Cardiac Support

Emphasis on Venoarterial ECMO

Christopher S. King, MD[a,*], Aviral Roy, MBBS[b], Liam Ryan, MD[c], Ramesh Singh, MD[c]

KEYWORDS

- Venoarterial extracorporeal membrane support • Cardiogenic shock
- Extracorporeal cardiopulmonary resuscitation • Pulmonary hypertension
- Pulmonary embolism

KEY POINTS

- Venoarterial extracorporeal membrane oxygenation (ECMO) can be used as a bridge to recovery or definitive therapy for several conditions, including cardiogenic shock, pulmonary embolism, intoxication or poisoning, and hypothermia.
- Important considerations when developing a cannulation strategy for venoarterial ECMO include cardiac and pulmonary function, need for mobilization, anticipated duration of support, and the urgency of the time to cannulation.
- Careful management of patients having venoarterial ECMO is required to minimize the risk of common complications, including limb ischemia, bleeding, infection, thrombosis, and cerebral ischemia.

INTRODUCTION

In 1972, the first successful use of venoarterial (VA) extracorporeal membrane oxygenation (ECMO) was reported in a 24-year old man who was severely injured in a motorcycle accident.[1] After 3 days, the patient was weaned from ECMO and eventually recovered. Major advances in extracorporeal support have been made since this groundbreaking first case. Increasing experience, as well as advances in ECMO equipment and options for definitive therapy following ECMO support, have led to improved outcomes and increased use of this technology.[2] Since data collection started in 1990, support of more than 10,000 adult patients with VA ECMO has been reported to the Extracorporeal Life Support Organization (ELSO) registry, with 40% of these patients surviving to hospital discharge.[3] This article provides an

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[a] Department of Medicine, Inova Fairfax Hospital, 3300 Gallows Road, Falls Church, VA 22042, USA; [b] Department of Critical Care, Cooper University Hospital, 427C Dorrance, 1 Cooper Plaza, Camden, NJ 08103, USA; [c] Department of Cardiothoracic Surgery, Inova Fairfax Hospital, 3300 Gallows Road, Falls Church, VA 22042, USA
* Corresponding author. 18674 Fawn Ridge Lane, Reston, VA 20194.
E-mail address: Christopher.king@inova.org

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overview of VA ECMO for clinicians not well versed in this technology. It first discusses the components of the VA ECMO circuit and contrasts VA ECMO with venovenous (VV) ECMO. It then addresses patient selection, including indications and contraindications to use of ECMO. It next covers cannulation strategies and basic management of VA ECMO, including commonly encountered complications.

WHAT IS VENOARTERIAL EXTRACORPOREAL MEMBRANE OXYGENATION AND HOW DOES IT DIFFER FROM VENOVENOUS EXTRACORPOREAL MEMBRANE OXYGENATION?

The basic components of any ECMO circuit include a cannula to drain blood from the venous system (inflow cannula), a pump, an oxygenator, and a cannula to return blood to the body (outflow cannula). In addition to these essential components, most ECMO circuits contain a console where pump speed can be adjusted, a heat exchanger, various ports for blood sampling and medication infusion, a saturation sensor on the inflow cannula, and a flow sensor on the outflow cannula. The inflow cannula generally sits in the right atrium or inferior vena cava (IVC). Modern adult ECMO circuits are typically powered by a centrifugal pump, which rapidly rotates a magnetically levitated impeller, generating negative pressure and entraining blood into the circuit. The entrained venous blood is then passed through a membrane oxygenator, which facilitates gas exchange. In the oxygenator, blood separated by a porous membrane is passed by a countercurrent sweep gas, allowing oxygen to enter the blood, carbon dioxide to be removed, and heat to be exchanged[4] (**Fig. 1**). The now oxygenated and warmed blood is delivered through the outflow cannula to the body. More detailed explanation of the individual circuit components is beyond the scope of this article but can be found elsewhere.[4,5]

In VV ECMO, the superoxygenated blood in the outflow cannula is delivered to the venous system, where it then traverses the pulmonary circulation and is pumped to the body by the native left ventricular (LV) output. This system allows respiratory support in patients with impaired gas exchange by bolstering the oxygen content of blood delivered to the right side of the heart. VV ECMO provides no direct hemodynamic support, although hemodynamic benefit is often seen with the initiation of VV ECMO because hypoxia, hypercarbia, and acidosis improve

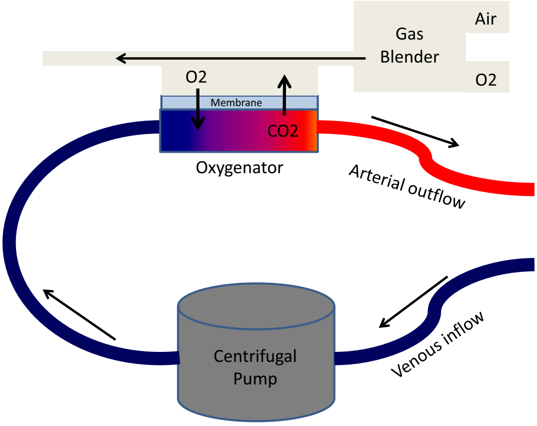

Fig. 1. An ECMO circuit. Blood is drawn into venous inflow by the centrifugal pump. It is then pumped through an oxygenator where the blood is separated from a countercurrent gas flow by a thin permeable membrane. Oxygen enters the blood and carbon dioxide is removed. The oxygenated and decarboxylated blood is then returned to the body.

and the adverse cardiac effects of high-level ventilator support required for respiratory failure are mitigated. In VA ECMO, the outflow cannula bypasses the heart and lungs and delivers oxygenated blood with a pressure that provide both respiratory and hemodynamic support. By doing so, VA ECMO not only augments the native cardiac output with returned flow but also unloads the failing heart by decreasing preload.[6] **Table 1** provides a comparison of the hemodynamic effects of VV and VA ECMO.

