

ECMO in trauma care: What you need to know

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ABSTRACT: Over the past 10 years, extracorporeal membrane oxygenation (ECMO) use in trauma patients has increased significantly. This includes adult and pediatric trauma patients and even combat casualties. Most ECMO applications are in a venovenous (VV ECMO) configuration for acute hypoxemic respiratory failure or anatomic injuries that require pneumonectomy or extreme lung rest in a patient with insufficient respiratory reserve. In this narrative review, we summarize the most common indications for VV ECMO and other forms of ECMO support used in critically injured patients, underscore the importance of early ECMO consultation or regional referral, review the technical aspects of ECMO cannulation and management, and examine the expected outcomes for these patients. In addition, we evaluate the data where it exists to try to debunk some common myths surrounding ECMO management. (*J Trauma Acute Care Surg.* 2024;96: 186–194. Copyright © 2023 Wolters Kluwer Health, Inc. All rights reserved.)

The first successful cannulation and prolonged extracorporeal circuit use was for the support of a trauma patient. Dr. J.D. Hill described the case of a 24-year-old man who presented with a ruptured aorta after a motorcycle accident and subsequently developed acute respiratory distress syndrome (ARDS). The patient was cannulated in a venoarterial (VA) configuration and was supported with a membrane lung for 75 hours before successful decannulation and survival.¹ Although these beginnings are well described, extracorporeal membrane oxygenation (ECMO) is often overlooked in trauma patients, as these patients frequently present with hemorrhage, brain injury, or other contraindications to systemic anticoagulation, which is thought by many to be necessary for the successful management of an extracorporeal circuit. This review aims to unpack these uncertainties to provide evidence for the thoughtful consideration and application of ECMO support for improved outcomes in severely injured patients.

PHYSIOLOGY OF ECMO SUPPORT

The most common indication for ECMO in the trauma patient is refractory respiratory failure in the setting of ARDS using

a venovenous (VV) configuration.² Venovenous ECMO drains deoxygenated blood from the venous system, usually via a cannula inserted in the femoral vein, and returns oxygenated blood to the venous system, either via the contralateral femoral vein or the internal jugular vein (Fig. 1). Alternatively, there is a single cannula technique for VV ECMO, wherein a dual-lumen cannula is inserted into the internal jugular vein, and blood is drained from the SVC and IVC via one lumen and returned into the RA via the other lumen (Fig. 2). Venovenous ECMO is useful in patients with refractory respiratory failure without primary cardiac dysfunction. The oxygenated blood, which is returned to the venous system, enters the right heart, circulates through the pulmonary vasculature to the left heart and is subsequently pumped through the systemic circulation to provide oxygen to end organs. This necessitates a functioning heart.³ The VV circuit does however provide indirect hemodynamic support through optimization of pH, PaCO₂, and PaO₂. Improvement of these parameters results in improvement of pulmonary arterial pressures and therefore right ventricular function.⁴ The resultant improvement in oxygenation after initiation of VV ECMO also allows for ventilator adjustments, which decrease intrathoracic pressure, thus increasing cardiac filling and output.⁵

In a Trauma Quality Improvement Program review from 2012 to 2016, ECMO was used in a total of 269 patients in 82 trauma centers. The rate of ECMO use in trauma appears to be rising significantly from 75 per 100,000 severely injured patients in 2012 to 179 per 100,000 in 2016.⁶ Venovenous ECMO for ARDS in severely injured patients is commonly seen in patients who have a pneumonia but can also be seen in patients with pulmonary contusions, severe aspiration, or significant abdominal trauma, which potentiates a systemic inflammatory reaction and capillary leak (Fig. 3). Trauma patients may also progress to an ARDS-like picture after transfusion reactions, such as transfusion-related acute lung injury or with transfusion-associated circulatory overload or overresuscitation with crystalloid in a patient after hemorrhagic shock.

Another interesting patient population to consider in the discussion of VV ECMO is the burn population. Patients who have sustained extensive burns can progress to ARDS secondary

Submitted: September 18, 2023, Revised: September 26, 2023, Accepted: September 26, 2023, Published online: October 16, 2023.

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DOI: 10.1097/TA.0000000000004152

