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Basics of Extracorporeal Membrane Oxygenation

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KEYWORDS

• ECMO • Respiratory failure • Cardiac failure • ARDS • Cardiogenic shock
• Lung-protective ventilation

KEY POINTS

- Understand the use of extracorporeal membrane oxygenation (ECMO) and patients that may benefit from this treatment.
- Discuss the components of ECMO and how it provides respiratory and cardiac support.
- Review management strategies for patients requiring ECMO support.
- Discuss weaning and discontinuation from ECMO support.

Video content accompanies this article at http://www.surgical.theclinics.com.

HISTORY OF EXTRACORPOREAL MEMBRANE OXYGENATION

Extracorporeal life support is the ability to supplement native pulmonary and/or cardiac function in the setting of native system failure. Development of modern extracorporeal life support devices began with the invention of the cardiopulmonary bypass (CPB) circuit by John Gibbon, successfully used in cardiac surgery for the first time in 1953 when extracorporeal support was used to repair an atrial septal defect in an 18-year-old patient.[1] Soon after, bubble oxygenators were invented by C. Walton Lillehei, MD and Richard DeWall. However, these early bubble oxygenators caused significant hemolysis thus limiting the use of a bubble oxygenator for prolonged gas exchange.[2] The development of silicone in 1957, a rubber material that allows for efficient gas exchange, led to the development of the "membrane oxygenator" and the coined phrase 'extracorporeal membrane oxygenation' (ECMO). This, along with the recognition that ECMO required continuous anticoagulation allowed for prolonged extracorporeal support to become a reality.[3]

The first successful use of ECMO in the ICU was reported in a 24-year-old trauma patient who was cannulated due to posttraumatic ARDS.[4] Modern ECMOs roots,

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however, are in neonatal critical care whereby Dr Robert Bartlett pioneered its use in pediatric cardiopulmonary failure and published the first randomized controlled trial comparing ECMO to standard care in 1985.[5] ECMO became more ubiquitous in the late 2000s during the H1NI influenza epidemic as ECMO was used successfully in many patients for treatment of ARDS. Since that time, ECMO utilization has expanded globally and thus clinicians in the critical care realm must possess a basic understanding of indications, contraindications, and complications of ECMO support.

COMPONENTS OF THE EXTRACORPOREAL MEMBRANE OXYGENATION CIRCUIT

Veno-venous (VV) or veno-arterial (VA) ECMO requires the drainage of deoxygenated blood from the venous system, moving it across a membrane oxygenator that removes carbon dioxide (CO_2), replenishes oxygen, and returns oxygenated blood back to the patient's venous or arterial system depending on the use of VV or VA, respectively. This process is facilitated by a simple system of cannulas, a blood pump, a nonmicroporous polymethylpentene oxygenator, and a heat exchanger.[6]

Multiple brands of pumps are commercially available. All are centrifugal pumps and provide an efficient flow for ECMO support. To provide oxygenation and ventilation for the patient, all ECMO circuits have an oxygen supply (Fio_2) and "sweep gas" flowmeters in line with the circuit. (**Fig. 1**) This oxygen flow will be the source of oxygen used for gas exchange in the membrane lung. The sweep gas allows for the removal of CO_2 in an efficient manner and allows low tidal volume ventilation and lung rest to allow for patient recovery. Lung-protective ventilation strategies are paramount to lung recovery and full utilization of ECMO can help facilitate recovery. (**Fig. 2**)

VENO-VENOUS EXTRACORPOREAL MEMBRANE OXYGENATION

Indications and Overview

Veno-venous extracorporeal membrane oxygenation (VV-ECMO) is indicated in primary respiratory failure that is refractory to conventional medical therapy and mechanical ventilation.[7](**Box 1**) Many candidates will have failed use of deep sedation, paralytics, prone position, inhaled pulmonary vasodilators, and diuretics.[7]

The primary goal of supporting a patient with VV-ECMO is to promote lung rest via lung-protective ventilation.[8,9] Lung-protective ventilation aims to decrease the incidence and severity of ventilator-induced lung injury (VILI) associated triggers such as volutrauma, barotrauma, atelectrauma, and biotrauma.[8] The advent of currently accepted lung-protective ventilation strategies arose from the recognition in animal

Fig. 1. Examples of (*A*) membrane lung, (*B*) flowmeters for oxygen deliver and "sweep gas" regulation, and (*C*) ECMO pump device.

