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THE PRESENT AND FUTURE

JACC SCIENTIFIC EXPERT PANEL

Venoarterial ECMO for Adults

JACC Scientific Expert Panel

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CME/MOC/ECME Objective for This Article: Upon completion of this activity, the learner should be able to: 1) identify the indications for venoarterial ECMO; 2) understand the differences between venoarterial and venovenous ECMO; 3) discuss the hemodynamic changes in patients on VA ECMO support; 4) understand the need and the options of decompression (venting) of the left ventricle on VA ECMO; 5) know the principles of building the ECMO team; and 6) recognize common complications of VA ECMO and know how to manage them.

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Venoarterial ECMO for Adults

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ABSTRACT

Venoarterial extracorporeal membrane oxygenation (ECMO) is a rescue therapy that can stabilize patients with hemodynamic compromise, with or without respiratory failure, for days or weeks. In cardiology, the main indications for ECMO include cardiac arrest, cardiogenic shock, post-cardiotomy shock, refractory ventricular tachycardia, and acute management of complications of invasive procedures. The fundamental premise underlying ECMO is that it is a bridge—to recovery, to a more durable bridge, to definitive treatment, or to decision. As a very resource- and effort-intensive intervention, ECMO should not be used on unsalvageable patients. As the use of this technology continues to evolve rapidly, it is important to understand the indications and contraindications; the logistics of ECMO initiation, management, and weaning; the general infrastructure of the program (including the challenges associated with transferring patients supported by ECMO); and ethical considerations, areas of uncertainty, and future directions. (J Am Coll Cardiol 2019;73:698–716) © 2019 by the American College of Cardiology Foundation.

The use of extracorporeal membrane oxygenation (ECMO) in cardiovascular disease is soaring. After the landmark CESAR (conventional ventilatory support versus extracorporeal membrane oxygenation for severe adult respiratory failure) trial, in which ECMO appeared to be superior to the ventilator in the adult population (1), this modality has been increasingly popular.

According to the Extracorporeal Life Support Organization (ELSO), an international voluntary registry, the number of adult cardiac ECMO runs increased 1,180% in the last decade, from <200 between 1997 and 2007 to over 2,000 to date (**Figure 1**) (2). Likewise, the number of ECMO centers, which increased by 15% (from 115 to 131) from 1996 to 2006, rose by a staggering 133% (from 131 to 305) from 2006 to 2016.

The indications for venoarterial (VA)-ECMO continue to evolve. Over the past decade, the primary indication shifted from post-cardiotomy shock (treated by surgeons) to multifactorial cardiogenic shock and/or cardiac arrest (treated in the setting of multidisciplinary teams including cardiologists or primarily by cardiologists) (**Central Illustration**). The proportion of post-cardiotomy shock patients supported on VA-ECMO decreased from 56.9% in 2002 to 37.9% in 2012. During this same period, the number of adult patients with cardiopulmonary failure supported on VA-ECMO substantially increased (3).

There are several reasons behind the dramatic increase in the use of ECMO in cardiology, including:

- Availability of durable membranes and portable circuits
- Ability of VA-ECMO to provide left, right, and biventricular support
- Ease of implantation in the catheterization laboratory or at the bedside
- Increased familiarity with the technology by cardiologists and surgeons
- The need for a short-term bridge to transplantation or mechanical support

Dr. Zucker has reported that he has served on the scientific advisory board for and received honoraria from Alnylam and Pfizer. Dr. Bozkurt has served as a consultant for Lantheus and Bayer. Dr. Estep has served as a consultant for Abbott; and as a medical advisor for Medtronic. Dr. Zwischenberger has received licensed patent royalties for Avalon Elite double lumen cannula (Maquet); has received an industry grant from Xenios Austria GmbH; served as a partner to WZ Biotech; has served as a consultant for CytoSorb; has served on and as chair of Cytosorb Cardiac Advisory Board; and has received grant funding from the National Institutes of Health. All other authors have reported that they have no relationships relevant to the contents of this paper to disclose.

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ABBREVIATIONS AND ACRONYMS

CI = confidence interval

CPR = cardiopulmonary resuscitation

ECMO = extracorporeal membrane oxygenation

ECPR = extracorporeal cardiopulmonary resuscitation

ELSO = Extracorporeal Life Support Organization

HR = hazard ratio

IABP = intra-aortic balloon pump

LV = left ventricle/ventricular

LVAD = left ventricular assist device

LVEDP = left ventricular end-diastolic pressure

PV = pressure-volume

ROSC = return of spontaneous circulation

RV = right ventricular

VA = venoarterial

VV = venovenous

- Progress in durable mechanical circulatory support devices, which enables ECMO use as bridge to a left ventricular assist device (LVAD)
- Financial incentives

Implementation of the new United Network for Organ Sharing donor allocation system in the fall of 2018 might result in further growth in use of ECMO in the United States. Under the current system, priority was primarily determined by hemodynamic status, with confirmation requiring a Swan-Ganz catheter. The new schema prioritizes allocation based primarily on the type of mechanical support device in place, with priority given to patients supported by ECMO.

ECMO has become the preferred device for short-term hemodynamic support in patients with cardiogenic shock. **Table 1** compares ECMO to other short-term devices. Most practicing cardiologists have not been trained on ECMO, prompting this comprehensive review.

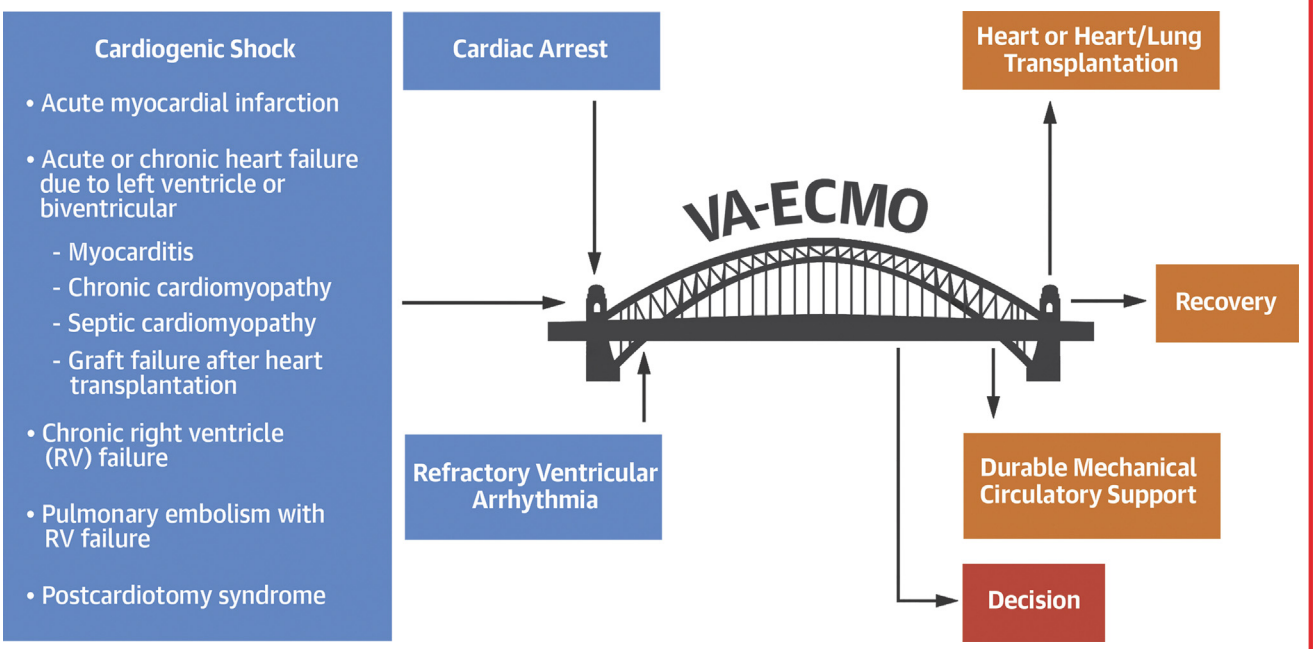
ECMO OVERVIEW

ECMO is a portable modification of cardiopulmonary bypass capable of supporting critically ill patients with refractory cardiopulmonary failure for days to weeks (4). Although available for over 40 years, ECMO was initially used primarily in neonatology. ECMO, predominantly venovenous (VV), was first used in adults with severe but potentially reversible lung disease, such as influenza pneumonia and adult respiratory distress syndrome. Over the past decade or so, the technology has gained momentum in adult cardiology.