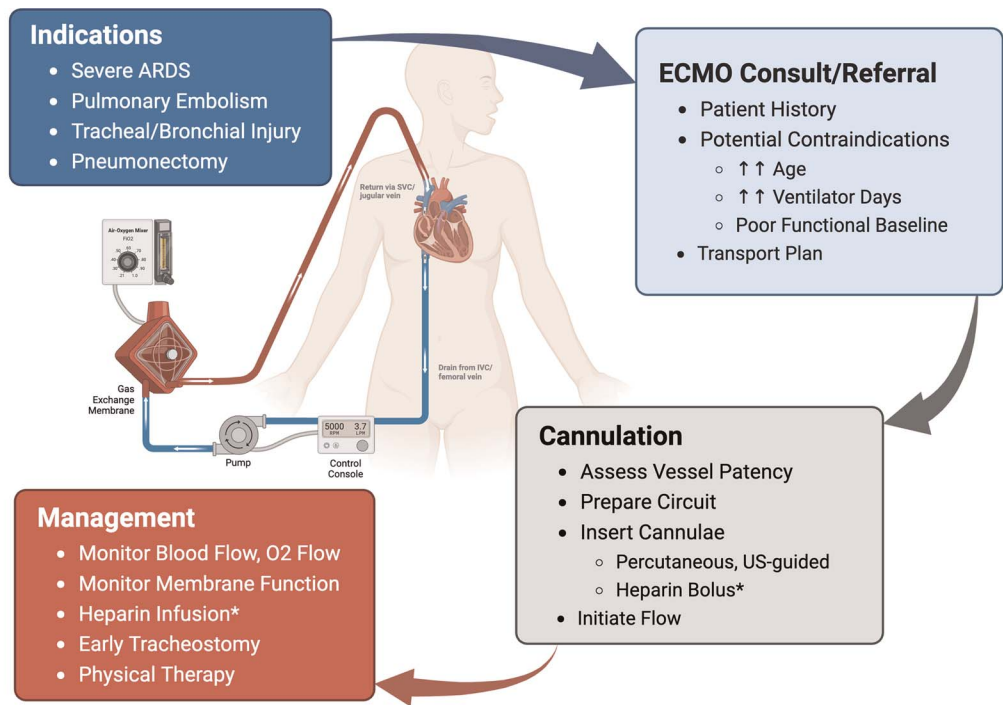


Figure 1. ECMO in trauma care. Indications include the most common examples where VV ECMO should be considered in critically injured patients, but this does not represent an exhaustive list of potential indications for either VV ECMO or VA ECMO in trauma. ECMO consultation should be initiated early in patients with potential indications. *Heparin bolus and infusion are preferred but not required in patients with a high risk of bleeding or in patients at risk of significant neurologic consequences from a bleeding complication (e.g., TBI, spinal epidural hematoma).

to extensive inflammation and capillary leak, which is often exacerbated by large-volume resuscitation. Injured patients with severe pulmonary contusions may also have life-threatening hypoxemia requiring ECMO support as a bridge to lung recovery. Venovenous ECMO may also be used to bridge the injured patient to the operating room. This is seen most commonly in patients who have sustained traumatic injury of the large airways.

OTHER CANNULATION STRATEGIES

Venopulmonary Artery ECMO

Despite the aforementioned hemodynamic support provided by VV ECMO through optimization of pH, PaCO₂, and PaO₂, patients may still have elevated pulmonary artery pressures and thus progress to right ventricular failure. When this happens, patients may require the addition of an arterial cannula for right heart offloading. Alternatively, some centers have moved toward cannulation of the pulmonary artery. In this technique, blood is drained from the venous system as in VV ECMO, and oxygenated blood is returned through a cannula placed percutaneously directly into the pulmonary artery via the internal jugular vein or subclavian vein. This effectively bypasses the right heart and has been used for both prophylaxis of right heart failure and in response to right ventricular failure.⁷

Venoarterial ECMO

Venoarterial ECMO is indicated in the setting of cardiogenic shock. Deoxygenated blood is drained from the venous system, usually via a cannula inserted via the femoral vein. Oxygenated blood is reinfused into the arterial system, usually via a cannula

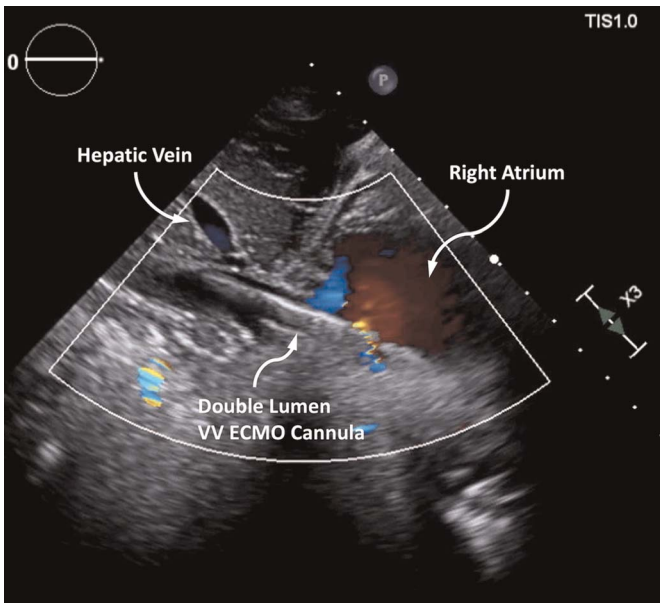


Figure 2. Transthoracic echocardiographic view of ECMO Cannula. Double lumen VV cannulation via right IJ vein. The catheter is shown coursing from the SVC across RA into the IVC. Note hepatic vein at top left of image; the distal/drainage lumen should rest in the IVC rather than the hepatic vein. The proximal/reinfusion lumen can be seen as an irregularity in the catheter wall. Color flow Doppler also demonstrates appropriate positioning of the proximal/reinfusion lumen, with blood flow directed into the right atrium.