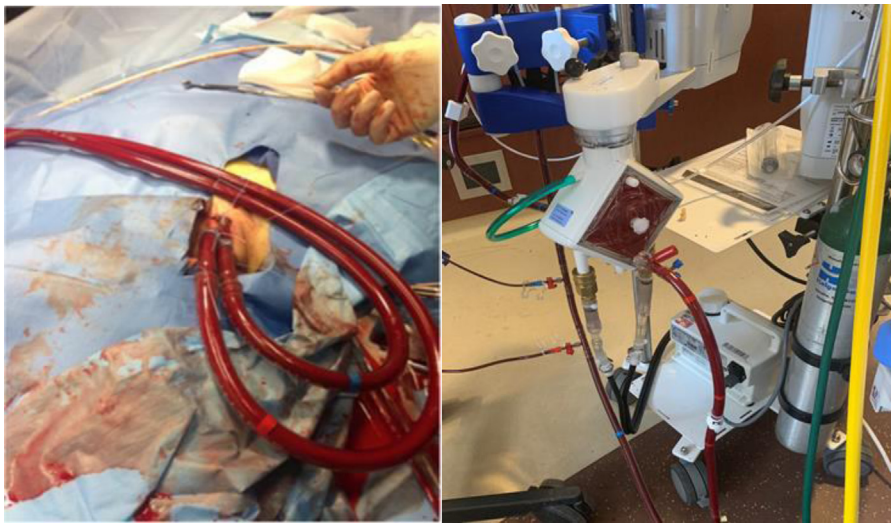

Fig. 2. Picture on the left showing completed dual lumen cannula in the RIJ with deoxygenated and oxygenated blood shown. Picture on the right showing a complete ECMO circuit with oxygen and medical-grade air connected to the flowmeters to control Fio_2 and sweep gas flows. Tubing can be seen connected to the membrane oxygenator.

models of acute lung injury, large tidal volumes (V_t) lead to lung endothelial, and epithelial disruption resulting in inflammation, atelectasis, hypoxemia, and inflammatory mediator release.[10] Brower and colleagues[10] first recommended the use of lower V_t in patients with acute lung injury/ARDS after finding significantly reduced mortality and increased ventilator-free days in patients treated with lower V_t than traditionally accepted volumes of 10 to 15 mL/kg. The decrease in stretch-induced lung injury thought to be occurring with lower V_t was supported by finding significantly decreased levels of the inflammatory mediatory interleukin-6 (IL-6) in these patients, suggesting that lower V_t led to decreased lung inflammation, contributing to their improved clinical outcomes. Later meta-analysis and Cochrane Reviews have provided further support using lung-protective ventilation with lower V_t (~7 mL/kg ideal body weight) and plateau pressures less than 30 cm H_2O, resulting in lower 28-day mortality and morbidity by avoiding VILI.[11,12]

Box 1 **Indications for VV ECMO[8,9]**
Acute respiratory distress syndrome (ARDS)
Bronchopleural fistula
Status asthmaticus
Bridge to lung transplant
Refractory viral/bacterial pneumonia
Acute lung injury
Refractory hypoxia/hypercarbia

Lung-protective ventilation strategies have been shown to improve outcomes and perhaps prevent progression to ARDS in patients without preexisting ARDS.[12] By using lung-protective ventilation strategies during VV-ECMO runs, VILI can be minimized, facilitating earlier ventilator weaning, liberation, and mobilization of patients with VV-ECMO, decreasing the likelihood of multiorgan dysfunction and decreasing mortality.[8,13]

Patient Selection

Patients being considered for cannulation onto VV-ECMO, or any form of ECLS, should be thoroughly investigated to rule out irreversible disease processes that would contraindicate the use of ECMO(**Box 2**). Echocardiography should be obtained before cannulation to rule-out cardiac etiologies of respiratory failure and to ensure near-normal cardiac function as VV-ECMO is dependent on the patient's cardiovascular system to maintain pulmonary and systemic perfusion.[7,8] If evidence of severe cardiac dysfunction is present, veno-arterial extracorporeal oxygenation (VA-ECMO) should be considered. Approximately 10% of patients with primary respiratory failure will develop right ventricular (RV) dysfunction secondary to hypoxemia, hypercarbia, and acidosis in ARDS.[14] Patients with RV dysfunction can oftentimes be managed with inotropes, pulmonary vasodilators, diuretics, and optimization of their acid/base status to reduce RV afterload and promote gas exchange without the need for VA-ECMO. In some patients requiring multiple inotropic/vasoactive medications before cannulation, VV-ECMO may not lead to worse outcomes or increased complication rates with some authors suggesting that VA-ECMO being reserved for patients with refractory hypotension after VV-ECMO cannulation.[15]

