ELSO GUIDELINES FOR ECMO CENTERS

PURPOSE

These guidelines developed by the Extracorporeal Life Support Organization, outline the ideal institutional requirements needed for effective use of extracorporeal membrane oxygenation (ECMO). The Extracorporeal Life Support Organization recognizes that differences in regional and institutional regulations especially concerning hospital policies may result in variations from these guidelines.

INFORMATION AND BACKGROUND

Extracorporeal Membrane Oxygenation (ECMO) was first used successfully for neonates with respiratory failure in 1975. Today it is an accepted treatment modality for neonatal, pediatric and adult patients with respiratory and/or cardiac failure failing to respond to conventional medical therapy.

ECMO is defined as the use of a modified cardiopulmonary bypass circuit for temporary life support for patients with potentially reversible cardiac and/or respiratory failure. ECMO provides a mechanism for gas exchange as well as cardiac support thereby allowing for recovery from existing lung and/or cardiac disease.

It has been estimated that approximately 2800 newborns could benefit could benefit from ECMO annually in the US (one of every 1309 live births). Pediatric and adult patients are being successfully treated in increasing numbers.

GENERAL

A. ECMO centers should be located in tertiary centers with a tertiary level Neonatal Intensive Care Unit, Pediatric Intensive Care Unit and/or Adult Intensive Care Unit

B. ECMO Centers should be located in geographic areas that can support a minimum of 6 ECMO patients per center per year. The cost effectiveness of providing fewer than 6 cases per year combined with the loss, or lack of clinical expertise associated with treating fewer than this number of patients per year should be taken into account when developing a new program.

C. ECMO Centers should be actively involved in the Extracorporeal Life Support Organization (ELSO) including participation in the ELSO Registry.

ORGANIZATION

A. **General Structure**: The ECMO center should be located in a tertiary level intensive care unit with the following components.

1. A single physician ECMO program director with responsibility for the overall operation of the center. While there may be several associate directors with specific interests or focus in limited areas of ECMO care, the primary medical director should be responsible for assuring appropriate specialist training and performance, directing quality improvement meetings and projects, assuring proper and valid data submission to ELSO, and should also be responsible for the credentialing of other physicians who care for ECMO patients or who manage the ECMO circuit.

2. An ECMO coordinator with responsibility for the supervision and training of the technical staff, maintenance of equipment, and collection of patient data.

3. A multi-disciplinary ECMO Team should have quality assurance review procedures in place for annual ECMO evaluation internally.

4. Formal Policy and Procedures outlining the indications and contraindications for ECMO, clinical management of the ECMO patient, maintenance of equipment, termination of ECMO therapy, and follow-up of the ECMO patient should be available for review.

5. Appropriate laboratory space for training and continuing medical education should be available.

B. Staffing Issues:

1. The ECMO physician staff should meet the requirements of their subspecialty training as set forth by their specific governing board (American Board of Surgery, American Board of Pediatrics, etc.). In addition, ECMO staff should meet the training requirements described below.

2. The medical director should be a board certified neonatologist, a board certified critical-care specialist, or a board certified pediatric, cardiovascular, thoracic surgeon, trauma surgeon, or other board certified specialist with specific training and experience in ECMO support.

3. The ECMO coordinator may be an experienced neonatal, pediatric, or adult intensive care registered nurse or registered respiratory therapist with a strong ICU background (minimum of 1 year of ICU experience), or a certified clinical perfusionist with ECMO experience.

4. An ECMO-trained physician will provide 24-hour on-call coverage for the ECMO patient. The physician may be a neonatologist, pediatric or adult critical-care specialist, a neonatology,critical care, subspecialty fellow, or other physician who has completed at least three years of post-graduate pediatric, surgical, or adult medical training and has specific ECMO training.

5. There shall be an ECMO clinical specialist in addition to the ICU nurse or an ECMO trained nurse, as described below, to provide care throughout the course of ECMO. (Refer to C-7)

6. The ECMO Specialist should have a strong intensive care background (at least 1 year of NICU, PICU, MICU, CCU or other critical care experience preferred) and have attained one of the following:

   (1) Successful completion of an approved school of nursing and achievement of a passing score on the state written exam given by the Board of Nursing for that state (this may also include nurse practioners with appropriate experience and training);
   OR
   (2) Successful completion of an accredited school of respiratory therapy and have successfully completed the registry examination for advanced level practitioners and be recognized as a Registered Respiratory Therapist (RRT) by the National Board of Respiratory Care (NBRC).
   OR
   (3) Successful completion of an accredited school of perfusion and national certification through the American Board of Cardiovascular Perfusion (ABCP).

OR

(4) Physicians trained in ECMO who have successfully completed institutional training requirements for the clinical specialists.

OR

(5) Other medical personnel such as biomedical engineers or technicians who received specific ECMO training and have practiced as an ECMO specialist since the initiation of their programs, and who have completed equivalent training in ECMO management as the other specialists, have successfully documented necessary skills as an ECMO specialist, and who have been approved specifically as an ECMO specialist by the medical director. These personnel can be approved institutionally as an ECMO specialist under the "grandfather" principle. However ELSO does not encourage or support the new training of individuals except as outlined in 1-4 above.

7. In clinical settings where the ECMO patient is primarily managed by the ICU nurse (the single care giver model) the ICU nurse should be specifically trained in ECMO patient and circuit management. Nurses with this responsibility should be approved by the program director. The ECMO specialist team is responsible for managing equipment and supplies, circuit preparation, troubleshooting, daily rounds, education, and service administration. Additional trained personnel should be readily available for support.