VA ECMO can provide 60% to 80% of predicted resting cardiac output.[7] Targeted flow rates in adults are generally 60 to 80 mL/kg/min.[8] ECMO flow rates are affected by preload, afterload, and the revolutions per minute (RPM) of the centrifugal pump. Preload delivery to the pump depends on the length and diameter of the inflow cannulas as well as patient volume status. Circuits are also afterload sensitive. Kinking of the outflow cannula, thrombus in the oxygenator, or high systemic vascular resistance can all decrease ECMO flow rates. These issues are discussed in greater detail later in this article.

HOW TO SELECT APPROPRIATE PATIENTS FOR VENOARTERIAL EXTRACORPOREAL MEMBRANE OXYGENATION. WHAT ARE THE INDICATIONS AND CONTRAINDICATIONS?

General Considerations

Initiation of extracorporeal support is a complex, resource-intensive undertaking that requires careful consideration and should only be performed at centers with sufficient resources to care for this patient population. Appropriate patient selection is of paramount importance. Given the lack of robust data supporting its efficacy, the cost, and the potential for complications, ECMO support should only be initiated in those patients with an appropriate indication who cannot be managed with more traditional therapies. Clinicians must also remember that ECMO is not a therapy but is a means of bridging to an ultimate destination. For some patients, that destination will be a durable ventricular assist device (VAD) or cardiac or lung transplant. For others, ECMO will support end-organ perfusion until the initial insult resolves, acting as a bridge to recovery. In some instances, ECMO provides a bridge to decision, providing time to determine whether an insult is recoverable or whether the patient is an appropriate candidate for destination therapies. In summary, before initiation of ECMO support, it is mandatory to ensure that the indication is appropriate and that conventional therapies are inadequate, to consider any contraindications, and to clearly delineate the

Table 1
Hemodynamic effects of venovenous and venoarterial extracorporeal membrane oxygenation

	VA ECMO	VV ECMO
Indication	Cardiac or cardiopulmonary failure	Pulmonary failure
Effect on RV	Decreased preload Decreased afterload	None
Effect on LV	Decreased preload Increased afterload	None
Hemodynamic support	Partial to complete	No direct support; decrease in ventilator support facilitated by VV ECMO may lead to hemodynamic improvement

Abbreviation: RV, right ventricle.

long-term goal of instituting ECMO therapy. Fig. 2 provides an algorithm for candidate selection for VA ECMO.

Indications for Venoarterial Extracorporeal Membrane Oxygenation

Refractory cardiogenic shock or failure to wean from cardiopulmonary bypass have been the traditional indications for VA ECMO support. Although these indications still account for most VA ECMO use, the technology is being successfully applied to an expanding number of applications (Table 2). The major indications for use of VA ECMO are reviewed later, along with outcomes data for each where available.

Refractory Cardiogenic Shock

There are several causes of cardiogenic shock, including myocardial infarction, acute valvular disorders, myocarditis, postpartum cardiomyopathy, takotsubo cardiomyopathy, postcardiotomy syndrome, decompensated chronic cardiomyopathy, refractory ventricular arrhythmia, and primary graft failure following heart transplant. Traditional therapy for cardiogenic shock focuses on correcting the underlying cause, optimization of volume status, and use of inotropes and vasopressors to maintain adequate tissue perfusion. The timing of initiation of ECMO for cardiogenic shock is controversial given the paucity of data and lack of guideline recommendations. In general, VA ECMO is initiated in appropriate candidates if there is evidence of ongoing tissue hypoperfusion and worsening end-organ dysfunction in the presence of escalating inotropic and vasopressor support. Outcomes of patients with cardiogenic shock supported with ECMO are poorly delineated because they are based primarily on the reports of case series and vary widely based on the causative condition.[9] Acute myocarditis seems to have the most favorable outcomes, with survival to discharge nearing 70%.[10] A meta-analysis of 4 cohort studies examining outcomes of patients with cardiogenic shock caused by myocardial infarction reported 30-day survival of 55% for those treated with VA ECMO compared with 29.7% for those treated with intra-aortic balloon pump.[11] Outcomes for postcardiotomy syndrome, defined as the inability to wean from cardiopulmonary bypass or need for mechanical support