Clinicians evaluating a patient for possible VV-ECMO cannulation, or treating an already cannulated patient, can use the respiratory ECMO survival prediction (RESP) score to assist with predicting survival (respscore.com) Given that VV-ECMO is a scarce medical resource, labor-intensive, and expensive tool for health care systems, the use of a validated predictive mortality model may assist clinicians better allocate these resources and create risk/benefit benchmarks.[16] (**Table 1**) Although the RESP score can aid in predicting survival in patients with adult respiratory failure requiring ECMO, it should not replace bedside clinical decision making or be the sole determinant of whether or not to use ECMO.[1]

Cannulation and Cannula Selection

Two cannulas are required to perform ECMO: an inflow and outflow cannula. The cannulae are named based on relation to the blood pump. That is, blood flowing from the patient to the blood pump is via the inflow cannula and blood returning

Box 2
Contraindications to VV ECMO

- Overwhelming sepsis/septic shock
- Multi-system organ failure
- End-stage chronic disease (ie, end-stage COPD)
- Nonsurvivable neurologic injury
- Advanced malignancy diagnosis
- Eldery over the age of 70
- Family refusal

Table 1
RESP score criteria and their associated points

	RESP Score Criteria[a]		
Age	18–49 (0)	50–59 (−2)	>60 (−3)
Immunocompromised status	No (0)	Yes (−2)	
Mechanically ventilated before ECMO initiated	>7 d (0)	48 h - 7 d (+1)	<48 h (+3)
Diagnosis	Viral pneumonia (+3)		
	Bacterial pneumonia (+3)		
	Asthma (+11)		
	Trauma or burn (+3)		
	Aspiration pneumonitis (+5)		
	Other acute respiratory diagnoses (+1)		
	Nonrespiratory or chronic respiratory diagnosis (0)		
History of CNS dysfunction	No (0)	Yes (−7)	
Acute associated nonpulmonary infection	No (0)	Yes (−3)	
Neuromuscular blockade before ECMO	No (0)	Yes (+1)	
Nitric oxide before ECMO	No (0)	Yes (−1)	
Bicarbonate infusion before ECMO	No (0)	Yes (−2)	
Cardiac arrest before ECMO	No (0)	Yes (−2)	
$Paco_2$ >75 mm Hg	No (0)	Yes (−1)	
Peak inspiratory pressure >42 cm H2O	No (0)	Yes (−1)	

[a] *Adopted from* www.respscore.com.

from the blood pump to the patient is via the outflow cannula. It should be noted that cannula nomenclature can be institutionally dependent.

VV-ECMO cannulation can be performed in multiple settings including emergency rooms, ICUs, ORs, and cardiac cath laboratories. Most VV-ECMO cannulations are performed percutaneously via Seldinger or modified Seldinger techniques.[8] Before cannulation, the patient's airway should be secured, arterial access should be obtained for hemodynamic management, and central venous access should be obtained, preferentially sparing the right internal jugular vein (RIJ) as this may be used for outflow cannula placement.[7] Cannula placement is typically confirmed under echocardiographic or radiographic image guidance. (**Fig. 3**)

Anatomic site of cannulation for VV-ECMO is primarily dictated by the patient's clinical stability, mode of ECMO to be used, and the experience of the treating team. A common cannulation strategy for VV-ECMO is a femoral-RIJ approach whereby the inflow cannula is placed in the femoral vein with its tip inferior to the RA-IVC junction and the outflow cannula is placed in the RIJ with its tip at the SVC-RA junction.[17] Another cannulation configuration is femoral-femoral whereby an inflow cannula is placed distal to the RA-IVC junction and the outflow cannula is placed in the opposite femoral vein with the cannula positioned at the SVC-RA junction. A femoral-femoral strategy can be more prone to recirculation whereby oxygenated blood being returned to the patient does not enter the pulmonary circulation but is immediately drained back into the ECMO circuit through the inflow cannula.[17,18] If this configuration is selected,