8. Additional support personnel from the permanent hospital staff should be available including:

   a. Physicians or other medical personnel:
      - Pediatric/adult cardiology
      - Pediatric/adult cardiovascular surgery
      - Pediatric/general surgery
      - Cardiovascular perfusion
      - Pediatric/adult anesthesiology
      - Pediatric/adult neurosurgery
      - Pediatric/general radiology
      - Genetics

   b. Biomedical engineer

   c. Respiratory therapists experienced in intensive care (in USA)

9. The following consultants should be available as needed.
    - Pediatric/adult neurology
    - Pediatric/adult nephrology
    - Pediatric/adult pulmonology
    - Pediatric/adult infectious disease
    - Occupational/physical therapist
    - Developmental/rehabilitation specialist
    - Speech therapy/feeding therapy specialist
    - Social Services/Palliative Care
    - Spiritual Support

10. If out of hospital ECMO transport is available, a fully trained and equipped transport team should be available 24 hours a day. A team for in-hospital transport should be available at all institutions.

11. Trained individuals capable of providing development follow-up or rehabilitation should be available and capable of providing long-term follow-up to the ECMO patient. Appropriate subspeciality services should also be accessible.

C. Physical Facilities and Equipment

1. If the space allocated for ECMO is located outside the ICU, it should be in close proximity to and have appropriate communication with the ICU to assure additional staff support for any emergency that may arise.

2. An ECMO system consists of a suitable blood pump, a system for servo-regulation to balance venous drainage rate from the patient and blood return to the patient, an appropriate blood heat exchanger and warming unit, appropriate disposable materials including membrane oxygenator tubing packs, and connectors, all suitable for prolonged extracorporeal support.

3. A device for monitoring the level of anticoagulation (ACT or other) with appropriate supplies should be at the bedside.

4. The following equipment should be readily available:

    a. Backup components of the ECMO system and supplies for all circuit components.

    b. Adequate lighting to support surgical interventions.

    c. Surgical instrument set for revision of cannulae or exploration for bleeding complications.

5. The following support facilities with staff should be available on a 24-hour basis.

   a. A blood gas laboratory

   b. Laboratory for blood chemistry and hematologic testing

   c. Blood bank

   d. Radiographic support including cranial ultrasound and CATscan

   e. Cardiovascular operating room facilities with cardiopulmonary bypass capabilities located within the hospital doing ECMO and available 24 hours a day.

D. Physician and Staff Training and Continuing Education

1. Each ECMO center should have a well-defined program for ECMO physician and staff training, certification, and re-certification. This program should include: didactic lectures, laboratory training with the ECMO equipment, bedside training, and a defined system for testing proficiency of the team members (See ELSO Red Book 4th edition, Chapter 34.)

2. Each member of the ECMO team should successfully complete this program.

3. A well-defined program of routine continuing education and emergency training for ECMO staff should be outlined with records documenting participation by active team members. Smaller ECMO programs (<20 cases/year) may need additional continuing education for all team members.

4. It is recommended that team members not involved in ECMO pump management for >3 months participate in a required recertification process as defined by the ECMO program.

E. Selection Criteria

1. ECMO is indicated for selected neonatal, pediatric and adult patients with severe, acute cardiac and/or respiratory failure who have failed to respond to conventional medical management.

2. Each ECMO center should develop institutional criteria for ECMO therapy, including indications and contraindications.

3. It is recommended that the ECMO center develop guidelines for transfer

of the potential ECMO patient and ECMO patients requiring services provided only at an ECMO referral center.

F. Patient Follow-up

Each ECMO center should have a well-defined developmental follow-up program for the ECMO patient with appropriate subspecialty support (refer to ELSO Guidelines for Follow-up).

G. Program Evaluation

1. A well-defined system should be instituted for assuring that formal meetings of key ECMO team members occurs on a routine basis to reviewcases, equipment needs, administrative needs, and other pertinent issues. Minutes to these meetings should be available for review.

2. A prompt review of any major complication or death should be held both with ECMO team members and with the responsible Morbidity and Mortality committee in the hospital. These reviews should be conducted under the relevant quality assurance laws for the state where the center is located.

3. Formal clinical-pathological case reviews with a multi-disciplinary approach should be regularly conducted (as outlined by JCAHO regulations).

4. An Annual Data Report, utilizing the center's collated data, or the collated report of data submitted to the ELSO ECMO Registry, should be available for quality assurance review.

5. Records documenting maintenance of equipment should be kept (as per JCAHO regulations).

Extracorporeal Cardiopulmonary Resuscitation in Adults. Interim Guideline Consensus Statement From the Extracorporeal Life Support Organization

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***Disclaimer*: Veno-arterial extracorporeal membrane oxygenation (ECMO) is increasingly being deployed for selected patients in cardiac arrest who do not attain a native circulation with conventional CPR (ECPR). This ELSO guideline is intended to be a practical guide to implementing ECPR and the early management following establishment of ECMO support. Where a paucity of high-quality evidence exists, a consensus has been reached amongst the authors to provide guidance to the clinician. This guideline will be updated as further evidence in this field becomes available.**

Key Words: extracorporeal cardiopulmonary resuscitation, extracorporeal membrane oxygenation, cardiopulmonary resuscitation, resuscitation.