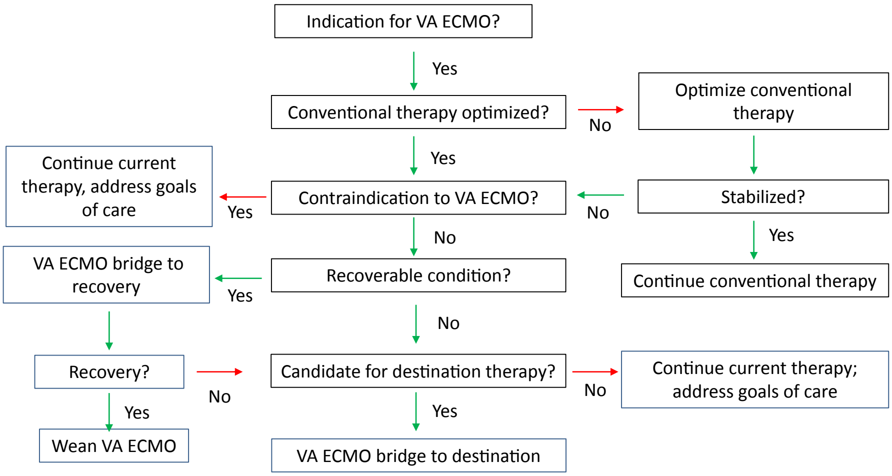

Fig. 2. Decision algorithm for candidate selection for VA ECMO.

Table 2
Indications and contraindications to venoarterial extracorporeal membrane oxygenation

Indications for VA ECMO	Contraindications to VA ECMO
Refractory cardiogenic shock • Acute coronary syndrome • Myocarditis • Peripartum cardiomyopathy • Decompensated cardiomyopathy • Primary graft failure after heart transplant Postcardiotomy shock Recurrent life-threatening arrhythmia ECPR Massive pulmonary embolism Accidental hypothermia Drug overdose Poisoning Periprocedural circulatory support for high risk procedures Septic shock Air embolism Anaphylactic shock Traumatic injury to the heart or great vessels Pulmonary hypertension Facilitation of transfer of critically ill patients	Absolute contraindications • Aortic dissection • Severe aortic regurgitation • End-stage cardiac dysfunction without destination (VAD or transplant) • End-stage pulmonary dysfunction in non–transplant candidate • Irreversible, severe neurologic injury Relative contraindication • Advanced age • Hepatic failure • Advanced malignancy • Active bleeding • Contraindication to anticoagulation (eg intracranial hemorrhage)

Abbreviation: ECPR, extracorporeal cardiopulmonary resuscitation.

in the immediate postoperative period following cardiac surgery, are poor, with most studies reporting rates of survival to hospital discharge of 25% to 50%.[12]

Predicting survival in individual patients before initiating VA ECMO is difficult. Data extracted from the ELSO registry on 3846 patients treated with VA ECMO were used to develop a clinical prediction tool (www.save-score.com) to estimate survival of patients with cardiogenic shock.[13] It should be noted that patients treated with extracorporeal cardiopulmonary resuscitation (ECPR) were excluded from this cohort so the tool cannot be extrapolated to this population.

Extracorporeal Cardiopulmonary Resuscitation

Survival of both in-hospital cardiac arrest (IHCA) and out-of-hospital cardiac arrest (OHCA) treated with conventional cardiopulmonary resuscitation (CCPR) is low, estimated at 15% to 20% and 10%, respectively.[14] ECPR refers to the rapid initiation of VA ECMO support in the context of refractory cardiac arrest. ECPR has been used in patients with IHCA in the cardiac catheterization laboratory or on the ward and in patients presenting to the emergency department with OHCA. It is hypothesized that use of ECPR can restore perfusion more rapidly and, in turn, improve both survival and neurologic outcomes. To date, CCPR and ECPR have not been compared in a randomized, controlled trial. A recent meta-analysis of 6 trials (3 IHCA, 2 OHCA, 1 mixed) containing 2260 patients concluded that ECPR improved both survival and long-term neurologic outcome. Survival rates in the ECPR arms ranged from 14.5% to 34.9% compared with 6.4% to 21.7% in the CCPR arm.[15] Criteria regarding candidacy for ECPR following cardiac arrest are a matter of debate. In general, patients must have had a witnessed arrest, minimal interruptions to cardiopulmonary resuscitation, presumed cardiac origin or pulmonary embolism (PE) as the cause of the arrest, and be less than 75 years of age.[16]

Massive Pulmonary Embolism

Massive PE can cause acute right ventricular failure resulting in cardiogenic shock or cardiac arrest, and is associated with a high mortality. Conventional treatment includes systemic or catheter-directed thrombolysis or surgical embolectomy. VA ECMO can provide cardiopulmonary support for PE while allowing the clot to resolve with anticoagulation alone or may serve a bridge to a surgical or catheter-directed therapy. **Box 1** details various uses of VA ECMO in the treatment of massive PE.

In 2015, Yusuff and colleagues[17] published a review of the reported cases of PE managed with VA ECMO to date. A total of 78 patients (11 case reports and 8 case series) were reported on, 43 (55%) of whom had a cardiac arrest. Overall survival of the cohort was 70.1%. For patients who presented with cardiac arrest there was a survival of 49%, compared with a historical rate as high as 75%. Based on the available data, use of VA ECMO may be a reasonable management strategy for a select group of patients with massive PE, including patients with clot in transit, marked hemodynamic instability at high risk for cardiac arrest, or unstable patients presenting to facilities with inability to provide definitive therapy for massive PE.

