Extracorporeal Membrane Oxygenation in the Emergency Department

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KEYWORDS

• Extracorporeal membrane oxygenation • ECMO • Extracorporeal life support • ECLS • Extracorporeal cardiopulmonary resuscitation • ECPR • VA ECMO

KEY POINTS

- Venovenous extracorporeal membrane oxygenation (ECMO) provides pulmonary bypass for severe respiratory failure, and venoarterial ECMO provides cardiac and pulmonary bypass for severe cardiac failure including cardiac arrest.
- Inclusion criteria for extracorporeal cardiopulmonary resuscitation (ECPR): reversible cause of arrest, witnessed arrest with bystander CPR, total chest compression time of less than 60 minutes, no known preexisting chronic terminal illnesses.
- The initiation of ECMO is divided into 3 stages: (1) vascular access, (2) insertion of ECMO cannulas and connection to the circuit once the patient is determined to be an ECMO candidate, (3) pump initiation.
- Post-circuit initiation critical care for ECPR includes establishing an arterial line and managing vasopressors, defibrillation if needed, checking an arterial blood gas on right upper extremity, therapeutic hypothermia, adding an inotrope for left ventricular distention, placing a distal perfusion catheter, and treating the underlying cause of arrest.

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

INTRODUCTION

Extracorporeal membrane oxygenation (ECMO) is an invasive form of artificial life support used for severe cardiac and/or pulmonary failure. The worldwide use of ECMO is rapidly growing and indications for its application are expanding. In the past decade, use of venoarterial (VA) ECMO to restore perfusion in patients with refractory cardiac

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arrest, called extracorporeal cardiopulmonary resuscitation (ECPR), has increased in emergency departments and in the prehospital setting.[1–6] This article highlights circuit configurations and physiology of ECMO, guidance for running an ECPR code, description of the cannulation procedure, postcircuit initiation critical care, patient selection, and the evidence for use of ECMO.

EXTRACORPOREAL MEMBRANE OXYGENATION MODES AND CIRCUIT CONFIGURATION

In VA ECMO, blood is drained from the central venous system, pumped through a membrane lung (ML), and returned to the central arterial system providing cardiopulmonary bypass. VA ECMO provides hemodynamic support. In venovenous (VV) ECMO, blood is drained from the central venous system, pumped through a ML and returned to the central venous system providing pulmonary bypass. VV ECMO provides no hemodynamic support, as the return blood is isolated to the venous system.

VA ECMO is used for severe cardiogenic or obstructive shock requiring mechanical circulatory support and for cardiac arrest refractory to advanced cardiac life support (ACLS). In peripheral VA ECMO, a venous drainage cannula is placed in the femoral vein draining blood from the right atrium and vena cava and blood is returned via a cannula in the femoral artery (Fig. 1).

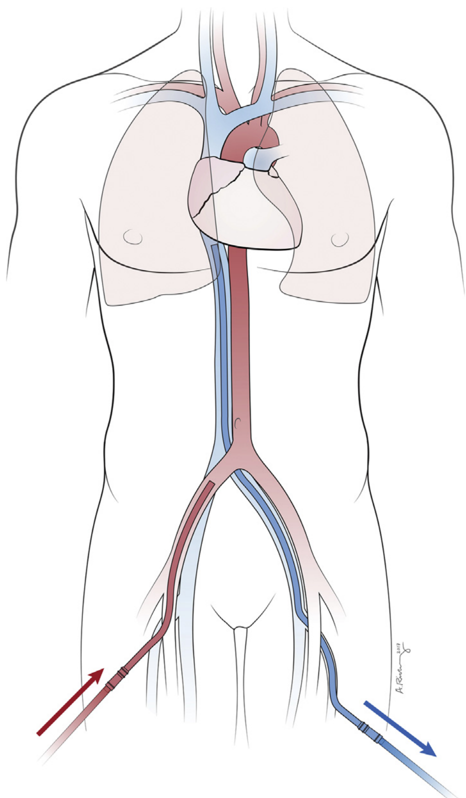

Fig. 1. Venous drainage cannula in the right femoral vein and return cannula in the femoral artery. (Image used with permission from CollectedMed.)

VV ECMO is used for hypoxemia and/or hypercarbia refractory to conventional therapies. In the most common configuration for VV ECMO, a venous drainage cannula is placed in the femoral vein draining blood from the inferior vena cava and blood is returned via a cannula in the right internal jugular vein with blood flow directed across the tricuspid valve (Fig. 2).