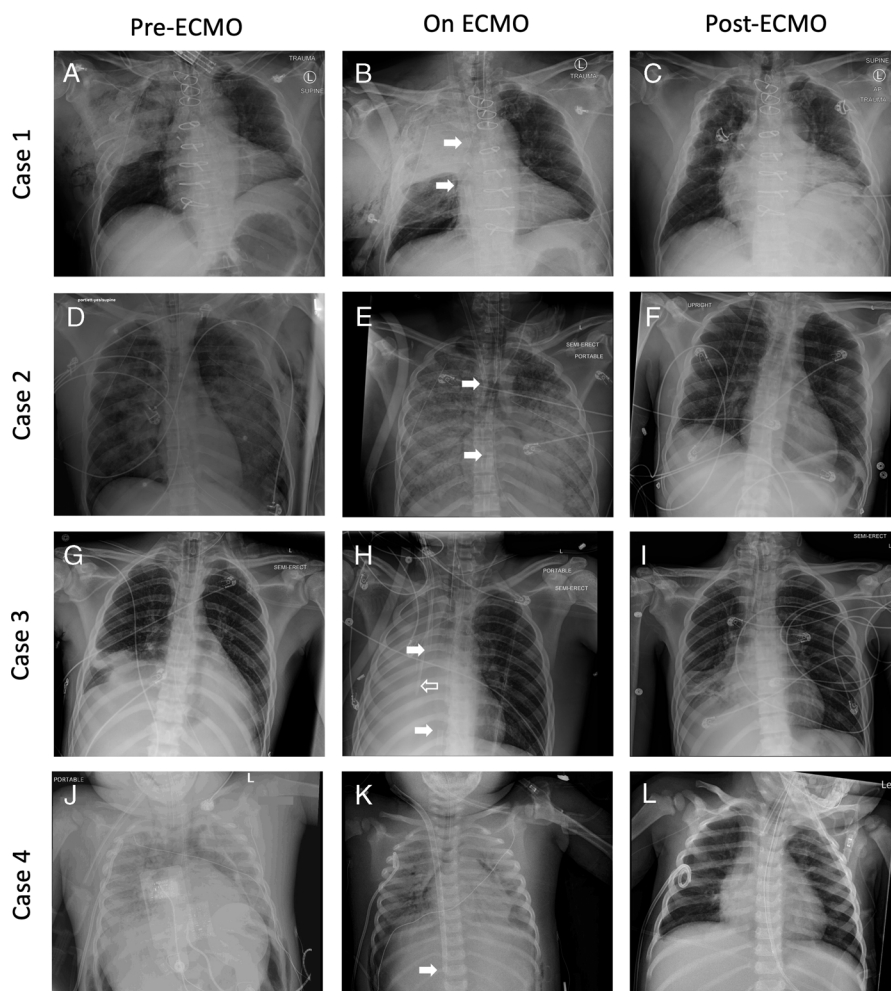


Figure 3. Clinical case examples. Of the 30 critically injured patients managed in our adult trauma center on ECMO from 2015 to present, 23 have survived to discharge (77%). ECMO patients included both blunt ($n = 18$, 60%) and penetrating ($n = 12$, 40%) mechanisms with a median ISS of 25. (A–C), 48-year-old male with a history of a heart transplant fell from a second floor story window. He was hypoxemic on initial evaluation and a chest tube was placed for significant subcutaneous emphysema and a presumed pneumothorax. His oxygenation did not improve; so ECMO cannulation was initiated (arrows). Mechanical stabilization of his ribs was considered but then not performed based on estimated risks in this patient outweighing potential benefits. He recovered and was discharged to home. (D–F), 27-year-old man involved in a motorcycle crash resulting in multiple rib fractures, a sternal fracture, bilateral hemo-pneumothoraces and pulmonary contusions, bilateral T4 pedicle fractures without spinal cord injury, a small subdural hematoma, and a femur fracture. After early femoral nail placement, he developed severe ARDS prompting transfer to our ECMO center. He was promptly cannulated (arrows) and remained on ECMO for 40 days. He subsequently recovered and was discharged to an acute rehabilitation facility in good condition. (G–I), 21-year-old man who suffered a GSW to the lower abdomen with injuries to the aorta and inferior vena cava as well as multiple bowel injuries. He developed a postoperative pulmonary embolism managed with catheter embolectomy; however, his oxygenation worsened post-procedure due to possible re-perfusion injury. VV ECMO was initiated (arrows), and he was placed on continuous renal replacement therapy as well (open arrow). He subsequently recovered, was decannulated, and transferred to an acute rehabilitation facility in good condition. (J–L), 18-month-old male who presented with inhalation injury after a house fire. He developed severe ARDS refractory to conventional interventions prompting transfer to our pediatric ECMO center 4 days after injury. He was promptly placed on VV ECMO via right internal jugular vein double-lumen cannula (arrow). After 8 days on ECMO, his gas exchange improved, and he was eventually discharged to inpatient rehabilitation in good condition.

inserted in the femoral artery. Peripheral VA ECMO bypasses the heart and lungs, and blood is introduced into the femoral artery in a retrograde fashion.

If the patient's cardiac output improves or in patients with RV failure but preserved left ventricular ejection fraction, differential hypoxemia can become a concern. When a patient is on peripheral VA ECMO, intrinsic cardiac output and the ECMO

flow rate will determine where in the aorta deoxygenated blood from the native circulation meets oxygenated blood from the ECMO circuit. This becomes imperative when ensuring that oxygenated blood is reaching vital organs. If the patient's cardiac output is such that the mixing point occurs distal to the takeoff of the right subclavian, for example, the right upper extremity and coronary arteries may not obtain adequate oxygen. This

becomes increasingly problematic as the mixing point moves distally and the carotid arteries receive deoxygenated blood. Sometimes, differential oxygenation requires the addition of a venous return cannula, thus creating a venoarterial-venous (VAV) ECMO circuit. This venous return cannula provides oxygenated blood to the venous system, which circulates through the right heart, through the pulmonary vasculature, to the left heart and then through the aorta thus providing oxygenated blood to the vasculature proximal to the mixing point. Differential oxygenation is also the reason that it is preferable to measure pulse oximetry and arterial blood gases from the right upper extremity, as this blood would be representative of the “least oxygenated” blood in a patient supported on VA ECMO.