Accidental Hypothermia

Excellent outcomes have been seen with the use of VA ECMO for rewarming of patients with cardiac arrest secondary to hypothermia, with rates of survival and good neurologic outcome of 67.7% and 61.5% respectively.[18] It should be highlighted that these results only apply to patients with cardiac arrest primarily caused by cold exposure and not with primary hypoxic arrest with associated hypothermia (eg, drowning, avalanche).[18]

Septic Shock

The use of VA ECMO for refractory septic shock remains controversial. Survival to hospital discharge reported in 3 recent cohort studies was a dismal 15% to 30%.[19–21] In contrast, a case series of VA ECMO therapy for septic shock complicated by severe LV dysfunction published by Brechot and colleagues[22] reported an impressive survival rate of 70%. One major reason for these discordant findings is that

Box 1
Clinical strategies for venoarterial extracorporeal membrane oxygenation in acute massive pulmonary embolism

Marked hemodynamic instability
- Bridge to recovery
- Bridge to embolectomy
- Bridge to catheter-directed thrombolysis
- Bridge to percutaneous thrombus removal

Hemodynamic instability with contraindication to systemic thrombolysis
- Bridge to recovery
- Bridge to catheter-directed thrombolysis

Clot in transit
- Bridge to embolectomy
- Bridge to percutaneous thrombus removal

Escalation of care
- Transfer to referral center for definitive therapy

ECPR after massive PE and cardiac arrest

Brechot and colleagues[19–22] initiated VA ECMO early (mean of 24 hours) and before arrest in all patients in their cohort, whereas the other series included patients who had cardiac arrest. Limited success with early initiation of VA ECMO in patients with septic shock with cardiac dysfunction has been achieved, but further research is required.

Pulmonary Hypertension

VA ECMO can serve as a bridge to recovery or lung transplant in patients with decompensated pulmonary hypertension. In patients with a reversible insult, ECMO can provide support while pulmonary vasodilator therapy and volume status are optimized. In those with end-stage pulmonary hypertension, ECMO can provide a bridge to lung transplant. Several innovative cannulation strategies have been used to provide ECMO support in patients with pulmonary hypertension, including (1) internal jugular venous drainage with subclavian arterial return, (2) drainage from the main pulmonary artery with reinfusion into the left atrium via sternotomy, and (3) use of a VV ECMO dual-lumen bicaval cannula to withdraw from the IVC with the reinfusion jet directed at an atrial septal defect or patent foramen ovale creating an oxygenated right-to-left shunt.[23]

Additional Indications

Other instances in which VA ECMO support has been successfully applied include poisoning or overdose, anaphylaxis, traumatic injury to the heart or great vessels, and for periprocedural support for high-risk cardiac interventions.[24–27] In addition, VA ECMO support has been used to stabilize critically ill patients for transport to tertiary care centers offering therapies unavailable at the referring center.[28]

Contraindications to Venoarterial Extracorporeal Membrane Oxygenation

Very few absolute contraindications to VA ECMO exist. There is general consensus that initiation of ECMO support in patients with irreversible major organ dysfunction without a means to correct it (eg, transplant, VAD) is inappropriate. Severe aortic insufficiency precludes VA ECMO use, because the return flow to the aorta would result in severe LV distention and pulmonary edema. Several relative contraindications exist, including advanced age, incurable malignancy, uncontrolled bleeding or other contraindication to anticoagulation, and morbid obesity. **Table 2** lists absolute and relative contraindications to ECMO.

THE DECISION HAS BEEN MADE TO PROCEED WITH EXTRACORPOREAL MEMBRANE OXYGENATION. HOW IS THE OPTIMAL CANNULATION STRATEGY DETERMINED?

Once the decision to initiate VA ECMO is made, the cannulation strategy must be determined. Several factors must be considered when determining the optimal cannulation strategy, including the urgency of the situation, the underlying cardiac issue (right, left, or biventricular heart failure), pulmonary status, the size of arterial vessels, the need for mobilization, and the anticipated duration of support. Consideration must also be given to the size of the cannulas to ensure that flows adequate to provide full support can be achieved. Cannulation can be performed centrally, through a sternotomy or thoracotomy, or peripherally.

Central Cannulation

Because of the need for thoracotomy or sternotomy, central cannulation is most commonly encountered in patients who are unable to wean from cardiopulmonary bypass. In this scenario, the cannula used for intraoperative cardiopulmonary bypass can be connected to the VA ECMO circuit. The inflow cannula typically drains the right atrium, whereas the outflow cannula instills blood into the ascending aorta.[7] Central cannulation is also sometimes used as an alternative to cardiopulmonary bypass during lung transplant.[29] Advantages of central cannulation include adequate delivery of oxygenated blood to the upper body and the ability to deliver high flow rates given the large cannula diameters. Disadvantages of central cannulation include the need for operative placement and removal, limited ability to mobilize the patient, and increased bleeding and infection risk.[30]