The basic ECMO circuit is composed of a venous drainage cannula, a centrifugal pump that pushes blood through an ML, and a return cannula. All of these components are connected with tubing. A flow probe is attached to the tubing and measures the rate of blood flow through the circuit. Sweep gas is composed of oxygen or a blend of oxygen and air that is supplied to the ML where blood is oxygenated and carbon dioxide (CO_2) is removed. A heat exchanger is connected to the ML and regulates temperature of the blood in the circuit. Some circuits have additional capabilities to monitor pressures throughout the system, detect air bubbles, and monitor hemoglobin and oxygen saturation (Fig. 3).

General Extracorporeal Membrane Oxygenation Physiology

Most adult ECMO circuits use a centrifugal pump; therefore, speed, in revolutions per minute (RPMs), is the independent variable set by the clinician, which controls blood flow. As blood flow increases, inlet pressures will become more negative and return pressures more positive.

Centrifugal pumps are preload dependent and afterload sensitive. Therefore, impediments to venous drainage (preload) including hypovolemia, a small, kinked, or

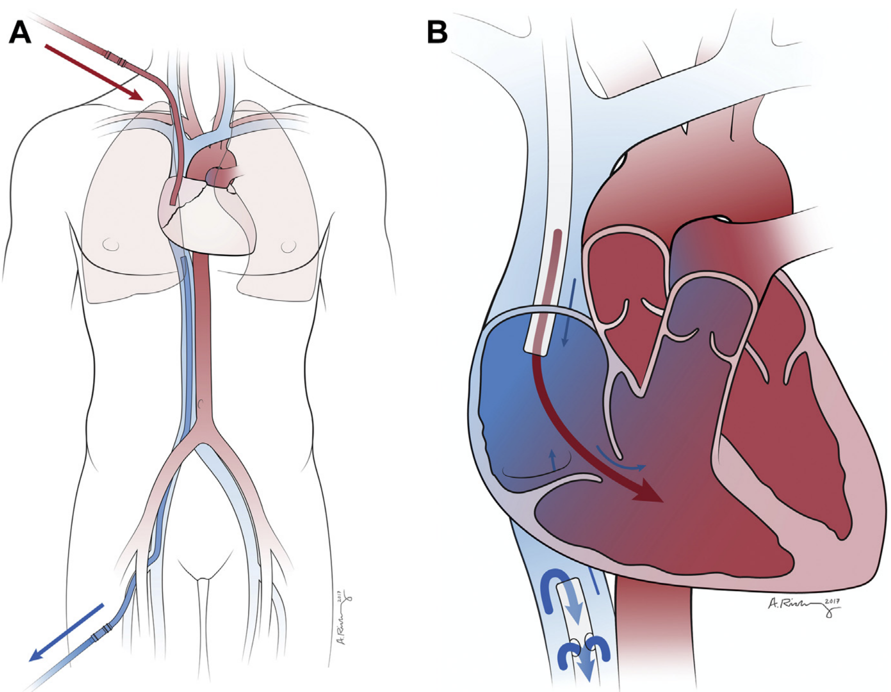

Fig. 2. (*A*) Venous drainage cannula in the right femoral vein and return cannula in the right internal jugular vein. (*B*) Blood is drained from the IVC and returned across the tricuspid valve into the right heart. (Image used with permission from CollectedMed.)

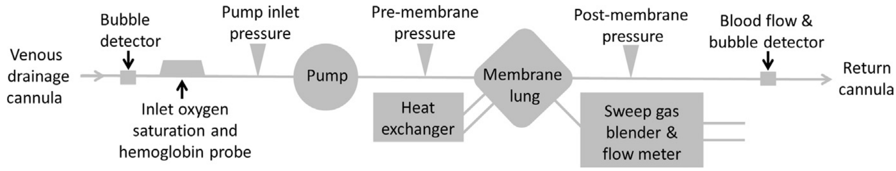

Fig. 3. Schematic of an example ECMO circuit.

clotted drainage cannula, tamponade, tension pneumothorax/hemothorax, or abdominal compartment syndrome will result in lower blood flow at a given speed. Causes of high afterload including a small, kinked, or clotted return cannula, clotted ML, or high systemic vascular resistance (only in VA ECMO) will also result in lower blood flow.