Evidence favoring adult VA-ECMO came from prospective observational propensity-matched studies of extracorporeal cardiopulmonary resuscitation (ECPR), both demonstrating a neurologically intact survival benefit over conventional cardiopulmonary resuscitation (CPR) (5,6).

The closed ECMO circuit withdraws deoxygenated blood from the venous system through 1 or multiple drainage cannulae, pumps the blood through an oxygenator where gas exchange occurs, and returns the blood to the venous (VV) or arterial (VA) circulation through a reinfusion cannula (**Figure 2**) (7).

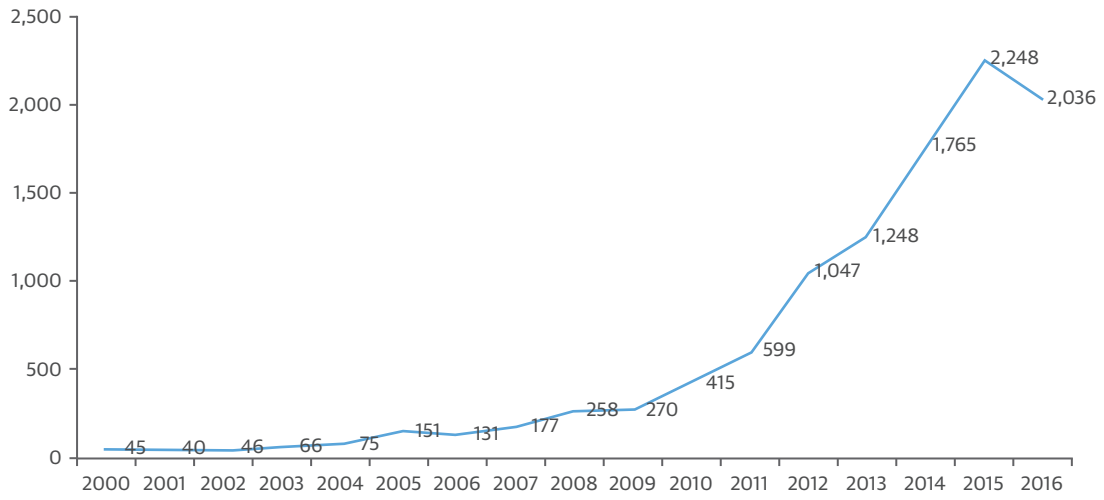
CENTRAL ILLUSTRATION **VA-ECMO Is a Bridge**



Guglin, M. et al. J Am Coll Cardiol. 2019;73(6):698–716.

The fundamental premise underlying extracorporeal membrane oxygenation (ECMO) is that it is a bridge—to recovery, to a more durable bridge, to definitive treatment, or to decision. This figure shows indications for ECMO and the potential outcomes. RV = right ventricular; VA = venoarterial.

FIGURE 1 Growth of Adult Cardiac Extracorporeal Membrane Oxygenation Runs



Graph depicting the increase the number of adult cardiac extracorporeal membrane oxygenation runs. There was an increase of 1,180% in the last decade. There were <200 runs/year between 1997 and 2007, increasing to >2,000 runs/year in 2014 to 2016. Data are from the Extracorporeal Life Support Organization (2).

Whereas VV-ECMO replaces failing lungs, VA-ECMO provides both respiratory and hemodynamic support (i.e., replaces heart and lung). The focus of this paper is VA-ECMO.

The circuit uses a centrifugal pump such as the Centrimag (Thoratec, Pleasanton, California), Rotaflow (Maquet, Rastatt, Germany), or TandemHeart (TandemLife, Pittsburgh, Pennsylvania) and a blood-gas exchange unit that includes a heat exchanger and a membrane oxygenator. As the blood transits through the membrane oxygenator, hemoglobin becomes fully saturated with oxygen and carbon dioxide (CO_2) is removed. The degree of oxygenation is determined by the flow rate and fraction of inspired oxygen. The membrane oxygenator can provide up to full oxygen saturation. Even in the state of pulmonary edema or massive pulmonary embolism, oxygen saturation is normal.

CO_2 removal is primarily controlled by adjusting the rate of countercurrent gas flow through the oxygenator, otherwise known as the sweep speed (8). ECMO is extremely effective in removing CO_2. CO_2 is removed by diffusion. The sweep gas is typically 100% oxygen, and correction of respiratory acidosis can be rapidly achieved by increasing the sweep speed.

Both VV- and VA-ECMO can be used to treat refractory acute respiratory failure. VA-ECMO (in contrast to VV-ECMO) can provide complete circulatory support. Compared with other temporary mechanical circulatory support devices used to support patients with refractory cardiogenic shock, VA-ECMO addresses both right ventricular (RV) and left ventricular (LV) dysfunction, systemic oxygenation (pO_2), and acid-base balance via modulation of the partial pressure of CO_2. The circuit configuration (**Figure 2**) permits the withdrawal and pumping of desaturated blood from the right atrium or a central vein, with nonpulsatile pump outflow directed toward the membrane oxygenator then guided via an outflow cannula to a systemic artery (e.g., femoral or subclavian artery).

HEMODYNAMICS WITH CARDIOGENIC SHOCK AND VA-ECMO

The hemodynamic condition of the LV in all types of cardiogenic shock is best illustrated by the pressure-volume (PV) loop. This loop depicts the 4 phases of a single cardiac cycle and provides information about contractile and relaxation properties, cardiac work, and myocardial oxygen consumption (9–11). Typically, in cardiogenic shock, independent of underlying etiology, LV contractility, reflected by Emax, defined as the maximum slope at the end-systolic PV point, is reduced and LV end-diastolic pressure (LVEDP) is increased. Although there are differences in the magnitude of effect on stroke volume and LV stroke work with the different types and severities of

TABLE 1 Comparison of Commercially Available Devices for Short-Term Mechanical Circulatory Support

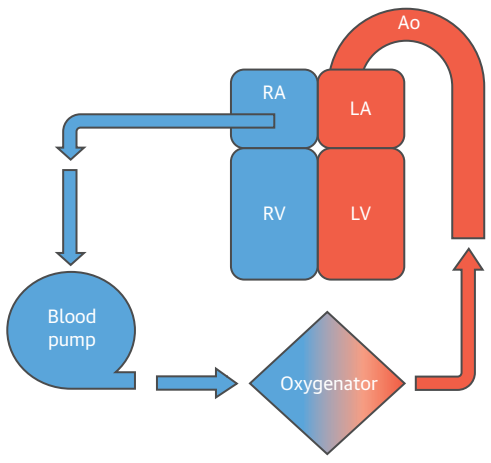
Device	VA-ECMO	IABP	Tandem Heart	Impella (2.5; CP; 5; RP)
Flow, l/min	4–6	0.5–1	4–6	2.5–5
Duration of support, FDA approved	6 h (limited by oxygenator durability)	9 days	21 days	4 days (2.5, CP), 6 days (5) 14 days (RP)
Ventricles supported	LV and RV	LV	LV or RV	LV or RV
Cannula size, F	Inflow 18–21 Outflow 15–22	7–9	Inflow 21 Outflow 15–17	12–21
Additional requirements	Potential need for LV venting, possible cutdown		Transseptal puncture	Surgical cutdown for Impella 5
Advantages	Highest cardiac output Complete cardiopulmonary support (including oxygenation and CO_2 removal)	Easy to place Good safety profile Fewer side effects, especially vascular	Highest cardiac output, comparable with VA-ECMO, and no LV distension	Multiple devices to choose from
Disadvantages	Requires more resources and support staff than other devices Retrograde blood flow with worsening of afterload (LV distension) Vascular complications Thrombocytopenia	Limited hemodynamic support Contraindicated in severe aortic regurgitation	Need tertiary or quaternary specialized care center Necessitates atrial transseptal puncture with its potential complications Vascular complications Retrograde blood flow	More invasive and complex to implant than the IABP Unstable position Frequent hemolysis Vascular complications

CO_2 = carbon dioxide; FDA = U.S. Food and Drug Administration; IABP = intra-aortic balloon pump; LV = left ventricle/ventricular; RV = right ventricle; VA-ECMO = venoarterial extracorporeal membrane oxygenation.

cardiogenic shock, these indexes are also typically reduced (**Figure 3**) (10). Different cardiac effects using PV loops with the different mechanical support devices have been reported (11).