Peripheral Cannulation

Peripheral cannulation is performed either percutaneously or by vascular cutdown. Percutaneous placement is performed via the Seldinger technique. Ultrasonography evaluation is useful in both accessing the vessels and in evaluating the size of vessels before cannulation. Thrombus, vascular stenosis, peripheral arterial disease, and prior vascular surgical procedures may render percutaneous cannulation difficult or impossible in some cases.[31] Advantages of percutaneous cannulation include decreased bleeding and infection risk, potential for patient mobilization, ability to cannulate at the bedside, and ability to cannulate expediently. Disadvantages of peripheral cannulation include vascular compromise of extremities, upper body hypoxemia, and development of aortic root or intracardiac thrombus (caused by LV distention caused by increased afterload from the ECMO return flow in patients with minimal LV contractility).[32]

Venous (Inflow) Cannula

The inflow cannula drains blood from the right atrium via the right internal jugular vein, subclavian vein, or the femoral vein. Venous cannulas of the greatest diameter and shortest length possible should be used to optimize preload to the circuit. Larger patients may require a second inflow cannula if adequate drainage cannot be achieved with a single inflow cannula.[7] Venous cannula are typically 19 to 25 Fr.[32] Both end and side holes are generally present on venous cannulas to facilitate drainage if the end of the cannula becomes occluded.

Arterial (Outflow) Cannula

Multiple sites can be used for the returned of oxygenated blood to the proximal arterial system. The femoral artery is a commonly used location for the outflow cannula when providing VA ECMO support. This vessel can be accessed percutaneously or by cutdown. The cannula should terminate in the common iliac artery or abdominal aorta. Complications of femoral arterial cannulation include limb ischemia, LV distention and pulmonary congestion, and upper body hypoxemia. Limb ischemia can be avoided by placing a perfusion cannula distal to the cannulation site in the femoral artery. This cannula is then perfused with oxygenated blood from a side port off the arterial cannula.[33] The right or left subclavian or axillary arteries can be used for arterial cannulation as well, which requires surgical placement of an end-to-side Dacron graft. These upper extremity arterial cannulation sites have the advantage of decreasing the risk of aortic root thrombosis and upper body hypoxemia. Upper extremity cannulation also may facilitate patient mobilization. Biscotti and Bacchetta[34] of Columbia University Medical Center described a cannulation strategy designed to optimize patient mobilizations using right internal jugular venous drainage and right subclavian arterial return, which they dubbed the Sport Model in 2014.[34] Cannula site hematoma and ipsilateral limb swelling can complicate use of this technique.[34] Although the right common carotid artery is frequently used for VA ECMO cannulation in the pediatric population, it is associated with an increased risk of stroke and not commonly used for adult VA ECMO support.

Arterial cannulas are typically 15 to 25 Fr and of a shorter length than venous cannulas. A recent study by Takayama and colleagues[35] found that smaller 15-Fr cannulas were able to provide support comparable with larger 17-Fr to 24-Fr cannulas and caused fewer bleeding complications. No side ports are present on arterial cannulas because they result in turbulent blood flow. The appropriate site for monitoring of arterial blood gases in patients on VA ECMO varies with the location of the arterial cannula. For instance, a right subclavian arterial cannula directs flow down the right arm, resulting in falsely increased blood oxygen levels in samples drawn from a right radial arterial line. It is therefore recommended that arterial blood samples in these patients be drawn from a left radial arterial line. **Table 3** lists the potential advantages and complications of the various arterial cannulation locations and the recommended site for arterial blood gas monitoring of each.

TRIPLE CANNULATION STRATEGIES

Venoarteriovenous Extracorporeal Membrane Oxygenation

As briefly mentioned earlier, upper body hypoxemia can complicate the care of patients who are peripherally cannulated for VA ECMO, particularly those with femoral

Table 3
Arterial cannulation locations

Location	Advantages	Disadvantages/ Possible Complications	Recommended Site for ABG Monitoring
Femoral	• Rapid cannulation	• Upper body hypoxemia • LV distention • Limb ischemia	Right radial
Right axillary	• Facilitates mobilization • Lower risk for upper body hypoxia	• Hematoma • Limb swelling • Requires surgical anastomosis	Left radial
Left axillary	• Facilitates mobilization • Lower risk for upper body hypoxia	• Hematoma • Limb swelling • Requires surgical anastomosis	Right radial
Central cannulation (ascending aorta)	• High flows possible • No upper body hypoxemia	• Bleeding risk increased • Infection risk increased • Requires sternotomy or thoracotomy • Requires surgery for decannulation	Right or left radial
Right common carotid	• Facilitates mobilization • Lower risk for upper body hypoxia	• Increased risk of stroke	Left radial

Abbreviation: ABG, arterial blood gas.

arterial cannulas. If a patient recovers ventricular function while still experiencing significant pulmonary dysfunction, the native cardiac output will pump poorly oxygenated blood to the coronary arteries and brain while well-oxygenated blood from the ECMO outflow cannula only reaches the lower half of the body. This phenomenon is known as north-south syndrome, harlequin syndrome, or differential cyanosis and may lead to coronary or cerebral ischemia. One strategy to overcome this is to split the arterial outflow with a Y connector and deliver highly oxygenated blood to the right internal jugular vein. This technique increases the oxygen content delivered through the pulmonary circulation to the left ventricle, improving oxygen delivery to the brain and heart. The relative flows of the 2 outflow cannulas can be modulated by clamps and should be monitored carefully.[32] This cannulation configuration is commonly referred to as venoarteriovenous ECMO.[7] Additional ways to combat differential cyanosis are summarized in Table 4.