Sweep gas runs through the lumens of small tubules bathed in blood within the ML (**Fig. 4**). The rate at which the sweep gas is pushed through the ML is called the sweep gas flow rate, which determines the partial pressure of carbon dioxide (P_{CO_2}) exiting the ML. As the sweep flow is increased, P_{CO_2} decreases. A blender can be used to change the percentage of oxygen in the sweep gas, called fraction of delivered oxygen (FdO_2). As long as the ML is functioning and the sweep gas is >0.5 L/min, blood leaving the ML will be 100% saturated with O_2.

Venoarterial Extracorporeal Membrane Oxygenation Physiology

Total blood flow in the arterial system (Q) during VA ECMO is the combination of native cardiac output and ECMO blood flow. ECMO blood flow is titrated to target ~80% of estimated resting cardiac output based on the patient's body surface area. In addition, echocardiography is used to guide ECMO blood flow titration. As ECMO flow is increased, more venous blood is drained leading to decreased native heart preload and ventricular decompression. At the same time, native heart afterload is increased due to retrograde ECMO flow up the aorta, which will eventually lead to left ventricular dilation. The goal is to find the ECMO blood flow that (1) achieves a perfusing mean arterial pressure (MAP), and (2) maximally decompresses the right ventricle without leading to left ventricular dilation. Although Q has a significant impact on MAP, additional increases in MAP can be achieved using vasopressors to increase systemic vascular resistance (SVR) as well as volume administration to address central venous pressure (CVP).

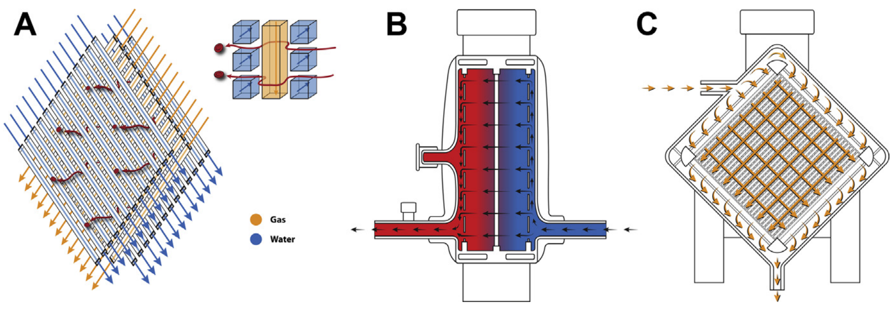

Fig. 4. (*A*) Red blood cells travel in-between tubules containing sweep gas in the lumen. (*B*) Deoxygenated blood enters the ML and oxygenated blood exits after interacting with the ML tubules. (*C*) Sweep gas enters the ML, travels through the lumen of the tubules and is exhausted out of the bottom of the ML. (Image used with permission from CollectedMed.)

$$\text{MAP} = (\text{SVR} \times \text{Q}) + \text{CVP}$$

The degree of cardiac failure determines where the mixing point is in the aorta between blood from the native heart and retrograde flow from the ECMO pump (Fig. 5). This concept is important because the O_2 and CO_2 content of the blood will depend on whether it is coming from the native lungs or the ML. If the native lungs are functioning poorly in the setting of native heart recovery, poorly oxygenated blood will be ejected from the native heart leading to upper body hypoxemia. This is termed differential oxygenation or north-south syndrome. Thus oxygenation via pulse oximeter or arterial blood gas is monitored on the right upper extremity for early detection of this pathologic state.

Venovenous Extracorporeal Membrane Oxygenation Physiology

When using VV ECMO, blood flow is circulated entirely within the venous system, therefore VV ECMO has no direct effect on hemodynamics. Blood is oxygenated and CO_2 is removed in the ML. The blood is then returned to the patient's right atrium where it moves through the native heart and lungs, thus obviating the requirement of the native lungs to contribute to gas exchange. When ECMO blood

