patients. The Multidisciplinary Care Model (MCM), also known as the "The Single Caregiver Model," uses the bedside nurse to care for the patient, while having a modified responsibility for monitoring and managing the ECMO pump with the support of an ECMO-trained multidisciplinary team. A secondary support structure to address ECLS complications must be in place for complex management issues and emergent interventions. The MCM model provides a safe, flexible, and fiscally responsible staffing model for variable ECMO activity [4].

12.2.2.1 Recommendations for MCM

1. Equipment:
   (a) Centrifugal technology
   (b) Minimal to no monitoring of ECMO pressures
   (c) Simple in an out-loop with no infusion ports
2. The ECMO nurse's primary responsibility is to care for the patient
   (a) Modified ECMO responsibilities
      (a) Performs simple circuit check every 4 h
      (b) Administers volume to patient in response to patient and circuit hemodynamics per-protocol
      (c) Performs the following ECMO pump emergency procedures:
         (i) Clamp off ECMO and call for help for:
            1. Arterial air: any volume
            2. Venous air: large volume
            3. Accidental decannulation
            4. Massive circuit clot/obstruction of centrifugal head or oxygenator
         (ii) Manual hand crank for pump failure (on applicable models)
      (d) May include
         (i) Titration of sweep gas flow and FiO_2 per-protocol
         (ii) Titration of blood pump flow by adjusting rpm's per-protocol
3. ECMO resources to support the ECMO nurse will need to be available with 24/7 coverage:
   (a) ECMO specialist with advanced training in all aspects of ECMO pump management including: circuit priming, cannulation, decannulation, ECMO circuit troubleshooting, and component/circuit changes. This role is often supported by an ECMO coordinator and/or the perfusion team.
   (b) ECMO physician.

12.3 Clinical Competence

12.3.1 Establishing Clinical Competence

Competence (noun). "The ability to do something well" [5]

The ECMO program director and ECMO coordinator are responsible for the training of the ECMO team, and for providing ongoing competency training and evaluation. Due to the unique characteristics and diverse nature of each ECMO

program, ELSO recommends that each center establish an educational training program to establish competence based on their patient population, ECMO equipment, and designated roles of each ECMO team member [1]. The primary goal of the organization's ECMO education plan is to provide consistent multidisciplinary education where all ECMO providers are exposed to a single curriculum for initial training. This approach will alleviate the dependence on an individual discipline to troubleshoot ECMO complications. The designated staffing model followed by each institution will assist in the development of competency training for the ECMO specialist or ECMO nurse (see definitions). Because the educational backgrounds of ECMO specialists differ, each organization will need to adapt their educational program to meet their staff's needs.

Bedside nursing staff (not responsible for ECMO equipment) will require additional training on caring for patients on ECMO support along with a basic understanding of ECMO physiology and equipment. The ECMO coordinator and unit-based nursing educators can work to develop and implement an annual ECMO competency class. The competency class basic objectives include: ECMO physiology, equipment safety, patient safety, cannula(s) care, resource management, and emergency patient management.

A standardized education curriculum for support staff will promote a multidisciplinary education model. Participants may include delegates from all specialty areas including: rehabilitation specialists, blood bank, pharmacy, laboratory services, and biomedical engineering. This education will help support staff anticipate the needs of these complex patients, and improve communication between disciplines.

Working collaboratively and communicating effectively are essential aspects in care to ensure patient safety. Bedside nurses must communicate the needs of their ECMO patients clearly and efficiently. A clear communication algorithm can help quickly identify resources to assist in providing care in an emergency situation. The nurses are the eyes and ears for the care team and will need to be calm in their approach to managing a crisis situation. The essential role of the bedside nurse in a crisis situation is to assess the environment and then immediately communicate their needs to the designated resources. Effective, seamless communication is the key to providing high-quality care and achieving best outcomes.

12.3.1.1 Verifying ECMO Clinical Competence

The institutional ECMO program guidelines should include the means to verify ECMO competency. ECMO clinical competence can be assessed in a clinical setting and/or simulation environment. This assessment and verification is best performed by institutional ECMO content experts (director, coordinator, or specialist). An objective evaluation of performance and defined metrics for clinical competence is required in the process of verifying clinical competence. Objectives can be outlined in the institutional policies and procedures or guidelines.