Another important consideration with VA ECMO is distal limb perfusion and placement of a distal perfusion cannula (DPC). Cannulas inserted into the femoral artery must be large enough in diameter to provide adequate flow but ideally would also be small enough to allow for antegrade flow around the cannula to the extremity distal to the cannula. Absent or inadequate antegrade flow to the extremity will result in ischemia. For this reason, patients will at times require an antegrade cannula to be placed in the superficial femoral artery (SFA) and attached to the circuit to provide oxygenated blood to the extremity. The SFA can be quite difficult to cannulate once most of its blood flow is being blocked. Therefore, it is recommended that wire access to the SFA be obtained prior to VA cannulation if possible. Timing of insertion of a DPC is not uniform among ECMO centers. Some centers opt for early preemptive DPC placement whereas others choose later selective placement if necessary. Regardless, tissue oxygenation must be monitored closely, either via physical examination (e.g., pulse examination, monitoring for temperature, mottling) or using such technology as near-infrared reflectance spectroscopy (NIRS). This technology employs oximeter pads, which are placed on the calves of both lower extremities. Saturation levels which are low (<50%) or a large saturation differential (>15%) between cannulated and contralateral limbs may prompt DPC placement.⁸

Central Cannulation

Occasionally, situations arise in which patients do not tolerate peripheral cannulation strategies. This can occur in the setting of DPC failure, inability to achieve adequate ECMO flow, or in patients cannulated with a VAV strategy who do not achieve enough venous or arterial reinfusion to offer full support. Central cannulation has been made more feasible through the establishment of novel cannulation strategies, which do not require patients having an open chest for a prolonged period. Access to the right atrium and aorta for direct insertion of drainage and reinfusion cannulas, respectively, can be accomplished via a miniature right anterior thoracotomy, if the patient's anatomy allows. These cannulas can then be tunneled out of the chest wall allowing for closure of the chest while the patient is maintained on central VA ECMO.⁹ This configuration drains deoxygenated blood directly from the right atrium and provides oxygenated blood to the aorta in a retrograde fashion. This eliminates the issue of differential oxygenation and provides both hemodynamic support and oxygenation.

ECMO CONSULTATION AND REFERRAL

Early identification of potential ECMO patients facilitates their multidisciplinary evaluation to include risk/benefit assessment

and discussion with family or legal medical decision-maker.¹⁰ Automated alerts tied to P/F ratio or ARDS rescue interventions like inhaled nitric oxide (iNO; Mallinckrodt, Bridgewater, NJ) initiation can facilitate this process.¹¹ When a patient is identified who may benefit from extracorporeal support, an ECMO team should be consulted. Ideally, this team should be multidisciplinary, consisting of both medically and surgically trained providers who can bring their unique perspective to the selection, cannulation, and subsequent care of these complex patients. On receipt of an ECMO consult, this team can help provide advice for continued optimization of the patient in question prior to cannulation.

Ideally, this team can help the patient improve without the need for ECMO support. Suggestions for a VV candidate may include changes to ventilator settings or mode, addition of pulmonary vasodilators, neuromuscular blockade, and proning, as outlined by ARDSnet.¹² Continued decline despite these adjuncts portends a possible ECMO cannulation. In addition, some injured patients may bypass portions of this algorithm as there may be contraindications to certain interventions. For example, neuromuscular blockade is not always possible in the setting of head trauma as serial neuromonitoring is important for these patients. Similarly, proning may be contraindicated in patients with an open abdomen. For these reasons, trauma patients may benefit from ECMO cannulation earlier in their ARDS course than noninjured patients.

In an ECMO center, the contact information for the ECMO team should be readily available to trauma providers. Patients being managed at a center that does not routinely cannulate or have an ECMO service are still eligible for this life-saving treatment. Many major ECMO centers also provide transport services wherein ECMO providers travel to non-ECMO centers, cannulate patients within these centers, and subsequently transfer the now ECMO-supported patients back to the ECMO center for further management. This order of operations has been established such that patients who may have previously been considered too unstable for transport (e.g., unable to be disconnected from the ventilator even briefly, requiring multiple vasopressors) are “stabilized” to the maximal extent with ECMO and are thus more suitable for transport.^{13–15} An example of a letter from an ECMO center to referring hospitals provides an outline for preparation (Supplemental Digital Content, <http://links.lww.com/TA/D285>) and a typical list of materials needed for successful cannulation are provided (Table 1).

CANNULATION PROCEDURE

Extracorporeal membrane oxygenation cannulation is an inherently high-risk procedure. Patients are critically ill and do not have the physiologic reserve to tolerate complications. In addition, the initiation of ECMO itself leads to increased inflammation and hemodynamic changes, which often require intervention. To prepare for cannula insertion, patients should have adequate intravenous access. Some centers may require central access with a central venous catheter or peripherally inserted central catheter. Ideally, this would be a left subclavian or left internal jugular central line while leaving the right neck and both groins unobstructed for potential cannula placement. This kind of accommodation is, of course, not always possible; however, small steps to make cannulation more seamless can make a great difference.