Specifically, with VA-ECMO, LV afterload increases, as reflected by the increase in effective arterial elastance, a known component of LV afterload, as depicted in **Figure 4** (12). This contributes to an increase in LVEDP. In patients with significantly reduced ejection fractions at baseline, VA-ECMO may cause an increase in wall stress and oxygen demand, which impedes myocardial recovery and may precipitate progressive pulmonary edema and acute lung injury and worsen outcomes (13). This complication is generally referred to as LV distension or ECMO lung.

FIGURE 2 Venoarterial Extracorporeal Membrane Oxygenation Circuit



A centrifugal pump withdraws desaturated blood from the right atrium with nonpulsatile pump outflow directed toward the membrane oxygenator then guided via an outflow cannula to a systemic artery. Reprinted with permission from Kapur and Zisa (7). Ao = aorta; LA = left atrium; LV = left ventricle; RA = right atrium; RV = right ventricle.

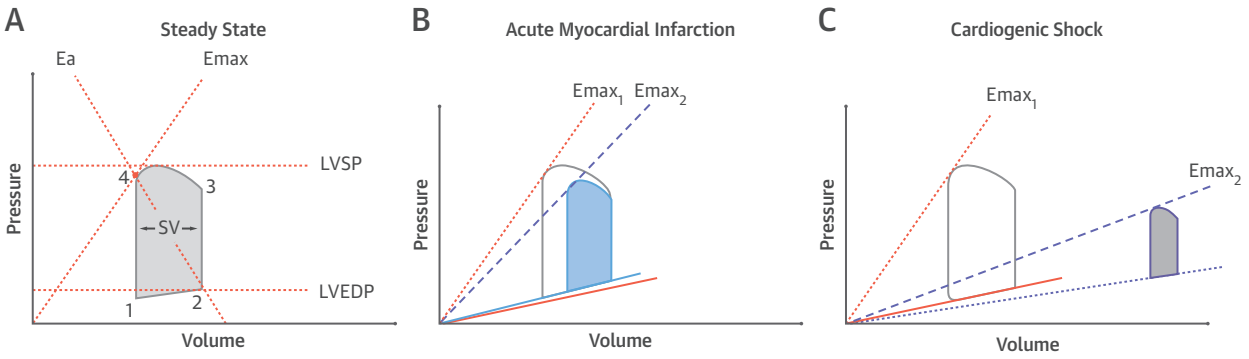
VA-ECMO-dependent increases in LV end-diastolic, left atrial, and pulmonary capillary wedge pressures can be mitigated by decreases in systemic vascular resistance or improvements in ventricular contractility (12). However, subtle increases in LV end-diastolic volume can be associated with substantial increases in LVEDP due to the nonlinear end-diastolic PV relationship (**Figure 4**) (12).

Monitoring for increasing LVEDP may include serial physical examinations, chest radiographs, or Swan-Ganz catheter monitoring. Treatment of anticipated or observed increases in LV systolic and end-diastolic pressure includes venting or decompressing the LV.

Multiple strategies to reduce pulmonary congestion during VA-ECMO support have been used (11,14–16).

1. Increase in forward flow by introducing inotropes or devices such as Impella (Abiomed, Danvers, Massachusetts) or intra-aortic balloon pump (IABP).
2. Decrease in LV afterload by placement of an IABP.

FIGURE 3 PV Loops in the Normal Condition, With Acute Myocardial Infarction, and in Acute on Chronic Heart Failure Complicated by Cardiogenic Shock

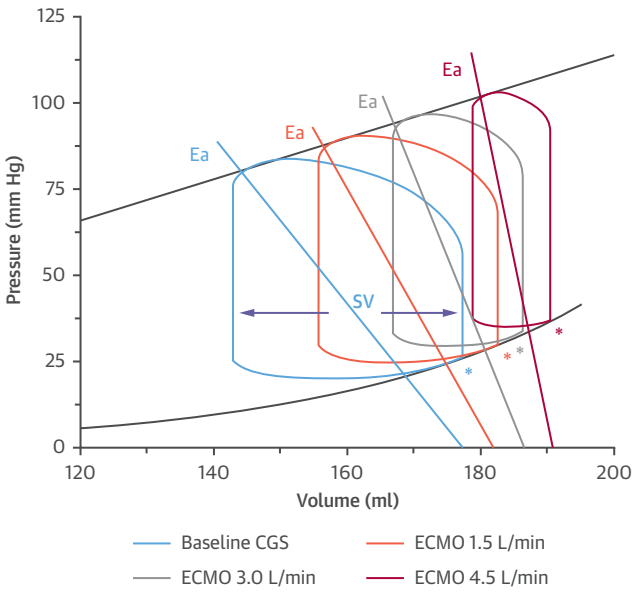


(A) Normal condition pressure-volume (PV) loop. **Point 1** notes the end of isovolumic relaxation. Phase 1 to 2 defines diastole. **Point 2** (end-diastole) represents maximum left ventricular (LV) volume and the onset of isovolumic relaxation. **Point 3** defines peak isovolumic contraction, where LV pressure exceeds aortic pressure and marks the onset of blood ejection into the aorta. Phase 3 to 4 defines the systolic ejection phase, and illustrates the decrease in LV volume. **Point 4** defines the end-systolic PV point where aortic pressure exceeds LV pressure and marks aortic valve closure. The width of the PV loop represents stroke volume (SV), defined as the difference between end-diastolic and end-systolic volumes. The **shaded area within the loop** represents stroke work. Emax represents load-independent LV contractility defined as the maximum slope of the end-systolic PV point under various loading conditions. Effective arterial elastance (Ea) is a component of LV afterload, and is defined as the ratio of end-systolic pressure and SV. **(B)** PV loop in acute myocardial infarction **(blue loop)**. LV contractility ($Emax_2$), LV systolic pressure (LVSP), SV, and stroke work are mildly reduced. LV end-diastolic pressure (LVEDP) is increased. **(C)** PV loop in acute on chronic heart failure cardiogenic shock **(dark gray loop)**. LV contractility ($Emax_2$) is severely reduced, LVEDP and LV end-diastolic volume are significantly increased and SV is significantly reduced. Adapted with permission from Rihal et al. (10).

3. Mechanical decompression of the LV by shunting the blood to the right side via atrial septostomy or removal of LV volume via placement of Impella, transseptal cannulation of the LV or left atrium (LA), or direct surgical LV apical drainage.
4. Removal of fluid from intravascular space using diuretic agents, ultrafiltration, or hemodialysis.
5. Reduction in ECMO speed and consequently ECMO flow (which may not be well tolerated).

The use of IABP counterpulsation in VA-ECMO is debated in published reports, but is thought to enhance systolic unloading and improve the myocardial oxygen supply-demand ratio (17). Two studies demonstrated smaller LV dimensions and lower pulmonary artery pressures with VA-ECMO plus active IABP support (11,15). In a retrospective cohort study of 1,650 adult patients with cardiogenic shock from the nationwide Japanese national inpatient database, 28-day and in-hospital mortality were significantly lower with VA-ECMO plus IABP (48.4% vs. 58.2%; p = 0.001) than with VA-ECMO alone (55.9% vs. 64.5%; p = 0.004) (18). However, an observational meta-analysis of 16 studies showed a lack of survival benefit of VA-ECMO with concomitant IABP (19). To date, no randomized controlled trials have been performed to clarify the role of venting and the strategy (IABP vs. alternative devices) that best attenuates the VA-ECMO flow-dependent increase in LVEDP.

FIGURE 4 LV Hemodynamic Effects of Venoarterial ECMO



The negative impact of venoarterial extracorporeal membrane oxygenation (ECMO) on PV loop curves with a flow dependent increase in LVEDP **(asterisks)** and associated increase in effective Ea, as defined in **Figure 2**. An associated flow-dependent decrease in LV SV is depicted in the PV loops and is represented by the width of the PV loop as the volume difference between end-systolic and end-diastolic volumes. Modified and adapted with permission from Burkhoff et al. (12). CGS = cardiogenic shock; other abbreviations as in **Figure 3**.