When assessing clinical competence, there are three skills to consider: cognitive, technical, and behavioral. Cognitive objectives help assess the critical thinking and

clinical reasoning of the participants. In nursing, critical thinking for clinical decision-making is the ability to think in a systematic and logical manner with openness to question and to reflect on the reasoning process used to ensure safe nursing practice and quality care [6]. Designated ECMO complications can be performed in a simulation environment, and cognitive behaviors can be assessed by the content expert to determine if critical thinking and clinical reasoning were adequately performed. Bedside nurses can benefit from this simulation exercise. Emergency response times and critical thinking of the bedside nurse can be assessed and measured based on desired behaviors and performance standards.

Technical objectives help assess the everyday physical components needed to perform ECMO procedures whether acute or nonacute. Technical skills can be assessed in a simulation environment. ECMO problems or procedures can be simulated, and content experts can observe the competency of a participant throughout the process. It is important for the learner to "know" the information, and they must also "know how" to take action and perform the skill in emergency situations. In order to engage participants, the content expert must create a simulation environment that closely matches the clinical environment. This effort to create a realistic scenario will test the technical knowledge of the participant. Bedside nurses will benefit from performing in this environment. The learner can be assessed in both standard nursing practices of patients on ECMO, as well as in ECMO emergencies.

Behavioral objectives help assess the communication techniques with individuals and teams [1]. Effective communication among individuals and teams can be observed in a simulation environment. Patient safety and quality of care are influenced by effective interprofessional communication. Competency in communication is a core clinical skill, which must be taught, tested, and practiced [7].

12.3.2 Maintaining Clinical Competence

It is recommended that ECMO centers establish institutional policies, procedures, and guidelines that are consistent with ELSO recommendations. ELSO recognizes that there are differences in regional and institutional regulations concerning policies and procedures that will result in variations from these recommendations [1]. It is recommended that policies and procedures cover the topics of ECMO indications, cannulation, initiation, patient management, decannulation, anticoagulation, emergency procedures, ECMO transport, equipment maintenance, training, and education. For the purposes of this section, we will be focusing on the policies, procedures, and guidelines surrounding ECMO continuing education and training.

Policies, procedures, and guidelines should describe the continuing education of the ECMO-trained staff. Appendix 12.3 is a sample of an ECMO specialist annual competency checklist. Subjects to be addressed include: formal team meetings, water drills/ECMO simulations, annual examination, and a minimum number of hours of direct ECMO patient care [8]. Formal team meetings can

include case reviews, debriefings, updates on ECMO therapy, quality assurance review, policy and procedure review, and administrative information. These processes are organized and supervised by the ECMO program director, ECMO coordinator, and/or ECMO Steering Committee. Attendance and participation of the multidisciplinary ECMO staff in these continuing education activities should be strongly encouraged. The frequency of these meetings will be based on the volume of the ECMO center and the size of the ECMO team. The monitoring and documentation of the multidisciplinary ECMO staff's attendance and defining the number of meeting attendances required for recertification as an ECMO practitioner are recommended.

12.3.2.1 Water Drills

Water drills and/or ECMO simulation participation is recommended to occur at a minimum of every 6 months. Water drills utilize fluid-filled ECMO circuits that can run in a practice setting, so that ECMO staff can practice hands-on interaction with the circuit. A basic session is a time to reinforce the functions of the ECMO circuit and ability to perform circuit checks, titrate ECMO pump flow, and sweep gas flow. If pressure monitoring is utilized, practice of zeroing and flushing transducers can be performed. Advanced sessions include a review of all possible circuit emergencies with practice of appropriate interventions. Each ECMO trainee should be able to describe the function of each ECMO circuit component and conceptually demonstrate component changes that meet the designated objectives.

12.3.2.2 High-Fidelity Simulations

High-fidelity simulation is a widely accepted educational forum for ECMO training and can be an adjunct to other "hands-on" skill sessions. High-fidelity simulation utilizes specialized manikins and software platforms to provide an interactive educational forum that can closely mimic clinical situations with emphasis on the fidelity of the ECMO circuit. Special effort must be applied to creating a functional ECMO circuit that can be manipulated to demonstrate ECMO emergencies. This function can be combined with the manikin and monitoring software to create a highly realistic environment where ECMO staff responds to ECMO problems. This can be done through advanced perfusion-based mannequins like the Orpheus Perfusion Simulator or other computer-assisted simulators. High-fidelity simulation enhances learning by providing immediate feedback, allowing repetitive practice, increasing level of difficulty with attainment of skills, addressing multiple forms of learner strategies, and permitting clinical variation in learner responses [9]. The number of simulation hours to be performed by an ECMO staff to maintain annual recertification is defined in the institution's policy and procedures.