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INTRODUCTION

Extracorporeal cardiopulmonary resuscitation (ECPR) is the application of extracorporeal membrane oxygenation (ECMO) in patients where conventional cardiopulmonary resuscitation (CCPR) measures are unsuccessful in achieving a sustained return of spontaneous circulation (ROSC) (Sustained ROSC is deemed to have occurred when chest compressions are not required for 20 consecutive minutes following cardiac arrest.).[1] The primary purpose of ECPR is to restore the circulation and gas exchange. By providing organ perfusion, it provides time for the delivery of interventions necessary to regain an adequate native circulation. These may include percutaneous coronary intervention (PCI) and recovery from myocardial stunning, pulmonary thrombectomy, rewarming, or toxin clearance.

Extracorporeal cardiopulmonary resuscitation is a time-sensitive, complex intervention that requires teamwork, clearly defined roles, and well trained healthcare providers.[2] Extracorporeal cardiopulmonary resuscitation can be deployed both for patients with in-hospital cardiac arrest and out of hospital cardiac arrest (OHCA). ECPR should be considered after 10–15 minutes of unsuccessful conventional resuscitation efforts,[2] because organization and preparation for ECPR will take some time and it has been clearly shown that time to ECMO correlates with neurologic outcome.[3,4]

Currently, there are no published randomized controlled trials comparing outcomes of ECPR to CCPR. Observational studies comparing ECPR to historical controls and case matched controls have demonstrated favorable results for ECPR.[5–9] However, these studies are heterogeneous and survival ranges from 15% to 50%. Among adult ECPR patients recorded in the international ELSO dataset, survival to hospital discharge is 29%.[10]

At the time being, we do not know whether the number of neurologic injured patients will increase with growing use of ECPR. A major task for the future will be to develop better neuroprognostication tools. In the current observational studies in selected populations,[5,8–10] >85% of survivors of cardiac arrest treated with ECPR had neurologic outcomes fall into favorable neurologic performance categories (cerebral performance categories 1 or 2).[5,8,9] Future trials involving ECPR should endeavor to report neurologic outcomes as well as mortality.

This document contains numerous additional literature references, organized by topic, found in the Supplemental Digital Content 1, http://links.lww.com/ASAIO/A584.

Table 1. Example of Inclusion Criteria for ECPR

Age < 70 years[14]
Witnessed arrest
Arrest to first CPR ("no-flow interval") < 5 minutes (*i.e.,* bystander CPR)
Initial cardiac rhythm of VF/pVT/PEA
Arrest to ECMO flow < 60 minutes "low flow interval"*
ETCO2 > 10 mm Hg (1.3 kPa) during CCPR before cannulation for ECMO
Intermittent ROSC or recurrent VF
"Signs of life" during conventional CPR may be a positive predictive factor for survival
The absence of previously known life limiting comorbidities (*e.g.* end stage heart failure/chronic obstructive pulmonary disease/end-stage renal failure/liver failure/terminal illness) and consistent with patient's goals of care
No known aortic valve incompetence (>mild aortic valve incompetence should be excluded)

*Unless other favorable prognostic features are present: *e.g.,* periods of intermittent ROSC/hypothermia prearrest/young age/signs of life during CPR. CPR, cardiopulmonary resuscitation; ECMO, extracorporeal membrane oxygenation; ECPR, extracorporeal cardiopulmonary resuscitation; ROSC, return of spontaneous circulation.

Patient Selection

Robust data to identify those who may benefit from ECPR are lacking. Protocols and guidelines strive to identify cases most likely to survive with favorable neurologic outcome—such as those patients who are witnessed to arrest and in whom high-quality CPR was initiated rapidly, in addition to cardiac arrests with a presumed reversible pathology, such as acute coronary occlusions.[1,11–13]

We recommend that locally agreed inclusion criteria be formulated to guide clinicians on balancing the wise use of resources amongst patients who are thought to have an improved chance of survival following cardiac arrest (**Table 1**).

Decision-making for ECPR is often time critical and relies on incomplete information. As such, it may be reasonable to start ECPR as a bridge-to-seeking further information regarding appropriateness of on-going support. Institutions may choose to use alternative inclusion criteria for OHCA *versus* in-hospital cardiac arrest given differences in etiology and expected survival.

Timing

The optimal time before initiation of ECPR in cases of refractory cardiac arrest is not well defined. If initiated too early, ROSC may have been gained with CCPR avoiding the additional risks of veno-arterial ECMO. If initiated too late, the risk of hypoxic ischemic injury to the brain and other organs increases significantly; resuscitation-related organ trauma and coagulation disorders may also increase. Among observational studies, shorter intervals between the cardiac arrest and ECPR initiation correlate with improved survival.[4,15,16]

The time required to establish ECMO support is highly dependent upon the capabilities of the resuscitation team and patient factors. It may be achieved in as little as 10 minutes but may take longer.[9] We therefore advise early assessment for ECPR candidacy. It is reasonable to consider commencing cannulation after 10–20 minutes of failed resuscitation efforts. Beyond 20 minutes of refractory arrest, the probability of ROSC and survival with CCPR is <5%[17,18]; thus, the risks of V-A ECMO and ECPR at this point, with appropriately selected patients and providers, may be justified.