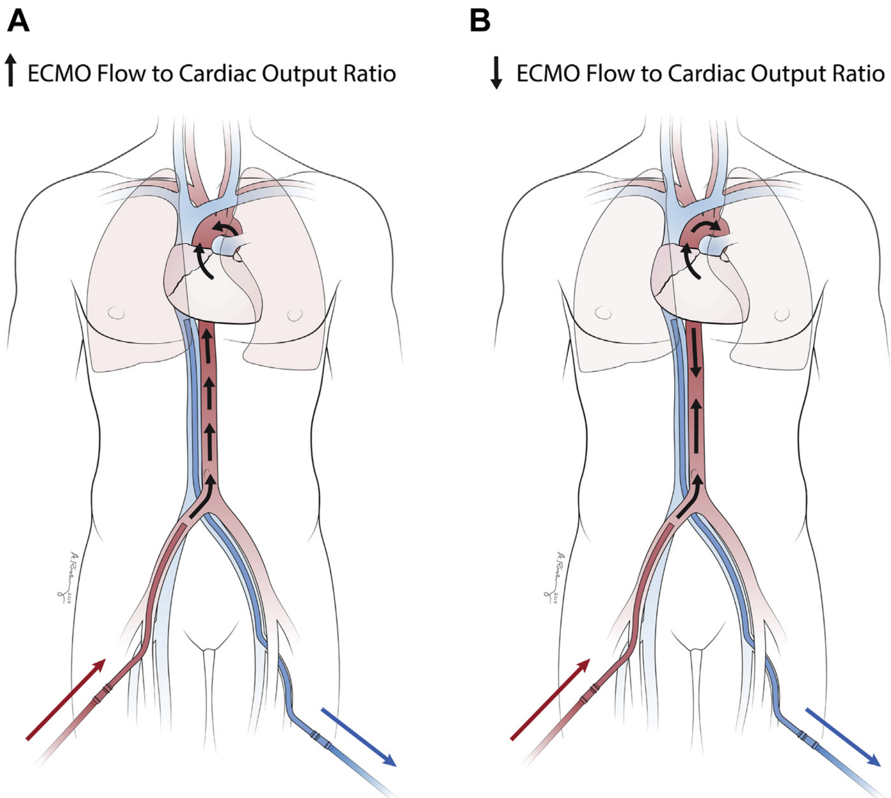

Fig. 5. (*A*) When native cardiac function is poor, the mixing point between native heart blood flow and ECMO blood flow is in the proximal aorta. (*B*) When native cardiac function improves, the mixing point moves further down the aorta. (Image used with permission from CollectedMed.)

flow is increased, the fraction of oxygenated blood entrained into the heart increases, raising the mixed venous oxygen saturation and subsequently raising the arterial oxygen saturation.

PATIENT SELECTION

In general, ECMO can be used for severe cardiac and/or pulmonary failure refractory to conventional therapies.[7] ECMO is a form of life support and is thus not a treatment but a bridge to native heart/lung recovery or durable organ replacement. Therefore, a patient should ideally only be placed on ECMO with a predetermined exit strategy. General contraindications for ECMO include multiorgan failure with a high risk of death despite use of ECMO, severe neurologic disease with poor neurologic prognosis or other preexisting terminal illness such as metastatic malignancy, end-stage organ dysfunction (lung, heart, liver, kidney) without possibility of transplant, severe coagulopathy, advanced age with poor functional status, and inadequate vascular access for implantation of cannulas. Although the bleeding patient was traditionally excluded from ECMO implementation, growing experience has shown that systemic anticoagulation is probably able to be safely held for periods of time, especially given the widespread use of heparin-bonded circuits.[8] Additional contraindications for VA ECMO include untreated aortic dissection and aortic valve insufficiency. For VV ECMO, prolonged high-intensity mechanical ventilation >7 to 10 days is associated with poor outcomes and is thus a relative contraindication.[9–12]

Extracorporeal Cardiopulmonary Resuscitation

For ECPR, the goal is to select previously high-functioning patients without known terminal illnesses who had a witnessed cardiac arrest from a reversible cause who have been supported with high-quality CPR. The optimal timing for initiation of ECMO is unknown but it is probably between 25 and 60 minutes. After 25 minutes of traditional ACLS, the patient is unlikely to achieve return of spontaneous circulation and survival with continued ACLS is dismal.[13] The time between arrest and initiation of ECMO should probably not exceed 60 minutes, after which the probability of a meaningful neurologic recovery steeply declines.[14,15] Reversible causes of arrest may include myocardial infarction treated with revascularization, massive pulmonary embolism treated with anticoagulation, thrombolytics, and/or thrombectomy, cardiotoxic drug overdose that resolves after drug metabolism or decontamination, and accidental hypothermia, which is easily corrected with rewarming on the ECMO circuit. Many centers have developed their own ECPR criteria that follow these general principles.[1–6,16]