Although there are benefits to commercial simulators, institutions can also create their own low-cost models. A standard mannequin can be used with standard

hemodynamic monitoring equipment. A simple fluid-filled reservoir can be used to manipulate ECMO circuit pressures, while the operator manipulates the simulated patient hemodynamics. The Hanuola ECMO Program of Hawaii has developed videos to demonstrate how ECMO simulation can be easily performed using standard ICU equipment and ECMO circuit [10].

12.3.2.3 Animal Labs

Animal lab sessions are an excellent adjunct to water drill simulations if institutions have such access to a vivarium. Animal labs are performed in accordance with institutional animal care guidelines. Animal labs focus more on the ECMO management of the patient and can provide learning through the practice of blood sampling, blood product administration, and medication administration. The impact of ECMO pump flow, sweep gas flow, and heparin management can be assessed adequately in this environment. Policies and procedures should dictate the number of animal lab sessions required to achieve institutional recertification. The recommended time period for animal lab sessions is 24–72 h, with each ECMO trainee participating in 4–8 h sessions [1]. In the United States, animal labs have become increasingly difficult to perform due to cost, availability of approved facilities, and difficulty maintaining rigorous animal care guidelines.

12.3.2.4 Annual Examination

ECMO policies require the passing of an annual didactic examination that is used to verify the cognitive skills of all ECMO-trained staff. Results will need to be documented and recorded for quality assurance or audit review. Aside from the didactic examination, it is recommended that a performance evaluation be conducted for all ECMO-trained staff annually. This can be done by observing trainees responding to ECMO complications during either a water drill or simulation session.

12.3.2.5 Minimum ECMO Care Requirement

A minimum number of patient care hours by ECMO staff from all disciplines should be outlined in their policies (e.g., 12 h per quarter or 1.5 patients per quarter). If the designated institutional requirement has not been met, then retraining and attendance of water drills and simulation sessions are recommended. An institutional goal of a minimum support of six ECMO patients a year is recommended in order to maintain the clinical expertise necessary to adequately support such complex patients [3]. Policies and procedures should be updated upon specific practice changes and reviewed and revised at a minimum of every 2 years.

12.3.3 Quality Assurance and Quality Improvement

Ensuring quality is critical to the success of the ECMO program. ECMO leadership has the responsibility to continuously seek out opportunities to improve while monitoring outcome measures. ELSO membership is of paramount importance as it supports many quality assessment tools for centers to utilize. Each ELSO member institution receives collective international and center-specific data reports through the ELSO Registry [1]. The ELSO ECMO program's data includes the common problems reported by each center and the rate of occurrence. This data can be benchmarked for comparison with the international community of ELSO centers. Each year, ELSO designates centers from around the world with the unique distinction of a Center of Excellence.

> "The Excellence in Life Support Award recognizes ECMO programs worldwide that distinguish themselves by having processes, procedures and systems in place that promote excellence and exceptional care in ECMO. ELSO's goal is to recognize and honor ECMO programs who reach the highest level of performance, innovation, satisfaction and quality. A designated Center of Excellence has demonstrated extraordinary achievement in the following three categories: Excellence in promoting the mission, activities, and vision of ELSO; Excellence in patient care by using the highest quality measures, processes, and structures based upon evidence; and Excellence in training, education, collaboration, and communication that supports ELSO guidelines and contributes to a healing environment" [11].

The ability to provide high-quality and safe ECMO care takes the dedication of a comprehensive, multidisciplinary team. Administrative hospital support committed to providing access to continuing education is essential to maintain the clinical competence of a multidisciplinary team. Nursing plays an integral role on the ECMO team regardless of the utilized staffing model. Aside from acquiring and maintaining appropriate licensure, nurses must ensure both initial and ongoing clinical competence. According to Whitaker, Winifred, and Smolenski [12], "The Joint Commission on Accreditation of Healthcare Organizations (JCAHO) requires hospitals to assess the competency of employees when hired and then regularly throughout employment." ECMO nurses have the professional responsibility to maintain their competency in the management of ECMO patients. Institutional resources are required to provide education to ensure that quality and safety remain the focus of all ECMO team members.