The maximum arrest duration before ECPR becomes futile and has also not been well defined. Neurologically intact survival has occurred following more than 3 hours of mechanical CPR before ECPR in the context of a hypothermic arrest. In contrast, among nonhypothermic arrests, the majority of survivors were established on ECMO support in <60 minutes from the onset of cardiac arrest. In one center, ECPR survival after 90 minutes of CCPR was 14%.[19] Until there are more robust data to the contrary, we recommend that the goal of ECPR is to establish adequate ECMO flow within 60 minutes of onset of cardiac arrest.

Location

The optimal location to provide safe and timely cannulation for ECPR in a hospital may differ between institutions depending on infrastructure, staffing, and other logistical considerations. Deployment of ECPR does not require an operating theater. Some centers have proven the feasibility of providing prehospital ECPR to minimize low flow time.[6] It is uncertain at present if provision of a prehospital ECPR system rather than transport of the OHCA patient to a center that provides ECPR leads to improved outcomes.

In the absence of definitive evidence, it is recommended that patients in refractory cardiac arrest who are suitable for ECPR should be transported to the nearest hospital which can provide this support as fast and as safely as possible. Early notification of a potential ECPR case is reasonable to gain time for hospital staff to mobilize the required team. If transport to a hospital-based ECPR setting is undertaken, emergency medical services systems should strive to minimize interruptions to high-quality CPR during the extrication, transport, and hospital hand over. Automated mechanical compression devices may facilitate this.

Before further data become available, at the present time, it is recommended to reserve out of hospital ECPR to highly specialized teams, possibly in the setting of controlled clinical trials.[6]

Mode of Support: Rationale for V-A extracorporeal cardiopulmonary resuscitation

The goal of ECPR is the rapid restoration of adequate organ perfusion with cardiopulmonary support utilizing V-A ECMO.

Cannulation Phase

The cannulation phase commences with skin preparation to the femoral areas with antiseptic solution at which point modification to the ACLS algorithm should occur. Concurrently, the following processes must occur:

External Cardiac Massage

External cardiac massage must continue throughout the cannulation phase, which may be assisted by application of an

automated mechanical compression device. Studies comparing the mechanical chest compression devices with human-performed chest compression during CCPR have shown similar survival outcomes. We, therefore, extrapolate that a mechanical chest compression device *may* offer advantages during a prolonged resuscitation attempt during ECPR by reducing staff physical fatigue, providing more space around the patient and minimizing body movements during the cannulation.[8,20]

Some mechanical chest compression devices require careful positioning over the lower third of the sternum in the midline and must be checked regularly throughout application. Migration toward the upper abdomen reduces the effectiveness of compressions and is potentially harmful.[21]

Cannulation

Percutaneous ECMO cannulation has been shown to be effectively performed by providers from many disciplines, including surgeons,[20,22] intensivists,[23] cardiologists,[9] and emergency physicians.[20,22,24] However, those performing this technically challenging procedure must have the requisite training to develop the required skills, and sufficient volume of experience to maintain competency. Ideally, cannulators should be performing conventional vascular access procedures regularly. We advise that the decision to initiate cannulation occurs after a risk/benefit assessment of the most skilled immediately available provider, within the context of patient-specific cannulation complexities and the risk of continued CCPR.

Cannula Insertion

Percutaneous

The common femoral artery and vein may be accessed using a modified Seldinger technique.[23] The femoral vessels should be imaged with ultrasound in real time to increase first-pass success rates. In suspected pulmonary embolism as the cause for arrest, ultrasound visualization of the vessels is particularly important to exclude inadvertent cannulation of a thrombosed vein. Chest compression pauses, if required, should be kept to a minimum during cannulation. The first cannula may be flushed with heparinized saline or periodically back-flushed, to prevent clot formation while the second cannula is inserted. This step is not required for the second cannula as connection to the preprimed circuit is imminent.

There is no strong preference regarding the side and, in the case of difficulty, unilateral cannulation of both femoral vessels is acceptable. Time to support takes precedence over these other considerations. If two trained operators are available, contralateral cannulation may be faster.

The venous and arterial guidewires should be imaged before cannula insertion to confirm correct location and avoid inadvertent nonphysiologic support.[25] This may be performed with bedside vascular ultrasound in combination with transthoracic or transesophageal echocardiography (for imaging of wires in the hepatic inferior vena cava and abdominal aorta) or with fluoroscopy.[25] If available, fluoroscopy offers advantages in that it can evaluate the course and size of the vasculature. However, cannulator preference with alternative methodologies is acceptable; minimizing time to support remains the priority. Intraarrest transesophageal echocardiography, in the hands of experienced providers, can facilitate placement and is supported by specialty guidelines.[26]

Distal Perfusion Cannula

Observational series suggest that ultrasound-guided placement of a smaller distal antegrade perfusion cannula (sometimes called distal limb perfusion cannula) in the ipsilateral superficial femoral artery, perfused off the side port on the arterial cannula, is associated with reduced critical limb ischemia.[27] Leg perfusion could also be *via* retrograde flow *via* cannulation of the dorsalis pedis or posterior tibial arteries. This distal perfusion cannula is not required for initial deployment—priority should be given to therapies such as coronary catheterization—but should be sited ideally within 4 hours to reduce the risk of limb ischemia and subsequent need for fasciotomy or limb amputation.[28] The use of calf tissue oxygen saturation with near infra-red spectroscopy may provide monitoring of leg perfusion and onset of ischemia.