TABLE 2 Common Objectives for Venoarterial Extracorporeal Membrane Oxygenation Insertion

Scenario	Explanation
Bridge to recovery	Temporize circulatory support while definitive and supportive treatment strategies are deployed to restore myocardial recovery and achieve successful weaning
Bridge to decision	To determine the reversibility of end-organ damage commonly seen after a catastrophic or critical myocardial event or to decide the next level of action
Bridge to bridge	To achieve a brief stability for end-organ perfusion until more definitive pump support (durable mechanical circulatory support) or cardiac replacement therapy (heart transplant or total artificial heart) is performed
Bridge to transplant	To achieve a brief stability for end-organ perfusion until cardiac transplantation is performed

ECMO provides continuous blood flow. Any pulsatility, if present, is created by the residual function of the LV. In severe cases of cardiogenic shock or in the presence of cardiac tamponade, Korotkoff sounds may be absent and only mean blood pressure can be measured, necessitating use of an arterial line. As cardiac function improves, pulsatility on the arterial tracing is increasingly pronounced and may be a sign of recovery.

INDICATIONS AND CONTRAINDICATIONS

INDICATIONS. The key to ECMO success is the principal of ECMO as a bridge to recovery or definitive treatment. ECMO does not cure the underlying condition; it provides time for the patient to heal or for the team of providers to find a long-term solution, such as a durable ventricular assist device or heart transplantation (**Central Illustration**). VA-ECMO insertion is usually done to: 1) provide circulatory support while the heart recovers, spontaneously or with treatment (bridge to recovery/wean); 2) determine reversibility of end-organ damage commonly seen after a catastrophic or critical myocardial event (bridge to decision); and 3) achieve a period of temporary stability until more definitive pump support (durable mechanical circulatory support) or cardiac replacement therapy (heart transplant or total artificial heart) is deployed (bridge to bridge) (**Table 2**).

TABLE 3 Indications for Venoarterial Extracorporeal Membrane Oxygenation

1. Cardiac arrest (extracorporeal CPR)
Cardiogenic shock due to
2. Acute myocardial infarction
3. Acute myocarditis
4. Progression of cardiomyopathy, ischemic or nonischemic
5. Acute RV failure due to pulmonary embolism
6. Progression of RV failure due to pulmonary disease
7. Progression of congenital heart disease
8. Primary graft failure and acute allograft rejection after heart transplantation
9. Overdose of cardiotoxic drugs
10. Septic cardiomyopathy
11. Refractory ventricular tachycardia
12. RV failure during LVAD support
13. Failure to wean off cardiopulmonary bypass*

*Surgical indication beyond the scope of this review.
CPR = cardiopulmonary resuscitation; LVAD = left ventricular assist device; RV = right ventricular.

Lack of a solution (listed previously) or a potential to recovery should discourage ECMO initiation. The ECMO team should consider objectives (**Table 2**) and indications (**Table 3**) for VA-ECMO before patient cannulation: 1) cardiac arrest; 2) cardiogenic shock; 3) refractory ventricular tachycardia; 4) RV failure during LVAD support; and 5) failure to wean off cardiopulmonary bypass.

CONTRAINDICATIONS. Contraindications for VA-ECMO include (20):

Absolute

Severe irreversible noncardiac organ failure limiting survival (e.g., severe anoxic brain injury or metastatic cancer)

Irreversible cardiac failure if transplantation or long-term VAD are not considered

Aortic dissection

Relative

Severe coagulopathy or contraindication to anticoagulation, including advanced liver disease

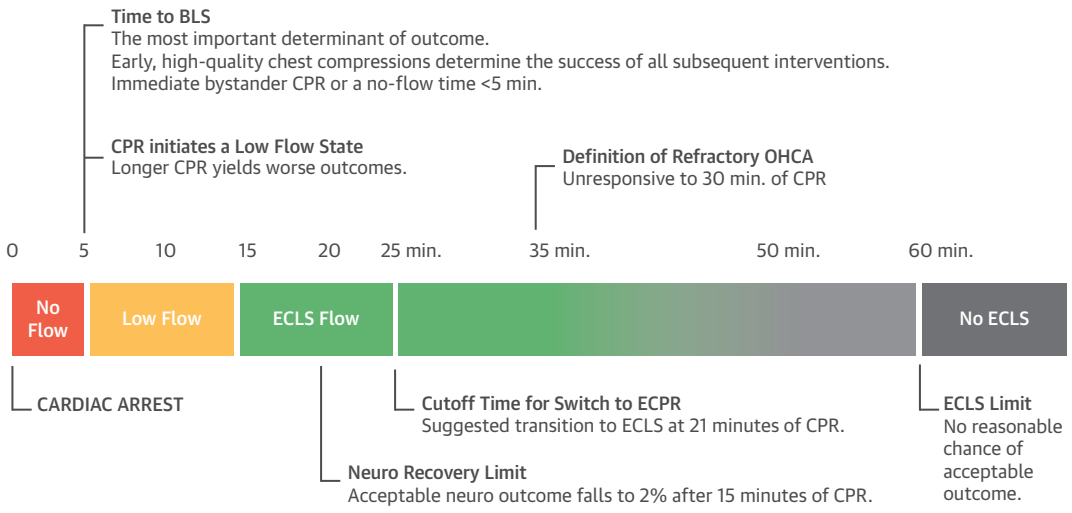
Limited vascular access (severe peripheral arterial disease, extreme obesity, amputated limbs, among others)

Predictors of mortality on VA-ECMO include older age, female sex, longer support time, decreased cardiac function at baseline (21), high lactate concentration, peripheral vascular disease, chronic obstructive lung disease, renal dysfunction (22,23), stroke, infection, hypoglycemia, alkalosis (24), device insertion during CPR, and decreased urine output (25).

CARDIAC ARREST

Increasingly, VA-ECMO is being used during initial resuscitation from cardiac arrest. ECPR, the acronym by which this modality is known, is the application of rapid-deployment ECMO to provide circulatory support in patients who fail to achieve a sustained return of spontaneous circulation (ROSC) (defined as 20 consecutive minutes without a need for chest compressions by conventional CPR) (26). Use of ECMO initiated for low cardiac output following sustained ROSC is not considered ECPR (27). This important distinction is often neglected in published reports,

FIGURE 5 ECPR Time for Patient Selection



The interval from the arrest to the beginning of cardiopulmonary resuscitation (CPR) should be considered a no-flow period **(far left)**, whereas time on CPR is a low-flow period with suboptimal circulation. The probability of survival with good neurological outcome declines rapidly with each minute of conventional CPR. When extracorporeal CPR (ECPR) is delayed until refractory cardiac arrest, CPR, survival is extremely poor **(far right)**. BLS = basic life support; ECLS = extracorporeal life support; OHCA = out-of-hospital cardiac arrest.

making outcome analysis difficult. A recent prospective cohort study of in- and out-of-hospital ECPR in selected patients boasted 54% survival to discharge with full neurological function (6).

The most important determinant of outcome is time to basic life support. Early chest compressions influence all subsequent interventions. Immediate bystander CPR or a no-flow time <5 min are prerequisites for ECPR (4). The interval from the arrest to the beginning of CPR should be considered a no-flow period, whereas time on CPR is a low-flow period (28) with suboptimal circulation. The probability of survival with a good neurological outcome declines rapidly with each minute of conventional CPR. When ECPR is delayed until refractory cardiac arrest, defined as no response to resuscitation efforts after 30 min of conventional CPR, survival is extremely poor (29).

ECPR should be attempted early after cardiac arrest, rather than after the complete failure of traditional measures (30). Studies suggest 21 min of conventional CPR before initiation of extracorporeal life support (VA-ECMO), with ECPR preparation in the first 10 min of CPR and cannulation within 20 min of collapse (**Figure 5**) (31).