The evidence for ECPR involves case series, registry data, and propensity analyses.[1–3,6,16–19] No randomized trials have been published to date. SAVE-J was a prospective observational study that compared out-of-hospital cardiac arrest survival between patients sent to ECPR centers versus hospitals without ECPR capability. Patients sent to ECPR centers had a statistically significant fourfold increased survival.[2] The most impressive ECPR case series have come from Minneapolis where out-of-hospital cardiac arrests are taken directly to the cardiac catheterization laboratory. Neurologically intact survivorship has been greater than 40% from that institution.[6,20] An emergency department in San Diego using emergency physician-initiated ECPR showed statistically significant improved survivorship for ECPR patients compared with ECPR-eligible patients who did not receive ECPR. In addition, this study showed that most of those who died did so early in their hospitalization. Prolonged hospitalizations among nonsurvivors were few.[5]

Venoarterial Extracorporeal Membrane Oxygenation for Shock

VA ECMO is most often used for patients with cardiogenic shock and obstructive shock due to massive pulmonary embolism.[21] For cardiogenic shock, VA ECMO can be rapidly deployed at the bedside to rescue an undersupported patient failing medical therapy or other temporary mechanical circulatory support (MCS) devices by providing full biventricular support. Ethical concerns regarding lack of equipoise between offering or withholding MCS for patients with critical cardiogenic shock make randomized controlled trials unlikely. However, multiple observational studies show improved survival when VA ECMO is used.[22–24] Medical causes of cardiogenic shock likely to be encountered in the emergency department include acute myocardial infarction,[25] myocarditis,[26] acute decompensated heart failure,[27] and cardiotoxic drug overdose.[28] Some centers consider use of VA ECMO for refractory septic shock with mixed results.[29–31] Expeditious transfer of the patient in cardiogenic shock to cardiogenic shock centers equipped with temporary MCS and other durable organ replacement options should be considered.[32]

Venovenous Extracorporeal Membrane Oxygenation for Respiratory Failure

VV ECMO can be used for patients with severe respiratory failure refractory to conventional support. Disease states include severe hypoxemia secondary to acute respiratory distress syndrome (ARDS) despite conventional therapies. Other examples include severe asthma exacerbations,[33] traumatic airway injuries, or bronchopleural fistulas, which all pose significant ventilatory challenges. VV ECMO can also be used when unable to establish a definitive airway via intubation or surgical airway.

Initial studies for use of VV ECMO for ARDS showed tentatively optimistic data but varied significantly as to when VV ECMO was initiated.[34–37] The question remained whether VV ECMO should be used early in respiratory failure or after all other therapies had failed. Recently, the large EOLIA trial was stopped early secondary to futility,[38] with much controversy surrounding the interpretation of the outcome.

RUNNING AN EXTRACORPOREAL CARDIOPULMONARY RESUSCITATION CODE

One key concept in not only ECPR but any new resuscitative technology is to ensure the resuscitation leading up to that intervention is optimized. Before jumping to advanced technologies, it is important to assess for simpler, rapidly correctable causes of cardiac arrest. A witnessed ventricular fibrillation arrest requires defibrillation, not ECMO. A patient in pseudo-pulseless electrical activity needs vasopressors and evaluation for rapidly correctable causes before ECMO initiation. Using your resources to efficiently optimize your traditional resuscitation efforts in concert with the added complexities of an ECMO initiation is key.

The first component in running the ECMO code is to set up a prearranged place for each medical device and health care provider in the room. Each institution will need to decide the optimal strategy and design of this room, but keeping uniformity within this design is ideal. Common medical devices used during ECMO codes include ultrasounds for cardiac imaging as well as vascular access, code cart with defibrillator, computer on wheels for charting and organization, mechanical chest compression device, airway equipment, and a stool for manual chest compressions. In addition to this standard equipment, 2 small procedural tables, covered with a large sterile drape at the end of the patient gurney extend the working space for ECMO-related equipment. This equipment includes cannulas for both femoral vein and artery, ECMO circuit, dilators, stiff and floppy guidewires, and clamps. Toomey syringes are needed with a crystalloid basin for the underwater seal necessary for circuit connection.

The second component involves limiting the number of people in the room to those directly involved in the resuscitation. Each person should have a dedicated place to stand and no other personnel should be allowed in the room.