12.4 Appendix 12.1: Institutional ECMO Physician Credentialing Guideline

12.4.1 Surgical and Medical Services

Clinical privileges for Extracorporeal Membrane Oxygenation (ECMO) resource physician

Supplemental hospital privileges for neonatal care and pediatric intensive care, prescribing ECMO physician

12.4.1.1 Extracorporeal Membrane Oxygenation (ECMO) Resource Physician

The ECMO resource physician and ICU attending physician will jointly determine the candidacy of the patient for ECMO support. All decisions to offer ECMO support to a candidate will be a two-physician decision. If a consensus cannot be reached, the ECMO program director or designee will be contacted to determine eligibility.

These credentials allow the ECMO resource physician to coordinate the services of the ECMO team with the intensive care teams. Privileges include the evaluation and selection of patients for ECMO, oversight of the cannulation and decannulation process, management of the extracorporeal life support circuit and patient, and provision of routine and emergency care to patients on ECMO. The minimum clinical training and/or experience required to apply for this privilege is as follows:

I. Initial privilege eligibility criteria

A. ECMO training and experience as attending physician or fellow in established ECMO program within 1 year of appointment to <*institution*>

1. Recommendation from <*institution*> Critical Care ECMO director
2. Reference letter from ECMO program director which specifically addresses the candidate's ability to select patients for ECMO support, oversee the cannulation and decannulation process, and manage both routine ECMO care and emergencies
3. Must complete <*institution*> review course with ECMO coordinator to review <*institution*> equipment, procedures, and policies
4. Completion requires passing scores on the written examination and simulation exercises

B. If ECMO training and experience as attending physician or fellow in established ECMO program greater than 1 year of appointment to <*institution*>

1. Recommendation from <*institution*> Critical Care ECMO director; and
2. Must complete full <*institution*> training course
3. Completion requires passing scores on the written examination and simulation exercises

C. ECMO Morbidity and Mortality (M&M)

Once ECMO Resource Physician credentialing is granted, a presentation at an ECMO M&M of an ECMO case that the individual has been involved will be scheduled in the first year of appointment via the ECLS coordinators or designee

II. Reappointment eligibility guidelines

A. Maintenance of clinical competency

1. Participate in supervised cannulation and decannulation of four patients within a 2-year period.

2. Demonstrate competent patient management for four patients within a 2-year period.
3. Completion requires concurrence of the ECMO program director. Patient management and cannulation/decannulation supervision may be met by involvement with different patients.

B. Maintenance of CME is required by completion of one of the routes described

1. Attendance of at least 75% of ECMO case debriefings (includes M&M) within a 1-year period.
2. Participation in an ECLS CME activity such as an ECMO training, annual ELSO conference, Keystone ECLS conference, other accredited ECLS activity or similar, every 3 years. CME credit documentation will be submitted at recredentialing.

C. If the number of ECMO cases does not meet the minimum volume per year, the ECMO program director may extend the time period under consideration

12.4.1.2 Prescribing ECMO Clinician (MD, Advance Practice Nurse)

Supplemental privilege for intensive care hospital privileges. Privileges to provide routine and emergency clinical care for the patient on extracorporeal life support (ECLS).

The minimum clinical training and/or experience required to apply for this privilege is as follows:

I. Initial Privilege Eligibility Criteria

A. Track 1

1. Completion of the full ECMO training course
2. Completion requires passing scores on the written examination and simulation exercises

B. Track 2

1. Completion of an alternate ECMO training course approved by ECMO program director
2. Completion of review course with ECMO coordinator to review equipment, procedures, and policies

3. Completion requires passing scores on the written examination and simulation exercises

Supervision Requirements

A. Maintenance of Clinical Competency

1. Demonstrate competent patient management for four patients within a 2-year period.
2. Completion requires concurrence of the ECMO program director. Patient management supervision may be met by involvement with different patients.

II. Reappointment Eligibility Guidelines

1. Maintenance of CME is required by attending at least 25% of ECMO case debriefings (including M&M) within a 1-year period.

12.5 Appendix 12.2: Training and Continuing Education for ECMO Specialists

12.5.1 Purpose

To establish guidelines for the training and continuing education for ECMO specialists. The criteria to maintain competency will be maintained by the ECMO coordinator and will be followed as outlined by the extracorporeal life support organization (ELSO).