Although the upper age limit for ECPR varies by center, some studies exclude patients >70 to 75 years of age (32,33). Commonly used inclusion or exclusion criteria for ECPR are:

Inclusion criteria

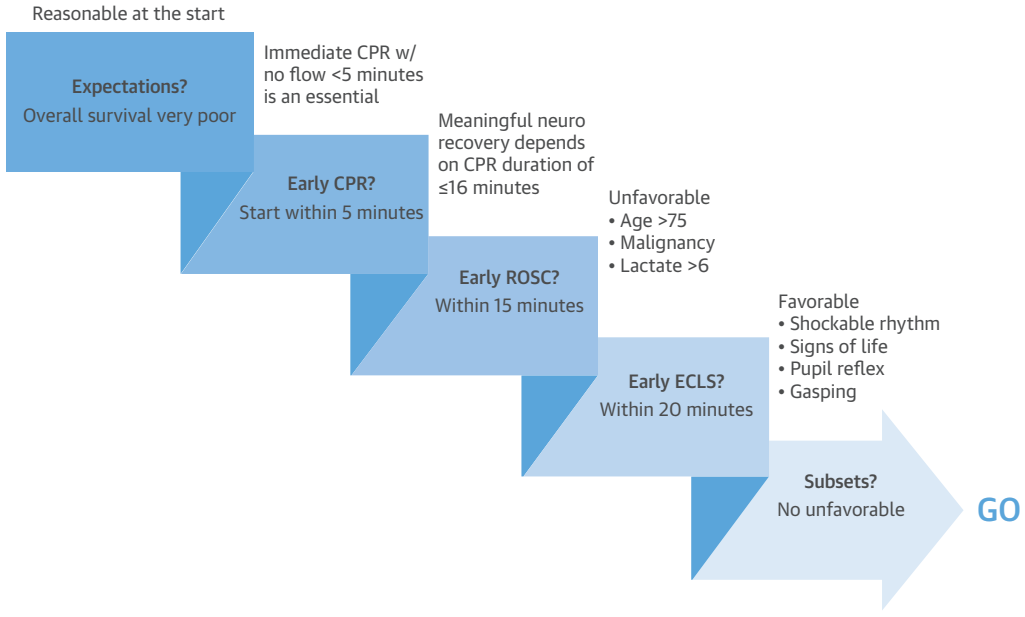
- Age <70 years
- Initial rhythm of ventricular fibrillation or ventricular tachycardia
- Witnessed arrest
- Bystander CPR within 5 min
- Failure to achieve ROSC within 15 min of beginning CPR (20)

Exclusion criteria

- Asystole as an initial rhythm
- Unwitnessed arrest
- Total cardiac arrest time >60 min
- Pre-existing severe neurological or systemic disease (including stroke, severe dementia, advanced malignancy, chronic neuromuscular dystrophy, psychiatric conditions, anoxic brain injury)
- Contraindications to anticoagulation
- Acute aortic dissection
- Suspicion of shock due to hemorrhage or other noncardiovascular cause
- Known “do not resuscitate” (DNR) status

A decision-making algorithm to initiate ECPR is presented in **Figure 6**. In-hospital cardiac arrest may

FIGURE 6 Decision-Making Algorithm on Initiation of ECPR



Possible outcomes after initiating CPR within 5 min **(far left)** leading to either favorable or unfavorable outcomes based on timeline decisions to start return of spontaneous circulation (ROSC) or ECLS. Abbreviations as in Figure 5.

be a particularly favorable setting for ECPR. In unmatched cohorts, ECPR resulted in a higher survival rate to discharge (log-rank $p < 0.0001$) and a better 1-year survival rate (log rank $p = 0.007$). Between the propensity score-matched groups, there was still a significant difference in survival to discharge (hazard ratio [HR]: 0.51; 95% confidence interval [CI]: 0.35 to 0.74; $p < 0.0001$), 30-day survival (HR: 0.47: 95% CI: 0.28 to 0.77; $p = 0.003$), and 1-year survival (HR: 0.53; 95% CI: 0.33 to 0.83; $p = 0.006$) favoring ECPR over conventional CPR (6).

A recent meta-analysis of ECPR studies showed that ECPR was associated with an absolute increase in 30-day survival of 13% (95% CI: 6% to 20%; $p < 0.001$; number needed to treat: 7.7) and a higher rate of favorable neurological outcome at 30 days (absolute risk difference 14%; 95% CI: 7% to 20%; $p < 0.0001$; number needed to treat: 7.1) compared with conventional CPR (34).

CARDIOGENIC SHOCK

Cardiogenic shock is a critical condition of hemodynamic instability with compromise of end-organ and tissue perfusion. Commonly accepted hemodynamic parameters defining cardiogenic shock include cardiac index <2.0 l/min/m^2 with systolic blood pressure <90 mm Hg and pulmonary capillary wedge pressure ≥24 mm Hg, and dependency on at least 2 inotropes or vasopressors, with or without IABP (35). With pharmacological treatment only, recovery is rare. If the cause of the shock is reversible, the patient should be considered for VA-ECMO.

Cardiogenic shock can originate from a variety of conditions, including LV, RV, or biventricular failure. Typical causes of cardiogenic shock are listed in Table 3, and a detailed review of published studies on each etiology can be found in our previously published work (36). Survival to discharge in cardiogenic shock due to acute myocardial infarction ranges from 19.2% (37) to 87.5% (38). Survival outcomes range from 47% (22) to 83.3% (39,40) for myocarditis and 57% (41) to 100% (42) for pulmonary embolism. VA-ECMO for acute rejection of cardiac allograft can be used as a preemptive measure, with a 79% rate of survival to discharge or as a salvage strategy with survival rate of 14% (43). Reports of successful ECMO use in drug overdose or drug intoxication exist, but are associated with severe depression of cardiac function (33).

Two groups of patients, those with fulminant myocarditis (Table 4) and those with pulmonary embolism with acute RV failure (Table 5), are of special interest due to excellent reported survival, and

VA-ECMO should be considered upon early signs of hemodynamic instability. The ELSO data review on acute myocarditis identified 147 patients with 61% survival to hospital discharge (44). Also, ECMO is becoming a universal rescue tool for an acute hemodynamic compromise resulting from a variety of invasive procedures, such as transcatheter aortic valve replacement (45).

REFRACTORY VENTRICULAR TACHYCARDIA

VA-ECMO is successfully used to hemodynamically stabilize patients in refractory ventricular tachycardia or fibrillation, regardless of etiology. Creating a continuous blood flow, ECMO maintains adequate hemodynamics in the setting of ventricular tachycardia, ventricular fibrillation, or electrical storm while antiarrhythmic therapies are administrated or radiofrequency ablation is performed (46), helping patients to survive, either to stability or to heart transplantation or LVAD implantation (47-52).

LOGISTICS OF VA-ECMO: ACTIVATION, CANNULATION, MANAGEMENT, WEANING

The logistics of placing a patient on ECMO can be divided into several steps, each requiring a specific skill set. Historical practice patterns will often determine which combination of specialists will be involved in care of the ECMO patient. Almost invariably, however, the team includes interventional and clinical cardiologists, critical care specialists, perfusionists, vascular or cardiothoracic surgeons, specially trained critical care nurses, and sometimes emergency physicians and palliative care specialists. At a minimum, there are at least 5 steps: 1) activation; 2) cannulation; 3) ongoing management; 4) weaning; and 5) decannulation.

ACTIVATION. Activation of the ECMO team requires (except in emergency circumstances) a priori interactive discussion between team members to make an initial assessment regarding the probability of success based upon the clinical scenario, institutional capabilities, and survival estimates. After the majority of team members agree to proceed, the inserting physician needs to coordinate the process with the perfusionists or catheterization laboratory nurses and arrange for a critical care bed and an advanced paramedic transport unit, when indicated.

CANNULATION. Cannulation is critically important. Access is usually achieved percutaneously in the catheterization laboratory or at the bedside, as may be needed during ECPR. In less urgent situations, surgical cutdown in the operating room may be considered. Insertion of a large-bore cannula into the artery in a patient who is going to be systemically anticoagulated has to be done meticulously to avoid hematoma, bleeding, and vascular compromise. For percutaneous insertion, this step is often performed using ultrasound guidance and micropuncture needles. To the extent possible, cannulation should be performed by experienced individuals, such as interventional cardiologists or cardiothoracic or vascular surgeons.