TABLE 1. ECMO Transport Checklists

Cannulation and Transport Supplies	Perfusion Supplies
☐ Sterile gowns (2)	☐ Cardiohelp pump
☐ OR caps (2)	☐ Cardiohelp oxygenator and circuit
☐ OR masks (2)	☐ Hand-crank
☐ Sterile gloves (size: #, number: #)	☐ Back-up oxygenator and circuit
☐ Angiography drape (1)	☐ Cannulas (primary and backup)
☐ Sterile half sheets for back table (2)	☐ Dilator kits (Estech + MC3 or Avalon)
☐ Blue OR towel packs (2)	☐ Tubing clamps (4)
☐ CHG prep sticks, large (3)	☐ Shears (1)
☐ Sterile 4 × 4 gauze packs (2)	☐ Needle driver (1)
☐ Sterile Kelly clamp (2)	☐ Guidewires (SupraCore, Amplatz)
☐ Sterile ultrasound probe cover (1)	☐ NS or LR, 250 mL (1)
☐ Leur lock syringes, 60 mL (4)	☐ Point of Care ABG machine
☐ Leur lock syringes, 12 mL (2)	
☐ Leur lock syringes, 3 mL (2)	
☐ Needle, 18 Ga (1)	
☐ Needle, 25 Ga (1)	
☐ Ti-Cron sutures, 0 (10)	
☐ CHG clear dressings (2)	
☐ Consent form	

All patients undergoing ECMO cannulation should have an arterial line. Continuous hemodynamic monitoring is imperative during the cannulation process and frequent blood gases will help guide titration of sweep and flow throughout the ECMO course. The ideal location for an arterial line is the right radial artery.

The cannulation itself can be accomplished either percutaneously or via surgical cutdown. Venovenous ECMO is almost exclusively accomplished via percutaneous access and dilation via Seldinger technique under ultrasound guidance (Fig. 1). Venoarterial-venous ECMO is also commonly executed in this manner, but providers may also opt for direct cannulation via cutdown.

Because of the size to which the tissue is being dilated, accuracy of access is imperative. The needle should be inserted at an angle such that the dilators will glide as smoothly as possible into the vessels. Bridging veins and nearby vessels must not be traversed. In addition, the vessel should be accessed from the anterior aspect, in the center of the vessel. Dissection, skiving, or through-and-through punctures can be catastrophic. For this reason, many ECMO providers avoid using a previously placed line for cannulation. Although “rewiring” an existing central or arterial line may be tempting, certain inaccuracies of access which may prove clinically insignificant with smaller catheters can lead to significant, harmful complications with ECMO cannulas. In addition, sterility is of paramount importance for ECMO further underscoring our strong preference for placing new, clean lines in patients we cannulate.

Cannulation can be safely accomplished in the operating room, in the cardiac catheterization laboratory, or at the bedside. Bedside cannulation is often necessary due to the instability of the patients requiring ECMO. If cannulation is emergent, or if it is taking place in another institution, it may be necessary to cannulate without immediate imaging confirmation. However, imaging adjuncts, such as portable x-ray, fluoroscopy, or echocardiography, when available, can help to avoid complications by confirming

appropriate wire placement prior to dilation. X-ray should always be used to confirm appropriate cannula positioning after cannulation.

PRINCIPLES OF ECMO MANAGEMENT

Patients on ECMO support require continuous monitoring by a well-trained, multidisciplinary team.¹⁰ Ideally, ECMO centers have teams which are made up of physicians (surgeons, medical intensivists, anesthesiologists) and advanced practice providers, nurses, perfusionists, and pharmacists. Some centers have expanded their teams to include counselors or therapists who provide psychosocial support for patients, families, and staff.

Bedside nurses are often the first line of defense in detecting and ameliorating circuit malfunctions. Perfusionists and ECMO specialists also fall into this category and may be assigned to the bedside continuously or may be more centrally located if a remote, continuous monitoring system is in place. These systems allow for perfusionists in a control room to continuously monitor multiple patients flow rates, sweep rate, venous and arterial pressures, and oxygen saturations in various portions of the circuit in real time. Alterations in these numbers should be discussed among the members of the team to avoid or promptly correct malfunctions such as oxygenator or pump failure, circuit disconnection, or inadequate support.

Cannulas should be appropriately secured to the patient with multiple sutures to avoid cannula migration. Cannula location should be monitored daily with X-rays. Coil length visible at the insertion site can also be measured daily to ensure adequate securement (Fig. 4).

Patients on ECMO often have dynamic hemodynamic presentations. Arterial monitoring and pulmonary artery catheter monitoring are used in most cases. For patients on VV ECMO, inhaled pulmonary vasodilators including iNO or epoprostenol (Flolan; GlaxoSmithKline, Brentford, United Kingdom) should be used routinely. In trauma patients specifically, management of the underlying etiology of lung failure is critical. If penetrating trauma that requires total ventilator protection is necessary, often the underlying anatomic pathology needs to be addressed. For patients with a bronchopleural fistula, ECMO can be used for ventilator rest. Once the surgical plan for repair and exclusion of large airway injuries is completed, slow introduction of tidal volumes with appropriate plateau pressures and peak airway pressures is started.