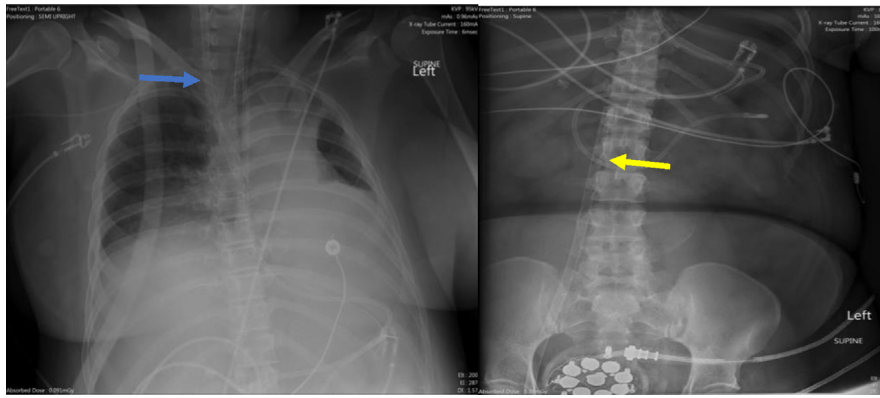

Fig. 3. Chest and abdominal radiographs showing appropriate cannula placement. Outflow cannula in the image on left noted by blue arrow and inflow cannula in image on right noted by yellow arrow.

the inflow cannula should be secured at approximately the level of the diaphragm or lower to prevent recirculation.

Alternatively, a single dual-lumen cannula approach with cannulation of the right IJ vein may accommodate faster ventilator weaning, liberation, decreased risk of groin site infections, and ultimately mobilization of a patient requiring VV-ECMO. A commonly used dual lumen device is the Avalon Elite (Maquet, Germany), sized 16 to 31 Fr. Additionally, this approach reduces the likelihood of recirculation, particularly at higher ECMO flow rates.[19]

Selecting appropriately sized cannulas for both inflow and outflow is vital to maintain adequate flows and provide sufficient support to the patient. To facilitate adequate oxygen saturation on VV-ECMO, flow rates of approximately 60 to 80 mL/kg should be targeted.[17] Determinants of achieving blood flow targets include cannula size, hemoglobin level, Fio_2 of the circuit, ECMO flow (L/min) relative to native cardiac output, metabolic demands, and the degree of recirculation occurring.[20] CO_2 removal alone requires approximately 20% of the flow required for oxygenation.

Maintenance and Complications

Caring for a patient on VV-ECMO requires a team composed of physicians, surgeons, respiratory therapists, nurses, perfusionists, pharmacists, nutritionists, and other personnel. All play a key role in maintaining safety and optimal function of the ECMO circuit.[20] Patients with VV-ECMO support should be monitored by many variables including ventilatory settings and pressures, arterial blood pressure monitoring, central venous pressures, and frequent laboratories including arterial blood gases to make adjustments to sweep gas flows and/or ECMO flows. Based on arterial blood gas findings, changes can be made to correct issues with oxygenation and ventilation and not require changes to the ventilator that may result in further mechanical damage to the lungs from mechanical ventilation. If hypercarbia and resultant respiratory acidosis are encountered, the sweep gas flow can be increased to eliminate more CO_2 through the membrane oxygenator. If hypoxemia is the issue, then increasing the flow on ECMO, administration of blood, or increasing Fio_2 on the ventilator can be tried to correct the hypoxemia. Issues resulting in refractory hypoxemia on VV ECMO such as recirculation will be discussed later in this article.

Complications during treatment with mechanical support are often either medical or mechanical in nature. In a systematic review of studies examining VV-ECMO used in ARDS by Vaquer and colleagues[21] (2017), medical complications were found to occur in 40.2% of patients with bleeding being the most common (29.3%). Complications involving mechanical support circuits including inflow/outflow cannula and the oxygenator occurred in 10.9% of patients with 12.8% of them requiring oxygenator replacement during their treatment period.