Surgical

Arterial (antegrade and retrograde) and venous cannulation can also be acquired *via* surgical cut down techniques. The main advantage of cut down technique is direct visualization of the vessels while cannulating. This can be used to salvage a failed percutaneous access attempt. Cut down approaches may increase subsequent bleeding or infection from cannulation sites.

Cannula Choice

Cannula size should be guided by the relative balance between vessel size and the anticipated need for flow. Some data suggest increased limb ischemia with larger cannula size[29] although this has not been confirmed in other studies. Arterial 15–17 Fr and 19–25 Fr multistage venous cannula provide satisfactory blood flow,[30] although smaller cannulae may be acceptable for small patients.[29] A single-stage drainage cannula is also acceptable. Most circuits can deliver >4 L/min blood flow with a 15 Fr arterial return cannula. For large males, a 17–19 Fr arterial return cannula may be used. Significant arterial vasospasm may be seen in prolonged cardiac arrest after multiple doses of IV adrenaline, which may impede percutaneous cannulation.

ACLS Modifications

Standard ACLS therapies should be applied throughout the resuscitation until the cannulation procedure commences. The code leader should not be engaged in the ECMO cannulation process, but should provide oversight of the parallel conventional and ECMO resuscitation. Extreme caution should be applied when defibrillating the patient once guide wire insertion commences, due to the risk of electrocution of the cannulators. It may be reasonable to suspend further defibrillation attempts from this point until the patient is established on V-A ECMO support. Brief rhythm and pulse checks may still occur at the discretion of the code leader, as ROSC may allow the cannulation team more time for cannulation. End-tidal CO2 and tissue oxygenation monitoring may help in assessing CCPR quality and ROSC detection.[31–33]

Pauses to chest compressions for any reason should be kept to a minimum. Adrenaline and other drug administration may continue through the cannulation phase as directed by the code leader. When V-A ECMO support is imminent, as the circuit is being connected to the cannulae, adrenaline boluses should

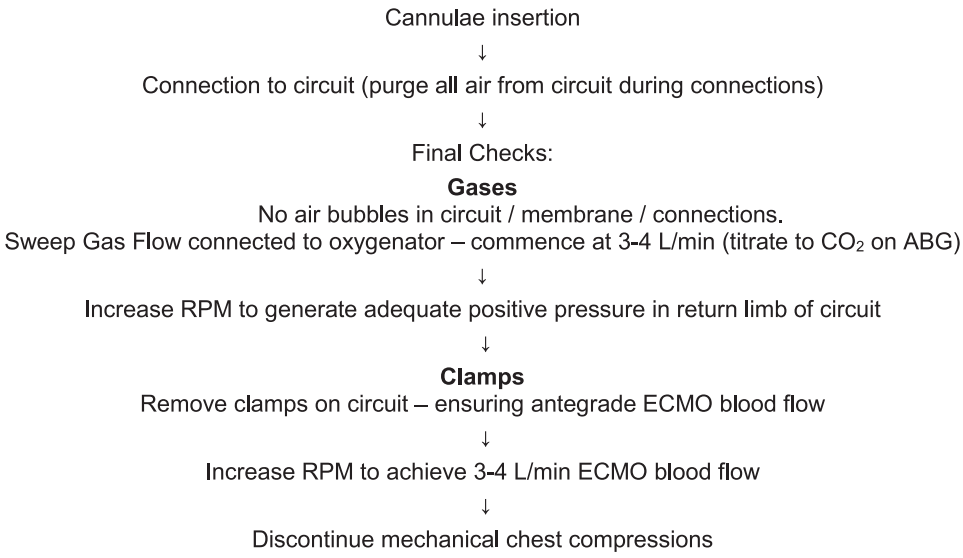

Figure 1. Cannulation sequence of events.

be discontinued as there is a risk of significant hypertension on establishment of a circulation with V-A ECMO blood flow.

Connection and Establishment of Extracorporeal Membrane Oxygenation Support

The primed circuit is connected to the inserted ECMO cannulae using a technique to purge all air from the lines, thereby avoiding risk of air embolism. There is no need to warm the saline prime in the circuit before V-A ECMO support in ECPR (**Figure 1**).

The console operator should increase pump revolutions per minute to generate positive pressure in the return limb of the circuit before releasing the final clamp, this ensures antegrade circuit flow. Gradual increases in V-A ECMO support should occur over 20 seconds, aiming for a blood flow of 3–4 L/min. The goal of ECMO support is to halt on-going global ischemia. The minimum flow rate required to achieve this goal is uncertain. Serial measurement of lactate to assess clearance and monitoring of organ function may be used to guide support.[34]

Once V-A ECMO blood flow is ≥3 L/min, mechanical compressions should be discontinued as an adequate circulation has been established. Vasopressor and inotrope infusions, if running, may need to be weaned rapidly.