If patients are on VV ECMO due to ARDS as a sequelae of trauma, then the underlying mechanism needs to be resolved. This typically involves standard sepsis management, antibiotic use for pneumonia, or medical and/or surgical management for pancreatitis as examples. It is important to use lung rest ventilator settings with emphasis low driving pressure <15 cm H₂O, PEEP 8-10, Tidal volumes <6 mL/kg, and mechanical power < 14 J/min.¹⁶ For those trauma patients on VA ECMO, management revolves around improving cardiac contractility and shock state such that there is adequate end organ perfusion. Weaning ECMO can be accomplished by improvement in cardiac contractility. It is important to ensure that cardiac arrhythmias are resolved prior to weaning from VA ECMO. Transvenous pacing and other adjunct medications may be necessary for maintenance of contractility and rhythm while the underlying myocardium recovers on VA ECMO.

Circuit Exchanges

ECMO circuitry creates a prothrombotic state. The foreign surfaces, plastic tubing, oxygenator tubules, and connectors are a

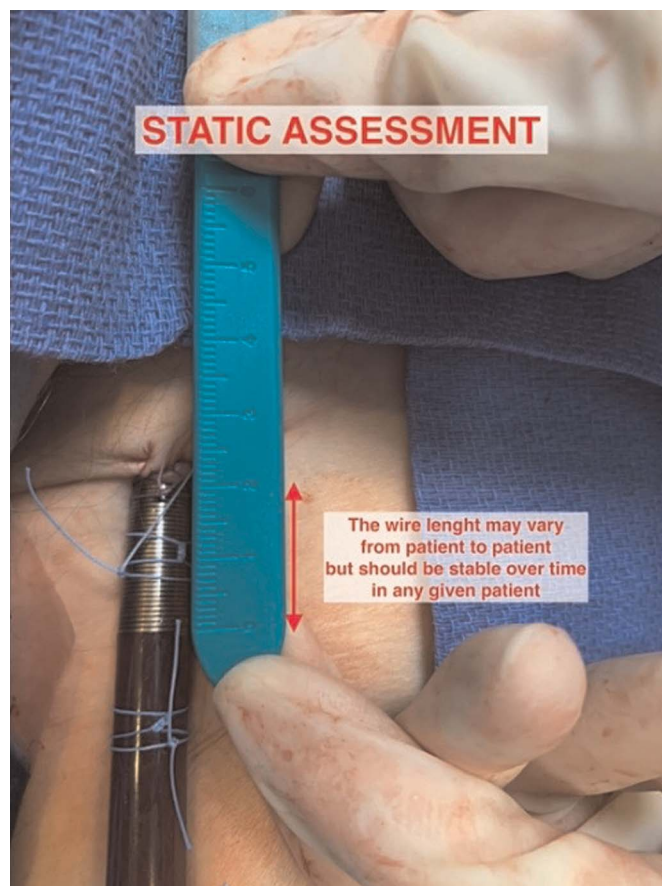


Figure 4. ECMO cannula securement and assessment. Cannulas should periodically be checked for intact suture fixation with no evidence of migration.

nidus for thrombus. Therefore, some degree of anticoagulation may be necessary throughout the duration of ECMO support. The modality of ECMO and the duration of intended support also impact the decision to use anticoagulation. With advances in bio-engineering, cannulas, oxygenators, and centrifugal pump heads with low drag and magnetically levitated discs with no blood contact has made anticoagulation free ECMO possible. Likewise, ECMO induces a simultaneous coagulopathic state. Consumption of platelets, fibrinogen and vWF are common with ECMO. The use of ECMO in trauma needs to balance these risks when choosing to initiate ECMO and for the duration of ECMO.

Avoidance of thrombosis in circuit components is a key aspect of ECMO management. Especially in a trauma situation wherein systemic anticoagulation may not be feasible, clot formation must be carefully monitored. The presence of clot in the oxygenator can lead to less effective gas exchange, and thrombus in the return limb of an ECMO circuit can lead to patient thromboembolism, causing pulmonary emboli (in VV circuits) or systemic arterial emboli (such as stroke, in VA circuits). Clot movement through the circuit can also lead to oxygenator or pump failure. To avoid this, flow rates, arterial and venous pressures, and preoxygenator and post-oxygenator saturations are carefully monitored. If these numbers suggest potential clot buildup, the oxygenator or pump may require an exchange. This involves temporarily suspending ECMO support by clamping off the circuit to exclude the oxygenator

and/or pump from the patient and cutting the tubing to remove the ineffective piece and then reconnecting a new oxygenator and/or pump. Even a brief disconnection in the circuit can result in catastrophic hypoxemia or hemodynamic changes. Thus, certain measures should be ensured prior to exchange.

The ventilator should be appropriately adjusted to ensure optimal ventilator support during the exchange. Vasoactive infusions should be available and in-line for ease of use if necessary. Bolus dose medications, such as atropine and epinephrine, should be readily available. Circuit exchanges should be a multidisciplinary activity, with clear assignment of roles. If possible, two providers should be participating in the exchange itself (one to reconnect the drainage line and one to reconnect the return line) to limit time off circuit as much as possible.