The size of the cannulas required for arterial and venous cannulation for VA-ECMO support is not clearly defined by current published data. It is usual practice to select cannulas that will yield full support

TABLE 4 Survival With ECMO in Fulminant Myocarditis

First Author, Year (Ref. #)	n	Survival on ECMO (%)	Survival to Discharge (%)	Days on ECMO
Asaumi, 2005 (84)	14	71	71	5.4*
Pages, 2009 (40)	6	83	83	13 ± 4
Kawahito, 1998 (39)	6	83	83	8.3 ± 2.1
Kato, 1999 (85)	9	100	78	6.4 ± 2.2
Carroll, 2015 (22)	13	80	70	–
Hsu, 2011 (86)	75	–	64	7.1 ± 5.0
Mirabel, 2011 (87)	35	–	69	–
Gariboldi, 2010 (88)	10	–	70	12.0*
Ishida, 2013 (89)	20	–	60	–
Wu, 2012 (90)	16	–	88	–
Montero, 2018 (91)	11	72	72	–
Liao, 2017 (92)	33	–	79	3.0 ± 1.9
Lorusso, 2016 (93)	57	–	71.9	9.9 ± 19
Nakamura, 2015 (28)	22	–	59	7.5 ± 1.1
Aso, 2016 (94)	122	–	45	–

Values are mean ± SD, unless otherwise indicated. *Median value.
ECMO = extracorporeal membrane oxygenation.

TABLE 5 Survival With ECMO in Pulmonary Embolism With Acute RV Failure

First Author, Year (Ref. #)	n	Survival on ECMO (%)	Survival to Discharge (%)	Days on ECMO
Kawahito, 2000 (41)	7	57	57	2.8 ± 2.8
Maggio, 2007 (95)	21	–	62	4.7 ± 4.1
Munakata, 2012 (96)	10	–	70	2 ± 1.9
Akkanti, 2015 (42)	4	100	100	–
Aso, 2016 (94)	353	57.2	34	–
Dolmatova, 2017 (97)	5	60	60	10.4 ± 4.4
Corsi, 2017 (98)	17	59	47	4.0*
George, 2017 (99)	32	65.6	53.1	–
Pasrija, 2018 (100)	20	95	95	5.1*

Values are mean ± SD, unless otherwise indicated. *Median value.
ECMO = extracorporeal membrane oxygenation; RV = right ventricular.

for a given patient, that is, to achieve an index of 2.2 l/min/m^2.

Investigators from the University of Michigan state that a pressure drop in the circuit should not exceed 100 mm Hg across the venous cannula and 300 mm Hg across the arterial side. The flow required for full support in an adult is about 60 cm^3/kg/min. Not only are the length and diameter of the cannula important, but there are special flow characteristics for each cannula, that can be described by a pressure flow curve. A unique number, called a UM number (flow achieved at a pressure drop of 100 mm Hg across a cannula) may be used to describe the cannula and its flow characteristics (53).

Cannulation can be performed peripherally or centrally. Peripheral insertion may be quicker, but it is known to be associated with vascular compromise of the lower extremity due to the large size of the cannula, particularly in small women or in a high systemic vascular resistance ("clamped down") state. It is generally stated that unless the vessel is at least 1 to 2 mm larger than the cannula, there is the risk of limb ischemia. This problem can be addressed by placing a small 6-F to 8-F antegrade sheath or introducer into the superficial femoral artery at the time of cannula insertion and diverting a small portion of the arterial return flow down the limb (reperfusion catheter).

Femoral vein to femoral artery is the most common approach. Nonemergent VA-ECMO patients may be considered for internal jugular vein to subclavian artery cannulation, termed the "sport model" (54,55). This development in technique moved nonemergent VA-ECMO cannulation sites from the groin (femoral) to the upper body (subclavian) vessels, facilitating ambulation (56,57). Ambulatory ECMO is particularly important in patients awaiting transplantation to reduce the risk of patients deconditioning as they await transplantation. (58).

Unique patient needs can be accommodated by the addition of a second venous cannula (including dual-lumen cannulae, such as the Avalon Elite [Getinge, Gothenburg, Sweden] or OriGen [OriGen Biomedical, Inc., Austin, Texas]) to convert between the VV and the venoarterial-venous hybrid configuration. Venoarterial-venous cannulation is rarely used as an initial strategy, but may be used for additional oxygenation. A case series by Cheng et al. (54) resuscitated 11 patients using hybrid ECMO with a 36% survival rate.

MANAGEMENT. ECMO flow. Usually, an ECMO flow of 50 to 70 ml/kg/min (~4 to 6 l/min) is sufficient for full markedly decreased and the aorta is filled by retrograde flow from the arterial ECMO cannula. Therefore, the afterload faced by the LV is increased. This may result in an elevated LVEDP, elevated pulmonary capillary wedge pressure, and ultimately pulmonary congestion. In this situation, the use of inotropes may be considered or, in unusual circumstances, an interatrial balloon septostomy can be performed to shunt blood from the LA to the right atrium and reduce the elevated left-sided pressures. Multiple approaches to LV unloading or "venting" are reviewed in the Pathophysiology section. Another disadvantage to VA bypass is that any particles, bubbles, or emboli that may be infused into the arterial or venous circuit can result in an adverse cerebral event. Finally, the decreased flow through the lungs may permit the development of microvascular intrapulmonary thromboses, which may further worsen the pulmonary pathology.

Monitoring. An ECMO patient should invariably have an arterial line and may have a pulmonary artery catheter. The pulmonary artery catheter is normally used to monitor mixed venous saturation, although some of the newer pumps (Maquet CardioHelp) do continuously monitor mixed venous saturation, perhaps obviating the need for the pulmonary artery catheter. Use of the thermodilution cardiac output is misleading, as an unknown amount of the cold bolus is drawn into the ECMO circuit, invalidating the calculation. A Swan-Ganz catheter should be placed and used as a tool to monitor pulmonary arterial pressure as a surrogate of LV distention. Intermittent measurement of lactate might be helpful.

Anticoagulation. Systemic anticoagulation therapy minimizes interaction of blood products with the surface of the ECMO circuit. Fibrinogen and albumin adsorb to the circuit's biopolymer components, resulting in platelet aggregation, activation, and consumption within 1 h of ECMO initiation (59). The activated coagulation system may result in thrombocytopenia, which can be profound, sometimes requiring platelet transfusions.

The choice of agent used for anticoagulation, as well as monitoring of the level of anticoagulation, varies from site to site. Heparin is the most common anticoagulant, used according to a standard weight-based protocol and monitored either by activated thromboplastin time, goal 50 to 75 s (1.5× to 2.5× baseline) or anti-factor Xa, goal 0.3 to 0.7 IU/ml. Some centers prefer to follow the activated clotting time, due to its bedside availability and rapid turnaround time, goal 180 to 220 s.

Direct thrombin inhibitors, such as parenteral bivalirudin and argatroban, represent alternatives to heparin in individuals with heparin-induced thrombocytopenia. Patients anticoagulated using these direct thrombin inhibitors are monitored for activated partial thromboplastin times between 50 and 60 s (60).

VENTILATOR MANAGEMENT. Patients on ECMO may or may not require ventilator support. Because ECMO provides up to full gas exchange, the conscious patient in cardiogenic shock can breathe spontaneously while on ECMO, regardless of respiratory function. However, ventilator support may be necessary for airway protection in patients requiring sedation, such as cardiac arrest patients. Most centers use low tidal volume ventilation (3 to 5 ml/kg) to reduce the risk of lung injury. Protective mechanical ventilation settings include a rate of <8/min, positive end-expiratory pressure of 10 to 15 Torr, fraction of inspired oxygen <0.40, and low tidal volume (61).

Hemodialysis on ECMO. Continuous VV hemodialysis can be done via ECMO circuit or via separate vascular access. Conventional hemodialysis is also an option.

Temperature. An integral heat exchanger is included with the membrane oxygenator. Thus, a patient may be warmed or cooled as necessary. This may obscure the presence of a "fever" and make the recognition of an infection more difficult. Should ECMO be used for a patient after an anoxic insult, maintaining a temperature no higher than 36°F for up to 24 h might be of value (62).

WEANING. If a patient improves on ECMO, weaning is the next step. ECMO flow is decreased by approximately 1 l/h over a period of 3 to 4 h, although slower rates of weaning at 0.5 l every 6 to 24 h have been reported as well (57). The patient should be able to maintain a mixed venous saturation >65%, and an arterial saturation of >90% with an ECMO flow <1.5 l/min. A bridge between the arterial and venous cannulae can be also used to completely separate patient circulation from the ECMO circuit without decannulation. If there are signs of decompensation, the bridge is clamped, and the patient is placed back on full support (63). Decannulation typically occurs in the catheterization laboratory or in the operating room.