Extracorporeal Cardiopulmonary Resuscitation-Specific Immediate Postcardiac Arrest Care Management

1. The access cannula position should be confirmed with fluoroscopy or echocardiography before cannula securing and dressing. The tip of the drainage cannula should be positioned in the right atrium. Both cannulas should be secured once an acceptable position is achieved.
2. Mean arterial pressure measurement: This is best achieved with a right-sided upper limb arterial line (radial or brachial). Right upper limb blood gas sampling gives the easiest indicator of native circulation P_aO_2 which may represent the cerebral oxygen delivery depending on the mixing point in the aorta between native circulation and V-A ECMO blood flow.[35] Until an arterial line is placed, noninvasive measurement using a Doppler and a cuff will assist with initial vasopressor dosing.
3. An optimal mean arterial pressure (MAP) target following ECPR has not been identified. We recommend titrating vasopressors to MAP target ≥60 mm Hg for organ perfusion pressure and <80 mm Hg to minimize risk of left ventricular (LV) distension. Animal data suggest higher MAP targets during initial reperfusion may improve neurologic outcome.
4. Titrate sweep gas flow mechanical ventilation if ROSC has occurred by frequent arterial blood gases monitoring to avoid hypocarbia.
5. Address potential drainage insufficiency (drainage line chatter) with fluids/transfusion/weaning of V-A ECMO blood flow if excess to requirement; total circulation is made up of native cardiac output, if present, plus ECMO blood flow.
6. Ensure correct placement of endotracheal tube.
7. Central venous access.
8. Sedation and analgesia.
9. Perform bedside ultrasound: cardiac, thoracic, and abdominal imaging to identify possible complications (pneumothorax and thoracic/abdominal bleeding) and assess valve competence and LV distension.
10. Temperature monitoring and control.
11. 12 lead ECG.
12. Chest x-ray.
13. Establish end-tidal CO2 monitoring to assess native cardiopulmonary circulation.
14. Formal laboratory bloods including cross match.

Further Care Within the First Few Hours

1. Check circuit blood flow stability. Unstable (falling) ECMO circuit blood flow should prompt a search for intraabdominal, including retroperitoneal, and thoracic sources of hemorrhage, cardiac tamponade (associated with prolonged chest compression or trauma), or ECMO-driven LV distension with pulmonary congestion.

2. Restoration of a potentially perfusing rhythm increases likelihood of native circulation with LV ejection and thus reduces risks of LV distension, valvular regurgitation, pulmonary edema, and intracardiac thrombus formation. Patients in refractory arrhythmias should have another attempt at electrical cardioversion after several minutes of extracorporeal support. The restoration of coronary perfusion pressure with the V-A ECMO along with improving acid–base status may lead to a successful cardioversion at this point. However, coronary ischemia and other reversible factors need to be addressed. Therefore, multiple attempts should be avoided unless these factors are resolved.
3. Peripheral V-A ECMO may increase LV afterload. If LV distension and pulmonary congestion occur, consideration to LV venting should be given. Options include: an intraaortic balloon pump, direct LV vent, Impella, or atrial septostomy.[36]
4. Consider mechanical ventilation with positive end expiratory pressure ≥10 cm H_2O to reduce LV afterload and prevent or treat pulmonary edema. Due to reduced pulmonary blood flow, reduce minute ventilation to achieve a low normal etCO_2. Lack of etCO_2 may indicate the absence of a native circulation.
5. Hyperoxia may be associated with worse neurologic outcome after cardiac arrest, including in the ECPR population.[37] Avoidance of hyperoxia can be achieved through careful blending of ECMO fresh gas flow with an air and oxygen mix. We recommend targeting a patient arterial oxygen saturation of 92–97%.
6. Carbon dioxide (CO_2) targets after resuscitation from cardiac arrest are conflicting, but a predominance of studies demonstrates increasing mortality with initial hypocarbia.[38] There is insufficient data among ECPR-specific populations to provide further recommendations.
7. Targeted temperature management can be precisely achieved using the heat exchanger on the ECMO oxygenator. Based on protocols with best outcomes and consensus, we advise on 33–36 for 24 hours, then gradual rewarming to 37°C.[8,9]
8. Siting a distal limb perfusion cannula is known to be associated with decreased limb ischemia in V-A ECMO.[27] Accordingly, we recommend a distal perfusion cannula should be sited on the side of arterial cannulation. This should be performed within 4 hours of cannulation, although this should not delay cardiac reperfusion or urgent diagnostic imaging for bleeding or pulmonary embolism if these are required.[28]

Coronary Angiography/Percutaneous Coronary Intervention

Studies suggest improved outcomes in cardiac arrest patients treated with PCIs. Extracorporeal cardiopulmonary resuscitation series targeting cardiac arrest believed to be due to acute coronary etiologies, which used protocolized catheterization postcannulation are associated with increased survival.[8,9,20] Accordingly, we recommend emergent coronary angiography for all ECPR patients without an obvious alternate noncardiac cause, independent of age and presenting rhythm.

The cardiology team should be informed at the time of setup for all ECPRs and be presented with the history and 12 lead ECG postcannulation for assessment.

Imaging

In adults, as well as initial ultrasound, we recommend routine computerized tomography (CT) imaging is performed in all ECPR cases as soon as practical. If the cause of the cardiac arrest is unclear, or if there are signs for significant internal hemorrhage, CT should take place immediately after the cannulation, otherwise after coronary angiography.

If the cause of the arrest is unclear, consider:

1. CT brain
2. CT pulmonary angiography (timing of contrast administration and ECMO blood flow may need to be adjusted to improve image quality)
3. CT abdomen/pelvis

If the cause for cardiac arrest is identified in the cath laboratory, consider imaging:

4. CT brain

If there is evidence falling ECMO blood flows or drainage insufficiency (drainage line chatter), these additional scans may be useful:

5. CT abdomen/pelvis
6. CT chest

The rationale for routine CT imaging is to identify causes of the cardiac arrest, early identification of catastrophic brain injuries and solid organ bleeding from prolonged mechanical chest compressions. If patient has drainage insufficiency and an abdominal ultrasound scan is suggestive of free fluid, arterial phase CT scan of the abdomen and pelvis should be considered to rule out injury to the liver and spleen. This often occurs early and may present with falling ECMO blood flow or drainage insufficiency. Liver and splenic lacerations are commonly amenable to embolization with interventional radiology.