MYTHBUSTERS

Anticoagulation

Anticoagulation is a key consideration when cannulating and managing a patient on ECMO. Traumatic injury was previously considered a contraindication to ECMO due to concerns that systemic anticoagulation was necessary for circuit patency, since systemically anticoagulating injured patients could result in hemorrhagic complications. However, mandatory use of systemic anticoagulation has proven to be false. The use of anticoagulation for extracorporeal life support (ECLS) was borne out of the acute inflammatory response identified with the initiation of cardiopulmonary bypass (CPB).¹⁷ Like in CPB, ECLS exposes circulating blood volume to a large surface area of artificial circuitry. However, unlike in CPB, the blood circulated in ECLS is not exposed to a surgical field or an acute wound, and the amount of blood exposed to nonendothelial surfaces per unit of time is less. Therefore, less anticoagulation is necessary to prevent clotting within an ECMO circuit than in CPB. Contact with synthetic, nonendothelial cell surfaces, as well as shearing force, turbulence, and cavitation directly damage blood. These factors lead to increased adhesion and aggregation of platelets, which ultimately results in platelet activation and consumption. Extracorporeal life support also promotes activation of cells, which express tissue factor (monocytes, macrophages, neutrophils, activated endothelial cells, and smooth muscle cells), leading to increased circulating thrombin and fibrin. Increased thrombin leads to activation of the fibrinolytic system; however, endogenous antithrombotic activity is thought to be overwhelmed by the procoagulant effects of ECLS and thus the need for exogenous anticoagulant.¹⁷ However, the safe and effective use of ECLS without systemic anticoagulation has been well documented.^{18–21} In fact, some centers have shifted away from routine anticoagulant use for ECMO. The University of Rochester is one such institution, having stopped using routine systemic anticoagulation for patients on VA ECMO unless otherwise indicated since 2016. Wood et al. published a retrospective study analyzing this institution's outcomes and found that significantly fewer patients in the no-anticoagulation cohort experienced complications than those in the anticoagulation cohort.²² When separated by complication type, the results were no longer significant; however, the no-anticoagulation group had an appreciably lower incidence of both hemorrhagic and thrombotic complications.

Olson et al. recently evaluated the literature on thrombosis and bleeding events for patients undergoing systemic anticoagulant-free

ECLS and found that the rates of thrombosis reported were similar to the rates of thrombosis reported by the Extracorporeal Life Support Organization (ELSO) registry.²¹ The analysis published by the ELSO registry does not include anticoagulation status, but given the ELSO recommendation for anticoagulation with heparin, presumably most of these patients were systemically anticoagulated.

Prior to these more recent publications, Arlt et al.¹⁸ had published a case series describing heparin-free cannulations for patients in hemorrhagic shock. Despite the use of massive transfusions and the need for coagulation factors before and during ECMO, the authors did not observe thromboembolic complications or unexpected clot formation. They report a 60% survival rate, suggesting that ECMO may play a role even in trauma patients with significant coagulopathy.

Central Nervous System Injuries

Like other injured patients at high risk for bleeding, traumatic brain injury (TBI) and spinal cord injury patients have been excluded from the ECMO conversation in the past because of fear of precipitating or exacerbating intracranial hemorrhage. However, ECMO use in TBI patients has been reported with varying degrees of success.^{23,24} Several case series have reported fair outcomes for multiply injured patients with TBI who underwent ECMO without worsening neurologic function. There have even been reports of successful craniotomies while on extracorporeal support.^{25,26}

Certainly, the use of extracorporeal carbon dioxide removal could be particularly helpful in TBI patients with ARDS for whom permissive hypercapnia is not an option. Extracorporeal support can help to lower arterial carbon dioxide, reducing intracranial pressure, without employing ventilation strategies with high mean airway pressures typically used in ARDS that may impede cerebral venous drainage.²⁴ Given the increasing acceptance of anticoagulation-free ECMO strategies, TBI should not be considered an absolute contraindication to ECLS.

OUTCOMES

Several studies have demonstrated the successful use of extracorporeal support in trauma patients. In a multi-center, retrospective cohort study comparing conventional ARDS management to ECMO in trauma patients, Guirand and colleagues²⁷ reported that 15 of 26 traumatically injured patients cannulated to VV ECMO survived to hospital discharge (a 57.7% unadjusted survival rate). After propensity score matching for age and PaO₂/FIO₂ ratio, survival was significantly greater in the ECMO group than the conventional management group. (Kaplan Meier survival 64.7% vs. 23.5%, $p = 0.01$).

Bosarge et al.²⁸ conducted a retrospective study comparing the early initiation of ECMO for management of severe ARDS in trauma patients to historical controls immediately preceding the development of the ECMO program at this institution. Mortality in the ECMO group was significantly reduced compared to the conventional management group. (ECMO 13.3%, CONV 64.3%, $p = 0.01$)

Kim et al.²⁹ retrospectively reviewed the medical records of patients with ARDS secondary to noninfectious etiologies who underwent ECMO support over an 8-year period and compared trauma patients to nontrauma patients. Mortality was not significantly different between the two groups. Intensive care unit stay was noted to be longer for trauma patients than nontrauma patients, however, this may have been related to the longer

pre-ECMO period experienced by the trauma group when compared with the nontrauma group. Overall, this study further supports the conclusion that ECMO support can be associated with favorable outcomes in trauma patients.