COMPLICATIONS

LIMB ISCHEMIA. Historically, limb ischemia occurred in 16.9% of patients supported by peripheral VA-ECMO. Fasciotomy, due to compartment syndrome, was needed in 10.3% of patients, with 4.7% requiring amputation (54). Currently, the use of prophylactic antegrade perfusion catheters (as described earlier) has probably reduced the incidence of this complication. Per Lamb et al. (64), none of 55 patients with a distal perfusion catheter placed prophylactically developed limb ischemia, as opposed to 12 of 36 patients without such a catheter. A meta-analysis by Juo et al. (65) reported a relative risk ratio of 0.41 with a distal perfusion catheter, so it is strongly recommended.

Typical symptoms of limb ischemia include pallor, loss of pulses, and gangrene. Compartment syndrome is rarely seen in profoundly ischemic limbs before reperfusion, with a distal perfusion catheter. After reperfusion, however, the limb may become swollen and the skin taut. If measurement of the compartment pressures reveals a value above 20 mm Hg, fasciotomy is usually required. A high index of suspicion is necessary as are frequent Doppler checks and hourly monitoring. The presence of an elevated creatinine phosphokinase or lactate level (although not consistently seen) is usually a late and very concerning finding.

STROKE. Ischemic and hemorrhagic stroke occur in approximately 4% of VA ECMO patients (66). The rate of stroke varies by indication and cannulation technique. Ischemic stroke is most common in ECPR patients, diagnosed in 7% of successful resuscitations (66). Cannulation via the carotid artery triples the risk of ischemic stroke compared with femoral artery cannulation (67). One in 4 cerebral ischemia patients on VA-ECMO survive, whereas only 1 in 10 cerebral hemorrhage patients survives (68), usually with neurological deficit. Cognitive function should be monitored continuously in ECMO patients.

The cause of stroke is multifactorial, with thromboembolic events, systemic anticoagulation, and hemodynamic instability thought to contribute. The presence of the circuit adds risk secondary to particles, bubbles, or emboli, which may be infused inadvertently into the arterial circuit. Because of the low-flow state, thrombi can form spontaneously in the LA and LV.

BLEEDING. Patients on VA-ECMO are typically anticoagulated and prone to bleeding. For optimal blood oxygen saturation, hemoglobin should be maintained between 8 and 10 mg/dl. Transfusions may be required, but they may allosensitize a potential transplant candidate and cause transfusion-related acute lung injury.

Bleeding is treated by reducing the dosage of heparin (or direct thrombin inhibitor) or stopping

anticoagulation. A number of reports suggest that it is safe to withdraw anticoagulation for up to 3 days in circumstances of anticoagulation intolerance (69). When modification of anticoagulation is inadequate, either protamine or, more commonly, factor-containing products are needed, and the possibility of heparin induced thrombocytopenia should be considered.

INFECTION. The most likely infectious complications of VA-ECMO are bacteremia and sepsis, with longer ECMO runs associated with higher infection rates. More than 53% of adults acquire an infection within 14 days of ECMO initiation. Mortality in patients with infectious complications reaches 60%. The sterile technique during cannulation is of paramount importance, especially considering the urgent or emergent nature of the procedure.

HARLEQUIN SYNDROME. As the LV recovers, it starts ejecting blood it receives from the pulmonary circulation. Forward flow of deoxygenated blood from failing native lungs mixes unpredictably with retrograde flow from the oxygenator, which can result in inadequate delivery of oxygenated blood into the aortic arch, resulting in upper body and brain hypoxia. This phenomenon, known as Harlequin syndrome, may result in cyanosis of the upper extremities while the lower extremities appear pink. Saturation monitoring for Harlequin syndrome is performed at the right hand, forehead, nose, or right ear, and arterial blood gas should be obtained from a right arm arterial line.

ECMO PROGRAM

ECMO is a complex and high-risk therapy that should be managed at experienced centers with appropriate personnel and sufficient resources to ensure it is used effectively (70,71). New ECMO programs should partner with larger and more experienced programs to not only learn from their personnel, but to acquire sample care plans, nursing protocols, and policies. Advanced heart failure care programs that offer multiple forms of mechanical circulatory support, heart and lung transplant, and advanced medical therapy at high-volume tertiary care centers should serve as hub ECMO centers. All centers participating in such a hub-and-spoke system of care should strictly adhere to written standardized protocols that detail criteria for the initiation of ECMO support, contraindications, follow-up care, and exit strategies.

ECMO TEAM STRUCTURE

Patients requiring ECMO support need the highest level of intensive care from a multidisciplinary team. Because the initiation of ECMO therapy is time sensitive, numerous interventions take place simultaneously or in rapid succession until the patient's condition is stabilized. Triage by ECMO experts to confirm appropriate candidates is necessary to avoid futile application of the therapy. Core ECMO teams generally consist of trained and dedicated physicians, an ECMO coordinator, nurse practitioners, staff nurses, perfusionists, and respiratory therapists (72). The ELSO guidelines recommend that program directors should be a board-certified critical care specialist; cardiovascular specialist; a thoracic, vascular, or trauma surgeon; cardiac and critical care anesthesiologist; or other board-certified specialist with training and experience in ECMO therapy (70,73,74). ECMO specialists should be available 24/7 to support the team and complete daily patient management. In some hospitals, emergency room physicians become an integral part of the program, fully capable of initiating ECMO (75).

After appropriate patient selection and team notification, a primary ECMO physician directs the team, performs cannulation, and leads multidisciplinary patient management. Critical care nurses manage intravenous lines, administer medications, monitor pressure and electrocardiogram data, request laboratory tests, and document care. Specifically, a nurse places defibrillator pads on the chest, ensures adequate intravenous access, prepares heparin, and types and crossmatches for red blood cells, fresh frozen plasma, and platelets. The perfusionist provides cannulas, primes and sets up the ECMO circuit, and initiates support after the circuit is completed. After support is initiated, cannula sites are secured with bands, a sterile dressing is placed, and x-rays are taken to check for proper cannula locations. Continuous ECMO support requires nursing at 1:1 or 1:2 ratios, and ECMO physicians should be in the immediate vicinity and should provide continuous medical management.

Staffing of the ECMO team varies considerably among institutions; case volume and other responsibilities are the primary determinant. Physician availability 24 h a day to cannulate and manage ongoing cases requires a minimum of 3 physicians, but this number depends largely on their total responsibilities while on duty. If the physician is also responsible for other critically ill patients, post-LVAD

or post-transplant cases, the acuity increases substantially.

When institutions initiate a new ECMO program, a thorough analysis of the potential patient volume, intensive care unit capacity, and staffing should be conducted to assure that an appropriate amount of financial support, human resources, and spaces are available. Hospital administration should be committed to the support of the program's initiation costs, but should also be aware that if the volume of cases exceeds the estimate, more equipment and personnel resources will be needed.

ECMO TRANSPORT PROGRAM

ELSO provides detailed guidelines for the transport of patients supported by ECMO (2). The establishment of advanced cardiac care systems that are designed with high-volume hub hospitals integrated with emergency medical systems and community-based spoke centers may affect the outcomes of patients with profound cardiac or pulmonary failure (71). A hub-and-spoke regional network consists of 3 levels of care. Level 1 centers provide all aspects of care, including transplant, durable VADs, and short-term circulatory support, including ECMO. Level 2 centers provide cardiac catheterization and surgery, with the capability of short-term mechanical support. Level 3 centers provide resuscitation, with medical therapy for stabilization (**Figure 7**) (76). Bringing together these different-level centers to provide ECMO support requires commitment and communication from a variety of health care professionals. Protocols that define communications, triage and patient selection, patient management, and the transport process must be in place and strictly adhered to by all participating centers so that debate is minimized during the triage process. The overall coordination of the ECMO system is the responsibility of the Level 1 hub hospital.