Recognizing evolving complications through constant communication with clinical staff and physical examination of the patient and ECMO circuit is essential. As mentioned, recirculation is a common problem encountered during VV-ECMO. Its classic presentation includes refractory hypoxemia and high pre-oxygenator oxygen saturation (SpreO2). Although multiple factors can affect recirculation percentage, greater separation of inflow, and outflow cannulae tips should be performed if a two-site cannulation strategy is used to reduce recirculation. If the cannula's tips cannot be further separated, either switching to a single dual lumen catheter or addition of an additional venous drainage catheter can be performed.[20,22]

When native cardiac output exceeds the flow rate of the ECMO circuit, mixing of deoxygenated blood with oxygenated blood returning from the ECMO circuit occurs, potentially leading to poor systemic oxygenation and low SaO2. To maintain SpO2 greater than 88%, it is recommended for ECMO flows to be at least 60% of total systemic flow.[23] The most common etiology of increased cardiac output during treatment with ECMO is sepsis, with approximately 13.5% of patients with adult VV-ECMO developing antimicrobial-resistant bloodstream infections.[24] In addition to organic pathologies, iatrogenic supra-normal cardiac output due to inadequate sedation or analgesia should be avoided.

ECMO circuit components are prone to failure including the cannulas, blood pump, membrane oxygenator, and other tubing. They must be continually assessed by both clinicians and other ancillary bedside providers.

The inflow cannula can commonly vibrate or "chatter". This is due to high negative pressures in the inflow cannula due to collapse of the vein around the cannula and vibrations within the tubing to occur. (Video 1) A common etiology of this is hypovolemia that can be corrected with the administration of either colloid or crystalloid solution.

Membrane oxygenator failure is due to either oxygen supply failure or thrombus formation.[20] After ensuring that oxygen supply is intact, findings suggestive of thrombus formation include direct visualization of thrombus, particularly on the preoxygenator side of the membrane along with a large pressure gradient across the membrane (normal gradient is < 50 mm Hg).[25]

Complications from bleeding account for a large majority of morbidity and mortality during ECMO. Maintaining circuit patency while preventing thromboembolic complications with systemic anticoagulation can be challenging. Absolute anticoagulation strategies for VV-ECMO do not yet exist.[26] Anticoagulation with systemic heparin is typically initiated at the time of cannulation and monitored with serial activated clotting time (ACT), activated partial thromboplastin time (aPTT), anti-factor Xa (aXa) assays, and thromboelastography (TEG). Monitoring approaches are oftentimes institutionally dependent, with aPTT being the predominately monitored laboratory value. However, concordance between monitoring techniques should be seen regardless. If contraindication to anticoagulation develops or is present from the time of cannulation, VV-ECMO may be performed without anticoagulation, though flows should be at least 3.5 L/min[20,27,28]

Weaning Veno-Venous-Extracorporeal Membrane Oxygenation

ECMO support should be discontinued as soon as safe to do so. Determining the optimal time to decannulate is not well described or protocolized and is oftentimes institutional and provider dependent. In general, once native lung function has improved to the point that ECMO sweep gas flow can be reduced to minimal allowed settings and the patient's V_t, respiratory rate, peak pressures, and plateau pressures are acceptable, the patient can be decannulated and supported with mechanical ventilation until extubation is deemed appropriate.

VENO-ARTERIAL EXTRACORPOREAL MEMBRANE OXYGENATION

Indications and Overview

VA-ECMO provides not only the gas exchange capabilities of VV-ECMO but also provides mechanical circulatory support, in parallel to native cardiac function, in the setting of either isolated cardiac failure or combined cardiopulmonary failure.[29] The components of the VA-ECMO circuit are similar to VV-ECMO. The difference is that the outflow cannula is placed into an artery to provide circulatory support to the patient. Cannulation for VA-ECMO can either be central or peripheral. Central cannulation, whereby a venous inflow cannula is placed in the right atrium and the outflow cannula is placed in the ascending aorta, primarily occurs postcardiotomy in patients who are failing to wean from CPB despite high dose inotropic and vasopressor support.[17] These patients often have preexisting heart failure, incomplete revascularization, poor intraoperative myocardial protection, or underwent a technically difficult surgery.[30] Peripheral cannulation for cardiogenic shock and cardiac arrest is commonly accomplished by placing a venous inflow cannula in either a femoral vein or the right IJ vein and placing an arterial outflow cannula in either the femoral artery or grafting it onto the right subclavian or axillary artery.[7]

Patient Selection

Rao and colleagues outline 5 considerations that should be made before offering VA-ECMO to a patient: (I) the indication, (II) the cannulation strategy, (III) LV distension/venting strategy, (IV) distal limb ischemia/perfusion strategy, and (V) exit strategy.[29] Indications for initiation of VA-ECMO are listed in **Box 3**. However, there are currently no society-endorsed evidence-based guidelines for which patients are most likely to benefit from VA-ECMO.[29,31]