Venovenoarterial Extracorporeal Membrane Oxygenation

Venovenoarterial ECMO refers to the addition of a second venous drainage cannula, usually to the right internal jugular vein, in patients with a preexisting femoral venous inflow and femoral arterial outflow cannulas. The 2 venous cannulas can be joined with a Y connector. This configuration is indicated for patients with marked LV distention caused by inadequate drainage or in patients whose small vessel size precludes placement of a large enough drainage cannula to provide adequate preload to the circuit.[32]

Table 4
Common complications of venoarterial extracorporeal membrane oxygenation

Complication	Possible Sequelae	Possible Management Strategies
Loss of pulsatility	• LV or aortic root thrombosis • LV distention and ischemia • Pulmonary edema or hemorrhage	• Add inotropes • Decrease VA ECMO flow • Intra-aortic balloon pump • Direct LV decompression • Percutaneous LVAD
Upper body hypoxemia or differential cyanosis	• Cerebral ischemia • Coronary ischemia	• Treat pulmonary disorder • Increase ventilator support • Increase VA ECMO flows • Place upper body arterial cannula • Venoarteriovenous configuration
Limb ischemia	• Loss of limb	• Place a distal perfusion catheter • Move femoral cannula to upper body artery (subclavian or axillary)
Bleeding	• Hypotension • Inadequate oxygen delivery • Low ECMO flows • Death	• Local measures (direct pressure) • Decrease anticoagulation intensity • Surgical evaluation/ intervention

Abbreviation: LVAD, left ventricular assist device.

Additional Therapies

Several additional options for mechanical support in cardiogenic shock exist. Percutaneously inserted left ventricular assist devices (LVADs), such as the TandemHeart (Cardiac Assist, Inc, Pittsburgh, PA) and Impella (Abiomed) devices, are available to provide temporary LV support.[36] The TandemHeart device can also be configured to provide VV ECMO support.[37] Temporary right ventricle (RV) support can be achieved with the Centrimag (Levitrnix LLC, Waltham, MA) or Impella RP (Abiomed).[38] A detailed discussion of these devices is beyond the scope of this article.

How to Manage Patients Who Are Cannulated and on Extracorporeal Membrane Oxygenation Support

The management of VA ECMO patients is complex. The approach to support should be individualized based on the hemodynamic needs of the patient. Careful monitoring is required to ensure adequacy of support. Vigilance is also required to detect and correct frequently encountered complications in a timely manner. An overview of the basic management and monitoring of VA ECMO is provided here, and commonly encountered complications and the recommended corrective actions are also highlighted (**Table 5**).

Table 5
Troubleshooting guide for commonly encountered monitoring issues

Issue	Potential Corrective Actions
Low flow	• Inadequate preload ○ Administer volume or transfuse ○ Assess for bleeding ○ Assess for inlet cannula kinking • Increased afterload ○ Assess for kinking of outflow cannula ○ Assess for pump thrombus ○ Decrease MAP with antihypertensives • Increase RPM
Low MAP	• Assess for bleeding, systemic infection • Administer volume or transfuse • Start vasopressor • Increase ECMO flow
Low Pao_2	• Increase circuit Fio_2 • Increase circuit flow • Assess oxygenator function • Increase ventilator support
Increased Pco_2	• Increase sweep gas flow • Increase ventilator support
Low Svo_2	• Increase ECMO flow • Ensure Pao_2 adequate • Transfuse blood
Increased lactate level	• Assess for local ischemia (gut, limb) • Increase systemic O_2 delivery ○ Increase ECMO flow ○ Transfuse ○ Increase Pao_2 if low

Abbreviations: Fio_2, fraction of inspired oxygen; MAP, mean arterial pressure; Svo_2, mixed venous oxygen saturation.

HEMODYNAMIC SUPPORT

Determine the Degree of Support Required

The primary goal of ECMO support is to maintain adequate oxygen delivery to end organs.

Delivery of oxygen depends on cardiac output, the hemoglobin concentration, and arterial oxygen saturation. In ECMO patients, all of these variables can be manipulated to ensure adequate tissue perfusion. Recall that, in ECMO patients, the functional cardiac output is a combination of the native cardiac output and the ECMO flow. The optimal amount of ECMO support varies depending on native cardiac function. Patients with severely depressed native cardiac function frequently require maximal ECMO support. In contrast, patients who primarily have RV failure with relatively intact LV function typically only require partial support. The degree of support provided should be tailored to the pathophysiology of the patient being supported.

Optimize Flow

The flow produced by the ECMO circuit depends on the modifiable variables of preload, afterload, and RPM of the centrifugal pump, as well as the static variable of cannula length and diameter.[7] ECMO circuit flow is controlled by adjusting the RPMs of the centrifugal pump. Increasing RPM results in increased ECMO flow, assuming the system is not limited by preload, afterload, or cannula size. In the setting of a stable RPM, decreased flows can result from inadequate preload or increased afterload. Inadequate preload can result from hypovolemia (from bleeding, distributive shock, overdiuresis) or mechanical obstruction (from cardiac tamponade, tension pneumothorax, abdominal compartment syndrome, or cannula malposition or kinking) and typically manifests as chugging or chattering of the circuit and decreased flows.[7] When encountered, temporarily decreasing the RPMs of the pump and providing volume can correct the problem. The patient and circuit should also be inspected for evidence of bleeding or cannula malposition or kinking.