The mobile ECMO team must be available 24 h a day and be staffed with experienced personnel trained in cannulation and transport of patients, initiation of ECMO support, and patient management. An ECMO specialist at the Level 1 hub center needs to be available 24 h a day to consult with Level 2 and Level 3 centers regarding the choice of care for patients at the spoke centers. When ECMO is the treatment of choice, rapid implementation of therapy is essential (77). Patients with severe cardiogenic shock or pulmonary failure presenting at Level 3 centers should be promptly transported to the hub center if their condition is sufficiently stable. For unstable cases, an ECMO transport team is dispatched to initiate therapy onsite.

Depending on distance and the size of the metropolitan area, ground ambulance, helicopter, or fixed-wing aircraft may be used. Ideally, the hub hospital has helicopter service readily available and can provide timely transport. For transport of a stable patient to the hub hospital, a ground ambulance may be best if the distance is not excessive (78). In the regional program in Oklahoma, 250 patients from 4 different states have been transported by multiple modes of transportation.

DEVELOPING AREAS AND FUTURE DIRECTIONS

Many topics surrounding VA-ECMO use in cardiology are heavily debated. We discuss several of particular importance.

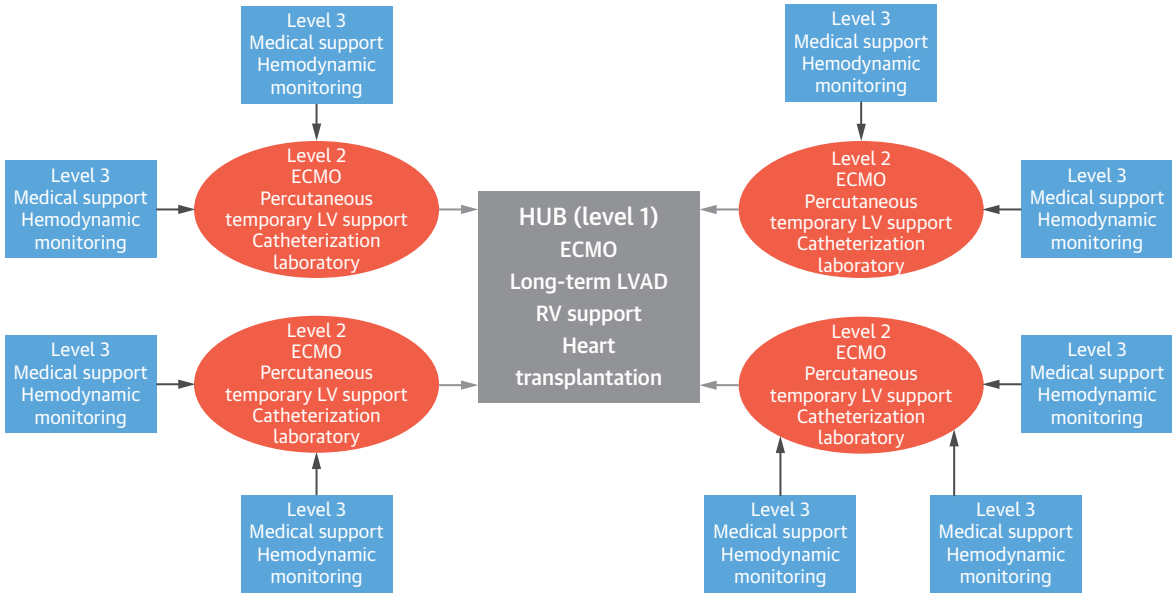
ETHICS

As with all critically ill patients with high odds of a bad outcome, ethical considerations play an important role in handling ECMO. Ethical considerations pertain to the 3 pillars: 1) patients and their families; 2) the health care team; and 3) society in general.

PATIENT AND FAMILY. ECMO is often instituted without adequate time for a detailed discussion between the health care team and the patients and their families. This can result in unclear perceptions of goals, poor understanding of limitations, and cases of futility and situations mandating withdrawal. An ECMO-specific consent form should be considered by institutions. In situations involving disagreement, early involvement of the ethics team, palliative care team, and hospital leadership may be beneficial (79).

HEALTH CARE TEAM. ECMO care can result in a significant burden on the health care team. It is not uncommon to observe disagreements among providers on goals of care, duration of support, and meaningful withdrawal (80). An ethics consultation should be considered early after initiation of ECMO support. Moreover, automatic referral to ethics may reduce the burden and sense of disagreement between health care team members. Institutions setting up ECMO teams may consider having policy guidelines to set up a framework for cases of discord between the various stakeholders involved. The meaning of DNR status in patients on ECMO support

FIGURE 7 Proposed Regional Organization of the ECMO Program/Transport: A Hub-and-Spoke Model



An organized system should consist of 3 levels of care. Level 1 centers (the hub) provide all aspects of care, including extracorporeal membrane oxygenation (ECMO), durable long-term ventricular assist devices (LVADs), right ventricular support (RV), and heart transplantation. Level 2 centers provide short-term care. Surgeons are available but not necessarily on site. Level 2 centers should house a catheterization lab and ECMO initiation or cannulation capabilities. Level 3 centers can provide diagnosis, resuscitation, hemodynamic monitoring, and stabilization with vasopressors and inotropes. LV = left ventricular.

may need further definition and may vary based on each scenario. DNR among VA-ECMO patients may take the forms of no escalation, including use of vasopressors, or no replacement of failing components of the ECMO circuit, if required.

SOCIETY. In the absence of definitive results on the utility and cost effectiveness of ECMO, it becomes challenging to accept its widespread use, which may strain limited resources in certain communities. Local and state laws may need to be addressed to allow termination and withdrawal of patients from support by clinicians in case of proven futility, scenario of bridge to nowhere, or irreversible injury with discord between patient-patient surrogate and the clinical teams. Finally, thorny issues, such as whether hospitals without ECMO capability should be mandated to transfer patients to ECMO centers, need to be addressed.

NEED TO CHANGE THE CLASSIFICATION

The classification of indications for VA-ECMO was inherited from the pediatric past, with heavy emphasis on congenital heart disease, which accounts for only fraction of VA-ECMO cannulations. ELSO divides cardiac runs by the following indications: cardiac arrest, cardiogenic shock, acute myocarditis, cardiomyopathy, congenital, and miscellaneous. From 1990 to 2016, according to the 2017 ELSO report, 4% of cardiac runs were done for congenital heart disease, 5% for cardiac arrest, 2.2% for myocarditis, 6.7% for cardiomyopathy, 24.4% for cardiogenic shock, and 58% for other indications (2).

Acute myocarditis and cardiomyopathy require ECMO only if they result in cardiogenic shock. Moreover, the “other” category is greater than all the rest taken together, showing that the classification system does not serve its purpose. To add to the confusion, “cardiac run” does not equal VA-ECMO, as there are some VV-ECMO in this category. We are proposing, therefore, to change the classification to the one we used in this paper.

STANDARDS OF TRAINING FOR ECMO TEAM MEMBERS

The initial level of qualification and advancement or maintenance of the qualification should be

standardized due to the high demands and specific skills required.

VA-ECMO FOR SEPTIC SHOCK. Sepsis has historically been considered a contraindication to ECMO. The standard explanation has been that sepsis is associated with multisystem organ failure and poor survival, regardless of extracorporeal life support. However, the lack of difference in survival between the septic and nonseptic groups indicated that infection does not adversely affect the outcomes on ECMO (10). ECMO can be beneficial in selected septic patients with sepsis-related LV dysfunction.

VA-ECMO USE FOR BETTER PRESERVATION OF DONOR ORGANS FOR TRANSPLANTATION. Transplant organs salvaged by VA-ECMO show exceptional promise. Single centers demonstrated that organs (kidney, liver) perfused by VA-ECMO after cardiac death have the same transplantation outcomes as do those procured after brain death, the current gold standard for posthumous donor harvesting (81). ECMO maintains an organ at body temperature and delivers perfusate to a mechanically ventilated "lung in a box" or a beating "heart in a box" to allow for organ improvement and assessment before transplantation with promising results (82,83).

CONCLUSIONS

VA ECMO is a powerful tool that needs to be used judiciously. As we gain proficiency, the lack of prospective randomized studies or a useful classification system and areas of uncertainty create multiple challenges. Appropriate infrastructure, appropriate skill set of team members, and thorough assessment of each ECMO candidate, with an evaluation of indications and contraindication to ECMO support, are key steps to ensure optimal outcomes.

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