Mortality among patients with VA-ECMO is 50% to 60% and 6-month survivorship as low as 30%.[32] Vetting candidates for VA-ECMO cannulation is thus of the utmost importance. Similar to VV-ECMO, irreversible disease processes should be ruled out before cannulation and echocardiography should be obtained to characterize the cardiac pathology. Echocardiographic studies should ensure that no greater than mild aortic insufficiency is present due to increased risk of severe left ventricular (LV) distension. Large bore central venous access along with an arterial line should be placed before cannulation for hemodynamic monitoring and fluid or blood product administration. Similar to the RESP score, the survival after veno-arterial ECMO (SAVE) score may be used before cannulation in attempting to predict survival in refractory cardiogenic shock requiring VA-ECMO therapy.[33]

Cannulation

Central cannulation is primarily performed when a patient fails to wean from CPB. The preexisting venous and arterial cannulas placed for CPB are often used for VA-ECMO initiation, eliminating the need for additional cannula placement. Disadvantages of

Box 3
Indications for VA ECMO

- Acute chronic heart failure
- Acute heart failure secondary to myocarditis
- Massive pulmonary embolism
- Mediastinal mass
- Refractory cardiogenic shock
- Refractory ventricular tachycardia
- Postcardiotomy shock
- Hypothermia
- Cardiac arrest with ongoing CPR (ECPR)

central cannulation include the need to reenter the chest for decannulation, increasing patients' risk of bleeding and infection, and inability to extubate while cannulated, limiting the potential for early mobilization.[2,34] Upper-body peripheral cannulation via arterial cannulation of the subclavian, innominate, or axillary arteries with an end-to-side Dacron graft, may offer the physiologic advantages of central cannulation including decreased potential for LV distension and decreased risk of cerebral hypoxemia but still allow for early extubation and mobilization.[17,35] Although peripheral cannulation via a femoral artery and vein is the most common cannulation strategy, it is not without significant risk including femoral artery occlusion, distal limb ischemia, compartment syndrome, and upper body hypoperfusion.[36]

Appropriate cannula sizing should accommodate the equivalent cardiac index of 2.2 to 2.5 L/m^2/min, considered full flow VA-ECMO.[17] Venous cannulas are typically 19 to 25 Fr although arterial cannulas are 15 to 24 Fr.

Maintenance and Complications

Special considerations for VA-ECMO include the risk of LV distension and pulmonary edema, ensuring adequate distal perfusion of the arterial cannulated leg, Harlequin syndrome, and anticoagulation requirements. Identification of LV distension is essential to promoting myocardial recovery, preventing blood stasis within the LV, and optimizing the patient for weaning.[29,31] Bedside recognition of LV distension may be accomplished in several ways. First, ensuring that the aortic valve is opening can be accomplished with an arterial line tracing, bearing in mind that as ECMO flows increase, the MAP will also increase and lead to lower pulse pressure and stroke volume.[29] Ideally, a right radial arterial line will have been placed to allow for both hemodynamic monitoring and to ensure adequate oxygenation of the right cerebral hemisphere and right arm; however, pulmonary edema due to new or worsening LV distention may be detected by progressively lower P_{O_2} values on the right radial arterial line.[29,37] Third, the presence of spontaneous echo contrast within the LV cavity likely suggests an increased risk of thrombus formation.[38] Lastly, serial chest x-rays may reveal pulmonary edema suggestive of LV distension; however, if chest radiographs alone are used for detection, one must rule out other etiologies of opacities and edema such as ARDS or infection. LV venting strategies include intra-aortic balloon pump (IABP), atrial septostomy, left atria to aortic cannula, and surgical or percutaneous venting with an Impella. Although the advantages and disadvantages

of each venting method are beyond the scope of this review, it should be acknowledged that there is not currently a standard-of-care LV venting practice.