The final component is defining the roles of each of the providers in the room. The most critical role is the code team leader. There are many advantages to assigning a nurse to this role. Their job is to be the sole voice in the room. They control the room and oversee the quality of chest compressions, dosing of medications, chest compression free times, and defibrillation. The second is the physician team leader. The job of this physician is to secure an airway and then determine the patient's inclusion/exclusion for ECMO. They will gather the patient's medical history and decide if deviations from the standard resuscitation are necessary. They need to resist, if possible, participating in the cannulation procedure. The third role is the physician cannulator who performs the cannulation procedure. The fourth role that is underappreciated, but imperative, is a wire assistant. This provider assists the cannulator in guidewire insertion and dilation particularly during the difficult task of femoral arterial cannulation (Fig. 6).

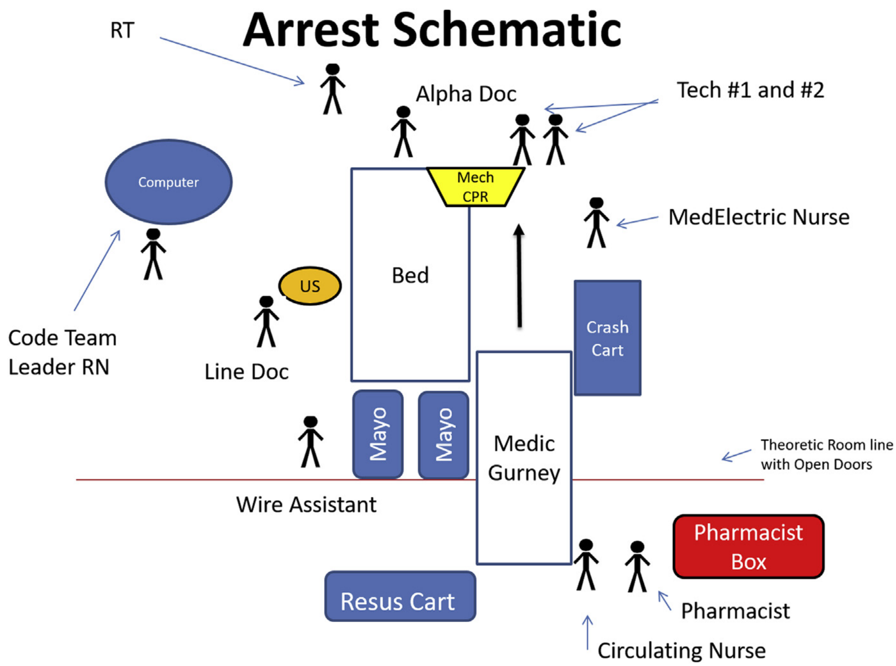

Fig. 6. ECPR provider roles. RT: respiratory therapist operating ventilator, Alpha Doc: doctor team leader who establishes airway and gathers patient's medical history to determine ECMO candidacy of patient, Tech #1 and #2 run mechanical CPR device (Mech CPR), MedElectric nurse: uses Crash Cart administering medications and electricity for defibrillation, Pharmacist: prepares medications, Circulating Nurse: primes and operates ECMO pump, Medic Gurney: location for paramedic's gurney, Mayo: additional small tables to extend working surface of emergency department bed, Resus Cart: location of ECMO supplies and equipment, Wire Assistant: assists Line Doc with cannulation, Line Doc: performs cannulation procedure using ultrasound, Code Team Leader RN: nurse who directs standard ACLS and records with computer.

Each provider should understand the basic metrics of minimizing interruptions in chest compressions, optimizing defibrillation, providing high-quality chest compressions, and troubleshooting medical equipment. This allows for the code to run quietly and standard resuscitation to be optimized. Frequent feedback about the initial phases of the resuscitation in addition to the ECMO specific components should be discussed during code debriefing and simulated training sessions. ECPR simulation at regular intervals is imperative to maintain personnel skillsets.

EXTRACORPOREAL CARDIOPULMONARY RESUSCITATION CANNULATION PROCEDURE

Although cannulation can be performed with 1 cannulator and 1 wire assistant, it is best done with 2 cannulators and 2 wire assistants. Ultrasound guidance is critical for minimizing vessel trauma and confirming that the correct vessel has been accessed. Sometimes, when ideal circumstances occur (right-handed cannulator on right femoral vessels with optimal ultrasound imagery), 1 cannulator can complete cannulation of both vessels before the opposite groin is accessed.