Afterload on the ECMO circuit is affected by the systemic vascular resistance (SVR) as well as resistance in the circuit distal to the pump. Decreased flows caused by increased afterload may be caused by increased SVR (increased mean arterial pressure [MAP]) or increased resistance in the circuit (kinking of the outflow cannula, clot in the oxygenator membrane). If the increase in afterload is caused by an increased SVR, this can be corrected by reducing the MAP with antihypertensives or decreasing vasopressors or inotropes.

Optimize Mean Arterial Pressure

Maintenance of blood flow alone is insufficient to ensure adequate tissue perfusion. A sufficient MAP is essential to maintain perfusion to vital organs, including the heart, brain, and kidneys.[39] There are numerous causes of hypotension in ECMO patients, including vasodilatory effects of sedatives, hypovolemia from volume depletion or bleeding, and distributive shock from sepsis or postcardiotomy vasoplegia. There is much debate over what the optimal minimal MAP goal should be, and it is likely that it varies among individual patients.[40] A reasonable MAP goal for most ECMO patients is 65 to 90 mm Hg. This range allows adequate end-organ perfusion without causing excessive afterload.

MAP is a product of SVR and cardiac output. In ECMO patients, increases in MAP may be achieved by increasing VA ECMO flows or by increasing SVR with vasopressors.

Maintain Pulsatility

VA ECMO has beneficial effects on the failing heart. Removing blood from the venous system leads to decreased preload, and, in turn, decreased LV end-diastolic volume and pressure and improved LV perfusion. These benefits are offset to varying degrees by the increase in afterload from the return of blood into the arterial system. Patients with poor cardiac contractility may be unable to eject against this afterload mismatch. When this occurs, the LV can become overdistended, leading to myocardial ischemia, as well as pulmonary edema or hemorrhage. In addition, blood may stagnate in the LV or aortic root, leading to thrombosis.[7] This issue can typically be detected by absence of pulsatility on the arterial waveform tracing. It can also be confirmed through echocardiography, which reveals LV distention and failure of the aortic valve to open.

There are several ways to offset the complications of afterload mismatch. Inotropic support can be used to augment contractility. In addition, VA ECMO flows can be reduced. Caution should be exercised when reducing ECMO flows to ensure that adequate tissue perfusion is maintained. Mechanical means of addressing this issue are sometimes used as well. Placement of an intra-aortic balloon pump can both augment coronary perfusion and reduce afterload. Alternatively, a percutaneous LVAD can be placed to facilitate LV decompression.[41] In addition, direct LV decompression can be achieved by placing a decompression cannula into the pulmonary artery, LA, or LV that drains directly to the inflow cannula of the ECMO circuit.[42]

Arrhythmias can compromise native cardiac function and should be addressed promptly. Antiarrhythmic medications, cardioversion, or pacing may be required.

Ensure Adequate Gas Exchange

The net systemic arterial oxygen content in ECMO patients is determined by contributions from both the native cardiac output and the output of the ECMO circuit. The relative contribution of the native cardiac output to systemic oxygenation varies based on both pulmonary status and myocardial function. As mentioned earlier, regional variation in arterial oxygen content can be seen, particularly in patients with femoral arterial cannulation. In patients with poor myocardial contractility, retrograde blood flow from the VA ECMO circuit to the aortic arch ensures adequate oxygen delivery to the coronary and cerebral circulation. However, as patients recover and regain myocardial function, the upper body may receive a substantial proportion of their blood flow from the native circulation. If patients have poor lung function this may result in delivery of poorly oxygenated blood to the upper body. Adequacy of systemic oxygenation should be assessed from an arterial cannula far removed from the influx of blood by the ECMO circuit to the arterial system. **Table 3** lists the recommended location of arterial blood gas sampling based on the location of the arterial cannula.

Extracorporeal Membrane Oxygenation Circuit

The ECMO circuit can regulate both oxygenation and ventilation. Oxygen delivery can be increased by increasing the fraction of delivered oxygen on the oxygen blender or increasing ECMO flow rates. Increased flow rates expose a greater blood volume to the membrane oxygenator, leading to greater oxygen delivery. Carbon dioxide removal is facilitated by the countercurrent sweep gas. Increasing the sweep gas flow rate results in more carbon dioxide removal. Alterations in ECMO blood flow rates do not affect carbon dioxide clearance.

Ventilator Management

To develop an appropriate mechanical ventilator strategy, clinicians must understand the physiologic consequences of positive pressure ventilation (PPV). PPV can be detrimental in the setting of RV failure caused by increased RV afterload.[43] In contrast, increased positive end-expiratory pressure (PEEP) may be beneficial in the setting of LV failure in which the increase in intrathoracic pressure leads to decreases in both LV preload and afterload.[44] Our practice is therefore to avoid high PEEP in patients with predominately RV failure. In patients with severely depressed LV function, we use moderate amounts of PEEP, because the increase in PEEP has beneficial hemodynamic effects and may help combat the development of pulmonary edema.[45–48] This issue is further addressed in respiratory strategies (See Bharat Awsare and colleagues' article, "Management strategies for Severe Respiratory Failure: as Extracorporeal Membrane Oxygenation (ECMO) is being considered," in this issue).