Ensuring adequate perfusion to the arterial cannulated leg is paramount as lower extremity ischemia occurs in 12% to 22% of peripherally cannulated patients, potentially resulting in compartment syndrome requiring fasciotomy or amputation.[29,39] At the time of peripheral VA-ECMO cannulation, many centers place a 6 to 8 Fr distal perfusion cannula in either the common femoral or superficial femoral artery to provide antegrade flow distal to the arterial cannulation site. Limb ischemia may not only lead to patients needing additional surgery, it may also contribute to unsuccessful weaning of VA-ECMO and is an independent risk factor for in-hospital death.[40,41]

Given that peripherally cannulated VA-ECMO flow is retrograde, a watershed region, sometimes referred to as a "mixing cloud", of blood may form between the aortic root and the level of the diaphragm depending on the cardiac output relative to VA-ECMO flow.[42] The watershed region is the direct result of impaired pulmonary gas exchange leading to hypoxic blood being ejected by the LV mixing with the well-oxygenated ECMO blood flowing retrograde in the aorta. Higher LV output will push the watershed region more distal, closer to the diaphragm, whereas lower LV output will cause the watershed region to remain closer to the aortic root.[43] The threat posed by the watershed region is that of differential hypoxemia, otherwise known as Harlequin syndrome or North-South syndrome, whereby the upper body is at risk for hypoxic blood flow to the brain, heart, and upper extremities whereas the lower body will be well perfused from the ECMO circuit. Recognition of the phenomenon depends on serial right upper extremity arterial blood gas measurements and continuous cerebral oximetry trends. Treating underlying lung pathology, maximizing ventilator oxygenation support, venting the LV if indicated, and placing a Y-connector onto the arterial outflow cannula to deliver well-oxygenated blood to the venous system through an additional vein cannula (venous-arterial-venous ECMO) should all be considered in treating Harlequin syndrome.[29,44]

VA-ECMO is inherently proinflammatory leading to increased risk of pump thrombosis, oxygenator failure, or thromboembolic events.[45] The risk of thrombosis must be weighed against the risk of major bleeding as up to 27% of patients with VA-ECMO will suffer a major bleeding event, with or without systemic anticoagulation present.[45] Most institutions align with current ELSO recommendations to use unfractionated heparin with a targeted ACT goal of 180 to 220; however, anti-Xa assays are becoming standard of care and a mixed approach to evaluating anticoagulation goals may be best.[1]

Weaning Veno-Arterial-Extracorporeal Membrane Oxygenation

Attempts to wean VA-ECMO should occur as soon as signs of myocardial recovery are noted. However, all organ systems should be optimized, particularly the pulmonary system which will become responsible for gas exchange once ECMO support is discontinued.[31] Inotropic and vasopressor medications should be titrated to low doses, with room to increase, before weaning attempts. Hemodynamic monitors including right upper extremity arterial line and PA catheter should remain in place for perfusion indices to be trended, ensuring that adequate myocardial recovery has occurred to support the end-organs.[31,46] Though there is not a standard-of-care approach to weaning, an algorithmic, step-wise approach is advocated.[31,47] Many centers adopt a 3 step approach consisting of daily weaning studies followed by bedside assessment for decannulation and ultimately a formal turn-down study under TEE guidance for decannulation in the operating room. Fried and colleagues detail daily weaning attempts as incremental decreases in flow by 0.5 LPM to a minimum

of 2 LPM. If the patient's MAP does not fall more than 10 to 15 mm Hg and filling pressures do not significantly increase, the patient is allowed to flow at the lowest tolerated rate and hemodynamics are trended for 8 hours.[46] Daily weaning trials are often performed sequentially with serial TTE examinations as successful weaning is associated with an aortic VTI greater than 10 cm, LVEF greater than 20 to 25%, and lateral mitral annulus peak systolic velocity greater than 6 cm/s[48] Once a daily weaning trial is tolerated, a bedside assessment for decannulation is often performed by decreasing ECMO flow to 1 LPM and hemodynamics are assessed. If well tolerated, the patient may be scheduled for a formal ECMO turn down the study in the operating room whereby ECMO flows will be decreased and the cannulae clamped for 30 minutes, up to 4 hours.[1] If this is successful, the patient can be decannulated and this typically involves surgical repair of the arteriotomy site.

SUMMARY

The use of ECMO continues to increase in ICUs across the world and the indications for its use continue to expand. Further investigation into its use in otherwise contraindicated states such as sepsis is ongoing and may lead to improved outcomes in this high-risk category of patients. Other areas whereby ECMO is beginning to show potential for the treatment of patients is in the realm of traumatic injury and burn patients. With this ever-evolving and increasing footprint, knowledge of ECMO and its day-to-day maintenance is going to be important for any clinician who works in the field of critical care medicine.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found online at https://doi.org/10.1016/j.suc.2021.09.001.

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