Cannulation starts with typical Seldinger insertion of a guidewire into the femoral vein and artery. Placeholder lines in the form of a 5-Fr arterial and 9-Fr venous sheath are used for blood pressure monitoring and medication administration while the decision to initiate ECMO is in question. Once the decision to initiate ECMO has been confirmed, the longer (150 cm) guidewires are inserted through the placeholder sheaths. Some long guidewires are floppy and some are stiff. There is some advantage to the stiff wires as they resist kinking; however, overly aggressive line/dilator/cannula insertion must be avoided. The mantra of “slow is smooth, smooth is fast” should be repeated frequently.

During cardiac arrest, differentiation of arterial from venous blood is difficult, and with chest compressions, ultrasound images can be misinterpreted. This makes confirmation of wires in the correct vessels difficult but still paramount. Fluoroscopy is ideal but not usually accessible. Ultrasound of the femoral vessels, inferior vena cava (IVC) and aorta or an abdominal radiograph after long wire insertion can be helpful. Once wires are in place and before insertion of the cannulas, a heparin bolus is administered.

Over the long guidewires, serial dilation is necessary to enlarge the venotomy and arteriotomy to the appropriate cannula size. For adult ECPR, arterial cannulas are typically between 15 and 19 Fr and venous are between 19 and 25 Fr. After dilation, the cannulas are inserted. Ideally the tip of the venous cannula sits at the IVC/right atrial junction and the arterial cannula will sit in the common iliac or distal aorta (Video 1).

Once cannulas are inserted, clamps are placed after removal of the internal obturator and guidewire. The cannulas are then connected to the circuit using the underwater seal technique in which continuous crystalloid is poured over the top to ensure no air bubbles are in the circuit (Video 2).

Before circuit initiation, the circuit is inspected to ensure it is air free and the sweep gas is set at a 1:1 ratio with the targeted blood flow (~4 L/min). Initiation occurs with removal of the clamp on the venous tubing of the circuit, increasing the RPMs to ensure no backflow, and removal of the arterial clamp on the circuit tubing (Video 3). RPMs should be increased to achieve a flow of 3 to 4 L/min.

On ECPR initiation, “chatter” is commonly encountered where the tubing shakes or jolts (Video 4). This is caused by inadequate pump preload manifest by a cyclic “suck down” of the drainage cannula onto the endothelium of the vena cava generating excessively negative suction pressures, followed by release once central venous blood pools. This should be treated by decreasing the RPMs and administering volume, for example, crystalloid or blood, as the cause is commonly hypovolemia. Tension pneumothorax, tamponade, and abdominal compartment syndrome can also cause chatter and should be ruled out if it persists.

POST EXTRACORPOREAL MEMBRANE OXYGENATION INITIATION MANAGEMENT IN THE EMERGENCY DEPARTMENT

Once ECMO has been initiated for ECPR, the provider should first visualize the circuit. The venous drainage blood should be dark and arterial return blood should be bright. If not, troubleshooting may involve confirming correct vessel cannulation and double-checking sweep gas settings and connections (Fig. 7).

Second, the provider should reassess the patient's rhythm. If the patient is in ventricular fibrillation, repeat defibrillation after a few minutes with a perfusing MAP. It is important to have an ejecting left ventricle (LV) on ECMO to prevent LV distention.

Third, a right radial arterial line should be inserted. This allows accurate measurement of the MAP, especially if the patient has nonpulsatile blood flow. Commonly, vasopressors, transfusion of blood, and/or crystalloid infusion are necessary. As with all patients on MCS, the MAP goal for an ECMO patient is typically 60 to 80 mm Hg. The MAP must be high enough to perfuse organs and low enough to avoid excessive afterload for the native heart and ECMO centrifugal pump. An arterial blood gas (ABG) from the right radial arterial line should be sent to determine if native circulation is sending poorly oxygenated blood to the coronaries and brain, that is, differential oxygenation or north-south syndrome. In this case, hypoxemia should be corrected with the ventilator. The ABG is also used to adjust the sweep gas flow rate.

Fourth, most patients should be started on an inotrope to prevent LV distention. This is especially important if the pulse pressure is narrow, that is, less than 10 mm Hg, or an echocardiogram reveals that the LV is distended and the aortic valve is not opening. If the distended LV does not eject, this will lead to myocardial ischemia and pulmonary edema, as well as stasis of blood, which leads to intracardiac clot.[39,40] If LV distention is not improved with an inotrope, an LV vent, such as an Impella (Abiomed, Danvers, MA), intra-aortic balloon pump, or atrial septostomy may be needed.[41]