The military experience with ECMO provides an illustration of successful management of injured patients using extracorporeal support. The successful utilization of ECMO for the support of burn and trauma patients by the US military ECMO team has been well-described in the literature.³⁰ Fang et al. described the Landstuhl Acute Lung Rescue Team's (ALeRT) experience with trauma patients in respiratory failure. This retrospective review of the ALeRT registry detailed successful activations of 24 of 27 missions launched (89%). This included two patients with severe bilateral pulmonary contusions requiring VV-ECMO support. Both patients ultimately recovered from their lung injuries and were successfully decannulated.³¹

There have also been several case reports outlining the use of ECMO overseas including the successful use of VV ECMO to support a patient with a significant tracheal injury after a blast injury sustained in Syria.³² The patient was successfully cannulated at a Role 2 in Baghdad and was transported back to the United States on ECMO and ultimately bridged to operative repair. These studies all provide support for the safety and efficacy of ECLS in the care of trauma patients.

PEDIATRICS

Injury is the leading cause of death among children and adolescents in the United States.³³ Approximately one in every six pediatric presentations to an emergency department is due to traumatic injury³⁴ and, importantly, a majority of children present for emergency care at general emergency departments rather than pediatric specialty centers.³⁵ The American Academy of Pediatrics, American College of Emergency Physician, and American College of Surgeons recommend "pediatric readiness" for all emergency care centers,^{35,36} and trauma centers with higher pediatric readiness are associated with superior survival in injured children.³⁷ Thus, it is imperative that trauma surgeons consider and prepare for the care of critically injured children.

Extracorporeal membrane oxygenation has been described as an advanced therapy for cardiopulmonary support in the critically injured child. In a systematic review, Puzio and colleagues identified 58 pediatric trauma patients whose treatment included ECMO. Approximately half of the patients identified by this review were cannulated at adult trauma centers. Most of these patients were cannulated for posttraumatic ARDS, though a majority were via VA cannulation technique. Puzio and colleagues³⁸ reported an overall survival to hospital discharge rate of 60%, which importantly is similar to the survival for nontrauma indications for pediatric ECMO. These data support that adult ECMO trauma centers should consider the use of ECMO and prepare for the possibility cannulation in critically injured children.

In a review of the National Trauma Data Bank, Watson and colleagues examined the use of ECMO in children with traumatic injury. The most common indications were motor vehicle collision (44%), gunshot wound (GSW) (17%), burns (17%), and drowning (11%). Children cannulated to ECMO after drowning had the greatest survival (75%), and children cannulated after GSW had the worst survival (33%). Propensity matching revealed that children treated with ECMO had a survival rate overall of 58%, which

was statistically similar to survival of similar patients treated with non-ECLS methods (65%). Watson and colleagues³⁹ findings reaffirmed that a large percentage of ECMO cannulations in pediatric trauma occur at adult centers (42%).

Finally, Behr and colleagues⁴⁰ recently published a review of the Extracorporeal Life Support Organization, examining outcomes of children cannulated to ECMO following traumatic injury. The group identified 573 pediatric patients with traumatic injuries, cannulated to ECMO between 1989 and 2017. The most common indications were drowning (39%), burns (21%), and thoracic trauma (18%). The most common mode of ECMO was VA (55%), though the percentage of VV increased and VA decreased over the study period. Furthermore, the majority of the children supported with ECMO were cannulated for primarily pulmonary (71%) rather than cardiogenic failure. Overall survival was 55%, which is comparable to other nontrauma ECMO indications in the pediatric population. In addition, of the patients who survived, approximately 50% were discharged straight home without the need for long-term rehabilitation or acute care facilities.

These data support the use of ECMO in critically injured children, even when cannulation takes place at adult ECMO centers. However, it is important to note differences in cannulation strategy for pediatric patients. Bilateral femoral VV ECMO cannulation may be challenging in small children, as the femoral vessels may not be able to accommodate a cannula large enough to support full ECMO flows.⁴¹ Cannulation of the internal jugular vein and femoral vein may provide improved support. Alternatively, single-site cannulation in the right internal jugular vein with a dual-lumen cannula has been shown to be safe and now is becoming more prevalent than multisite cannulation in pediatric patients requiring VV support.⁴² Venoarterial cannulation through the neck (jugular-carotid) is another viable option for cardiopulmonary support.⁴³ Given the smaller size of the vessels, pediatric cannulations may require a cut-down approach rather than a percutaneous approach. Ultrasound should be used to assess vessel size and patency prior to cannulation, and cannulation approach should be tailored based on patient and vessel size.

CONCLUSION

Traumatic injury in adults and children should not be considered a contraindication to ECMO. Patients with traumatic injury can be successfully managed with extracorporeal support with good outcomes. Patient selection as well as care by a well-trained, multidisciplinary ECMO team are paramount to the success of this life-saving therapy. Access to ECMO resources and teams is becoming more prevalent, and trauma surgeons should consider ECMO in the care of critically injured patients.

AUTHORSHIP

M.F., V.G.S., M.B., S.T.D., A.A.U., and J.W.C. contributed to the outline of this article. M.F. wrote the first draft of the article. M.F., S.T.D., and J.W.C. created the tables and figures. All authors provided critical revisions and approved the final version.

DISCLOSURE

Conflicts of Interest: Author Disclosure forms have been supplied and are provided as Supplemental Digital Content (<http://links.lww.com/TA/D286>). Department of Defense Disclaimer: The opinions and assertions expressed herein are those of the authors and do not necessarily reflect the official policy or position of the Uniformed Services University of the Health Sciences,

the United States Army, the United States Air Force, or the Department of Defense.

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