Early echocardiography to assess biventricular and valvular function is helpful in predicting complications of ECMO support. The presence of greater than mild aortic regurgitation dramatically increases the likelihood of catastrophic LV distension and pulmonary edema.

Weaning off Extracorporeal Membrane Oxygenation

Once the etiology of the cardiac arrest is addressed, native cardiac function may return and be sufficient for separating from V-A ECMO support after a period of recovery. There is a lack of consensus on the timing of weaning and decannulation for V-A ECMO, although a period of 3–4 days ECMO support is typically seen.[10,34] Premature decannulation results in hemodynamic deterioration and either urgent recannulation for support or cardiovascular collapse and possible death, whereas prolonging ECMO support unnecessarily may lead to significant morbidity and mortality.

V-A extracorporeal membrane oxygenation weaning usually consists of serial reductions in blood flow until a flow of 0.5–1.0 L/min is achieved, with serial echocardiographic

and hemodynamic assessment at each stage. Even with this minimal ECMO flow, right ventricular preload is reduced, and hence, right heart function is not tested under fully unsupported, loading conditions.

Trial off support, either by using an arteriovenous bridge within the circuit, or by clamping, allows temporary separation of ECMO from the patient. However, it requires intermittent circuit clamping and carries a significant risk of circuit thrombosis.

Once a successful weaning study has been completed, flow should be increased to 2 L/min until time of decannulation to minimize the risk of circuit thrombosis.

Some patients will survive ECPR neurologically intact, but fail to recover sufficient myocardial function for successful weaning and decannulation; for these, long-term mechanical cardiac support such as ventricular assist device (VAD) or cardiac transplantation may be the only option for survival.[34,39] We recommend early discussion with a referral center that offers durable VAD and cardiac transplantation for these patients.

For those patients that are not weanable and who are not considered candidates for durable VAD or cardiac transplantation, terminal decannulation with palliation may have to be considered.

Brain death is a common mode of death following ECPR and organ donation may be considered in this circumstance. Declaration of brain death has to follow national guidelines and may need an adjusted protocol with on-going ECMO support. Organ donation is also possible following circulatory death after withdrawal of ECMO support.

Consent

Consent for ECPR therapy from those receiving CCPR is not possible. Furthermore, it is unlikely that an appropriate consent process can take place with next of kin during this time. Whereas ELSO Guidelines for ECMO initiation recommend consent before initiation of ECMO, with a clear treatment plan including the rationale for withdrawing care due to lack of recovery or ineligibility for long-term mechanical support, this is usually not possible among those considered for ECPR. Patients are initiated on ECPR based on the presumption that they would want all efforts pursued.

We recommend that institutions offering ECPR develop a guideline for ECPR treatment which includes eligibility, goals of treatment, and a timeline with conditions for stopping ECMO in those without neurologic recovery, or in those ineligible for long-term mechanical cardiac support because of insufficient cardiac recovery. After ECPR initiation, an immediate meeting should take place with the next of kin to explain the basics of ECPR, the institutional guidelines of care for ECPR, and obtain consent for continued treatment.

PROGRAM DEVELOPMENT AND LOGISTICS

Program Development

The provision of ECPR should not be first entertained during CPR, but rather requires careful organizational consideration. An institution wanting to provide ECPR should engage in a multidisciplinary discernment process of clinicians and administrators to include: a needs assessment, program feasibility and sustainability, expectations, and resource availability.[20] Program development should consider human resources, infrastructure already in place and the resources required to maintain competency. Eligibility criteria need to be developed which are clear and reproducible.

Training and Maintenance of Competency

Given the complexities of instituting ECPR and its infrequent usage even in large centers, we advocate for regular system and team-based simulation with simulators that can be used to practice cannulations with on-going resuscitation measures. This training should be the cornerstone for any ECPR program development to aid in the delivery of consistent and safe care.

Quality Improvement

A quality improvement strategy needs to be developed to monitor process metrics and outcomes. With the added complexities of ECPR initiation, there is a risk to the quality of CCPR. Quality of care metrics for both CCPR and ECPR processes should be identified and monitored. Case reviews should be performed for every ECPR case, identifying areas for improvement and reporting institutional goal performance metrics. Goal metrics and outcomes should be monitored and reported.

Governance

We recommend each institution has a robust process for clinical governance of their ECPR program with multidisciplinary input and review. Demographic, outcome, and complication data should be collected and reported to the institution providing oversight of the service and consideration given to contributing to an international dataset, such as ELSO, to allow for benchmarking and research opportunities.

Additional Complexities for Out of Hospital Cardiac arrest

Providing ECPR for those with OHCA poses additional logistical obstacles. Integrated prehospital protocols are required to identify appropriate patients early, provide prearrival notification to hospital teams, and facilitate timely transport to hospital with continued high-quality resuscitative efforts. Prehospital teams should identify methods to mitigate the risk to CCPR quality during extrication and transport, and should participate in ECPR simulation exercises.