Monitoring Adequacy of Perfusion

Careful monitoring is required to ensure adequacy of ECMO support. Patients with adequate perfusion on stable ECMO settings can rapidly and subtly develop inadequacy of support for several reasons, including worsening pulmonary status, improving native cardiac function, anemia, arrhythmia, or deteriorating oxygenator membrane function. Most programs use ECMO specialists to monitor patients around the clock. Monitoring and frequent laboratory draws are used to detect changes and adjust support appropriately.

Flow meters on the circuit provide a continuous display of ECMO circuit outflows. Pressure monitors on the inflow cannula can detect excessive suction and ensure adequacy of venous drainage.[4] Inlet pressures should not be lower than −50 mm Hg.[7] Near-infrared spectroscopy can be used to detect changes in cerebral or limb perfusion.[49] These devices display a continuous read-out of tissue oxygen saturation (StO_2).[50] Changes in the StO_2 may detect alteration in perfusion, which can prompt early investigation and correction.

Mixed venous oxygen saturation (SvO_2) provides information regarding the balance between oxygen delivery and oxygen consumption. A normal SvO_2 is 65% to 75%. A low SvO_2 can be seen with either inadequate delivery of oxygen to tissues or a state of increased extraction.[51] Although a true SvO_2 cannot be measured in patients on VA ECMO, a sample from blood flow entering the circuit through the venous inflow cannula provides a reasonable surrogate.[7] When a low SvO_2 is observed on a prepump arterial blood gas measurement, it may reflect inadequacy of ECMO support. Possible corrective actions include increasing ECMO circuit flows to increase oxygen delivery or red blood cell transfusion to increase oxygen carrying capacity of the blood. Measurement of lactate level may be useful as well. There is increasing recognition that lactate level is not always simply a marker of inadequate perfusion and anaerobic metabolism but can also be caused by a hypermetabolic state caused by beta-2 stimulation and enhanced glycolysis.[52] Regardless of the cause, increase of plasma lactate levels seem to be associated with adverse ouctomes.[53] The authors think it is reasonable to periodically check lactate levels in VA ECMO patients. If increased levels are found, evaluation should be undertaken to assess for local (gut, limb) or global ischemia.

Hemoglobin Concentration

Historically, it was recommended that patients on ECMO support be transfused to near normal hemoglobin levels.[54] However, multiple studies in the general critical care population have shown no evidence of harm, and potential benefit from a restrictive transfusion strategy.[55] Limited data regarding transfusion practices exist in the ECMO population. Two small retrospective series specifically on ECMO patients showed no evidence of harm with restrictive transfusion strategies.[54,56] It is our practice to follow a restrictive transfusion strategy. Patients are typically maintained at a hematocrit greater than 25% and transfused only for bleeding or signs of inadequate oxygen delivery if above this threshold.

Anticoagulation and Bleeding

Significant disturbances of the coagulation system occur during extracorporeal support, leaving the patients vulnerable to both thrombosis and bleeding. Exposure of blood to the artificial surface of the ECMO circuit results in inflammation, cellular activation, and initiation of coagulation. In addition, turbulence and sheer stress compound this activation of coagulation and can lead to platelet and fibrin deposition.[57] Because of the alterations in hemostasis during ECMO support, anticoagulation is required to prevent thrombosis and preserve the patency of the circuit. Unfractionated heparin is most commonly used, although direct thrombin inhibitors are sometimes used as an alternative.[57] No consensus exists as to the optimal monitoring strategy or therapeutic range. Activating clotting time is the most widely used monitoring tool. Alternatives include the anti-Xa activity and activated partial thrombin time. Our center uses an anti-Xa–based strategy targeting a goal range of 0.3 to 0.5IU/mL. Fresh frozen plasma and cryoprecipitate transfusions are given to correct the International Normalized Ratio (INR) to less than 1.5 and fibrinogen level to greater than 100 mg/dL.[58] The authors typically transfuse platelets to maintain the count at more than 50 cells/mm^3; however, no consensus on the optimal transfusion threshold for platelets exists.

Bleeding complications are common, occurring in more than 20% of cases of VA ECMO support.[8] The severity of the bleeding dictates the response. Minor cannula site bleeding can be treated with hemostatic dressings or direct pressure. The cannula should also be examined to ensure it is properly positioned. The intensity of anticoagulation can be decreased and non–heparin-induced alterations in coagulation corrected (eg, fresh frozen plasma for increased INR). Antifibrinolytic therapy, such as aminocaproic or tranexamic acid, can be used as well. Severe bleeding may require surgical intervention and temporary cessation of anticoagulation. Recombinant factor VIIa use has been reported for uncontrollable bleeding in patients on ECMO.[59]

SUMMARY

VA ECMO can provide robust, highly customizable cardiac and pulmonary support for several conditions. It is likely that use of this powerful tool will continue to expand, so it is prudent for clinicians to familiarize themselves with its components and basic management strategies.

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