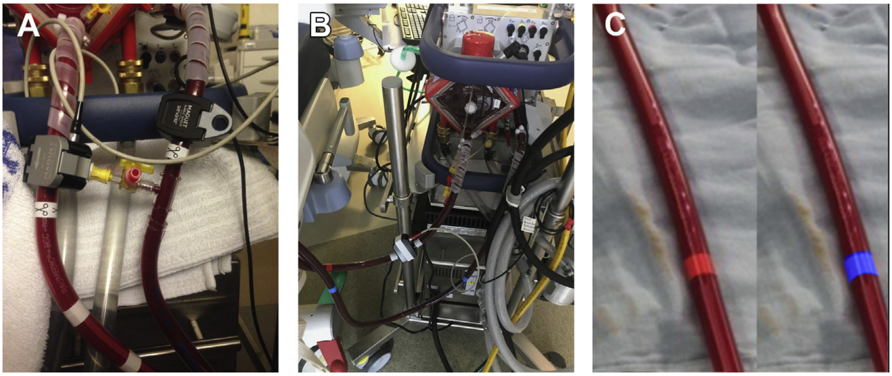

Fig. 7. (*A*) In a correctly functioning circuit, the drainage tubing is dark red and the return tubing is bright red. (*B*) If the ML is not functioning, most commonly due to a sweep gas disconnection, both drainage and return tubing are dark red. (*C*) If both drainage and return tubing are bright red, they may both be located in arteries or veins.

Important next steps in the process include the initiation of targeted temperature management and placement of a distal perfusion catheter in an artery in the leg with the arterial return cannula to prevent leg ischemia.[42] Clinicians should also evaluate for the etiology of the arrest and initiate appropriate treatment, such as transfer to the cardiac catheterization laboratory for acute coronary syndrome.[43,44]

SUMMARY

Indications

- ECMO, also called extracorporeal life support (ECLS), is a form of mechanical life support for the lungs and/or heart
  - VV ECMO provides pulmonary bypass for respiratory failure
  - VA ECMO provides cardiac and pulmonary bypass for cardiac failure with or without respiratory failure
  - ECPR uses VA ECMO for patients in cardiac arrest
    - Patients in cardiac arrest are potential candidates for ECPR if they have the following:
      - Reversible cause of arrest
      - Witnessed arrest
      - Bystander cardiopulmonary resuscitation (CPR)
      - Total chest compression time of less than 60 minutes
      - No known preexisting terminal illness
  - When running an ECPR code, care must be taken to continue high-quality traditional CPR in addition to ECMO initiation

Procedure

- Initiation of ECMO is divided into 3 stages:
  - Stage I: femoral and arterial sheaths are inserted into the femoral vessels and used for medication administration and hemodynamic monitoring while ECMO candidacy is determined
  - Stage II: if the patient is determined to be an ECMO candidate, the arterial and vascular sheaths are replaced with larger ECMO cannulas and connected to the primed ECMO circuit
  - Stage III: ECMO pump flow initiation

Postprocedure

- Post pump initiation considerations include the following:
  - Early right radial ABG and pressure monitoring
  - Defibrillate persistent ventricular fibrillation
  - Manage vasopressors and volume expanders based on arterial pressure tracings
  - Use the heat exchanger for therapeutic hypothermia
  - Start an inotrope to prevent LV distention
  - Early coronary revascularization in the cardiac catheterization laboratory for suspected acute coronary syndrome
  - Plan for distal perfusion catheter insertion

ECMO provides heart and/or lung bypass for the patient with severe cardiopulmonary failure. ECPR uses VA ECMO to restore perfusion in the patient with refractory cardiac arrest and can be deployed in the emergency department. Successful ECPR requires a well-rehearsed protocol with clear team-member roles to facilitate high-quality cardiac arrest resuscitation and a staged approach to vascular access, cannula insertion, and circuit initiation. Patient selection criteria for ECMO should be clear and predetermined and usually includes a witnessed arrest, bystander

CPR, a reasonable down time, and no known preexisting terminal illnesses. Post-ECMO circuit initiation critical care is crucial to ensure adequate perfusion pressure, gas exchange, perfusing rhythm, LV unloading, distal leg perfusion, therapeutic hypothermia, and steps to treat the underlying cause of arrest. Current evidence suggests a substantial benefit to ECPR compared with traditional ACLS for patients with refractory cardiac arrest; however, data are limited given lack of randomized trials.

DISCLOSURE

The authors have nothing to disclose.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found online at https://doi.org/10.1016/j.emc.2020.06.015.

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