ECMO specialists will undergo the technical training needed to manage the ECMO system and the clinical needs of the patient on ECMO. Upon completion of the required training, a competency assessment tool will be completed for each ECMO specialist.

12.5.2 Procedure

Didactic Course

1. A new ECMO specialist will attend the didactic course for ECMO, which will include the following:

   - Introduction to ECMO
   - Physiology of the diseases treated with ECMO
   - Pre-ECMO procedures
   - Criteria and contraindications for ECMO
   - Physiology of coagulation
   - ECMO equipment
   - Physiology of venoarterial and venovenous ECMO
   - Daily patient and circuit management on ECMO
   - Emergencies and complications during ECMO
   - Management of complex ECMO cases
   - Weaning from ECMO (techniques and complications)
   - Decannulation procedures
   - Post-ECMO complications
   - Short-term and long-term development outcome of ECMO patients
   - Ethical and social issues

Water lab or ECMO simulation sessions:

1. Sessions will allow each individual hands-on experience
2. Sessions will provide the specialist with a full understanding of all possible circuit emergencies, and the appropriate intervention should be accomplished by the end of the session
3. Emergency management (simulated)
4. The basic water lab session will consist of the following:

   - Review of circuit configuration and function (roller pump/centrifugal pump)
   - Circuit setup and priming techniques
   - Access and sample ports to the circuit
   - Pigtail and stopcock changes
   - The basic circuit check
   - Equipment components

Emergency water lab or ECMO simulation sessions (roller/centrifugal pumps)

1. Emergency exercise sessions will consist of simulation training in the management of

   - Circuit changeout
   - Handling of venous/arterial air
   - Power failure
   - Equipment failure
   - Emergent initiation of ECMO
   - Inadvertent decannulation
   - Loss of venous return
   - Raceway rupture (roller pump)
   - Pump motorhead replacement (centrifugal pump)

Evaluation and institutional certification of the ECMO specialist

1. Written Evaluation: Each specialist will have on record a checklist of their skills and competencies during all sessions of the ECMO training course, including course attendance, water lab sessions, and examinations.
2. Certification Exam: A certification exam will be given to each ECMO specialist after the didactic course and at the time of their performance evaluation. A certification exam will be given after the basic and emergency water lab sessions. A predetermined passing level will be established.
3. Institutional Certification: Institutional certification of ECMO specialists will be granted after successful completion of the ECMO training course (didactic, basic and emergency water labs, and bedside training) and successfully passing the written exams. The ECMO Assessment Competency will need to be completed between the ECMO specialist and the ECMO coordinator

Annual recertification after initial course:

1. Forty hours of clinical time on pump or 12 h of wet labs or ECMO simulation training
2. Completion of annual skills assessment and/or appropriate clinical experience
3. Four ECMO simulations and/or appropriate clinical experience
4. Completed certification exam
5. Satisfactory evaluation by ECMO program coordinator

Appendix 12.3: ECMO Specialist Annual Competency Checklist

ECMO Skills Assessment

Extracorporeal membrane oxygenation (ECMO) is a technique for providing life support in the ICU using an adaptation of conventional cardiopulmonary bypass technology. ECMO specialists are specially trained clinicians who monitor and maintain ECMO circuit and patient hemodynamic parameters.

Participants

- Registered nurses
- Respiratory therapists
- Perfusionists
- Physicians
- Advance practice nurses/physician assistants

Objectives

- Describe functions of all circuit components
  - Cannula (VV vs. VA)
  - Transducers (P1-P2 and gradient)
  - Bridge
  - SVO_2 monitor
  - Centrifugal pump/roller pump
  - Access ports (meds/labs)
  - Oxygenator (vent, exhaust, sighing)
  - Heater
  - Sweep flow meters
  - Continuous blood gas monitor

- Demonstrate navigation through menu options
- Perform transducer calibration
- Describe and demonstrate specialist responsibilities
- Perform full ECMO circuit check
- Describe and demonstrate procedures for circuit component changes
  - Stopcocks, pigtails, connectors, oxygenator
- Describe and demonstrate emergency procedures
- Describe and demonstrate blood gas management
- Perform simulated lab draws using aseptic technique
- Describe and demonstrate technique for blood product and volume administration
- Heparin infusion management and heparin pump manipulation

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