Regardless of specific details of the protocol, only a very small proportion of patients with OHCA will ultimately be considered eligible for ECPR.[40] Thus, prehospital resuscitation for the remaining patients with OHCA should ideally not be altered, which poses the risk of worsening CCPR quality in the majority of arrests, which could decrease overall survival. Thus, clear collaboration of hospital and prehospital systems is required to identify ECPR-candidates in the prehospital setting to achieve early transport to hospital.

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Extracorporeal Membrane Oxygenation for COVID-19: Updated 2021 Guidelines from the Extracorporeal Life Support Organization

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Disclaimer: This is an updated guideline from the Extracorporeal Life Support Organization (ELSO) for the role of extracorporeal membrane oxygenation (ECMO) for patients with severe cardiopulmonary failure due to coronavirus disease 2019 (COVID-19). The great majority of COVID-19 patients (>90%) requiring ECMO have been supported using venovenous (V-V) ECMO for acute respiratory distress syndrome (ARDS). While COVID-19 ECMO run duration may be longer than in non-COVID-19 ECMO patients, published mortality appears to be similar between the two groups. However, data collection is ongoing, and there is a signal that overall mortality may be increasing. Conventional selection criteria for COVID-19–related ECMO should be used; however, when resources become more constrained during a pandemic, more stringent contraindications should be implemented. Formation of regional ECMO referral networks may facilitate communication, resource sharing, expedited patient referral, and mobile ECMO retrieval. There are no data to suggest deviation from conventional ECMO device or patient management when applying ECMO for COVID-19 patients. Rarely, children may require ECMO support for COVID-19–related ARDS, myocarditis, or multisystem inflammatory syndrome in children (MIS-C); conventional selection criteria and management practices should be the standard. We strongly encourage participation in data submission to investigate the optimal use of ECMO for COVID-19.

Key Words: acute respiratory distress syndrome, coronavirus disease 2019, extracorporeal life support organization, extracorporeal life support program, extracorporeal membrane oxygenation, multisystem inflammatory syndrome in children, pandemic

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The role of extracorporeal membrane oxygenation (ECMO) support for patients with cardiopulmonary failure due to coronavirus disease 2019 (COVID-19) is evolving. A prominent feature of COVID-19 in critically ill patients is acute respiratory distress syndrome (ARDS). Early in the pandemic, data on ECMO use was limited, and guidance was offered based on best practices at the time.[1–4] Very limited case series available at the onset of the pandemic seemed to indicate poor survival for patients with ARDS placed on ECMO.[5] However, the role of ECMO for COVID-19–related ARDS and other indications has become more apparent as the pandemic unfolds and evidence is generated.

A multicenter French study of 83 patients with COVID-19–related ARDS managed with ECMO revealed an estimated 60 day mortality of 31%.[6] Subsequently, data from the Extracorporeal Life Support Organization (ELSO) Registry reported an estimated cumulative incidence of in-hospital mortality 90 days after ECMO initiation of 37.4%. This report included 1,035 patients with COVID-19 who received ECMO in 36 countries.[7] An additional observational study reported 45% mortality for 1,531 patients from 177 centers in Europe and Israel.[8]

According to prepandemic historical data from the ELSO registry, venovenous (V-V) ECMO results in an approximate mortality of 40%, venoarterial (V-A) 55%, and extracorporeal cardiopulmonary resuscitation (ECPR) 71%. Mean V-V run duration is generally longer (12 days) than V-A (7 days).[9] For patients with COVID-19, mortality is similar to historical V-V ECMO mortality; however, mortality is still being determined with ongoing data collection and may be increasing.[10] Median (14 days[7] and 20 days[6]) and mean (18 days[8]) run duration appears to be longer.

In the great majority (>90%) of reported cases, V-V ECMO was utilized for COVID-19.[6–8] Some patients with COVID-19 develop myocarditis, massive pulmonary embolism, stress cardiomyopathy, arrhythmias, and acute coronary syndrome,[11–13] which may require mechanical circulatory support such as V-A ECMO. Data on V-A ECMO for COVID-19 are limited in the ELSO Registry study and may be found in small case series, making the utility of V-A ECMO for COVID-19–related cardiogenic shock less clear.[6–8,14] As a general guide to practice, we recommend the use of ECMO for patients with COVID-19 and severe cardiopulmonary failure who meet traditional criteria and when appropriate resources are available.[15]

Given the paucity of available data when prior ECMO guidelines were published,[1,4] this guideline has been created to summarize currently available literature and offer recommendations to update select areas within the previous guidelines.[4] This document will focus on care specific to COVID-19 patients receiving ECMO and recommended alterations in the utilization of ECMO during a pandemic. We recommend referral to existing guidelines for general ECMO practices.[2]

Key Recommendations

V-V ECMO may be utilized for patients with COVID-19 and severe respiratory failure with expected outcomes comparable to patients supported with V-V ECMO prepandemic.

V-A ECMO may be utilized for patients with COVID-19 and severe cardiac failure; however, the experience is more limited.

Mobile ECMO is feasible and may be conducted safely for patients with COVID-19.

Organize ECMO centers within geographic regions to coordinate patient referrals, where feasible.

Unify patient selection criteria across a geographic region, where feasible.

Contraindications for ECMO use should become more stringent as ECMO capacity diminishes.

Data submission to facilitate research is essential for our evolving understanding of optimal ECMO care for patients with COVID-19.

While some centers have increased their anticoagulation targets, bleeding remains a concern, and there is no data to recommend deviation from conventional anticoagulation goals.

There is no data to recommend deviation from conventional ECMO practices, *e.g.*, blood product transfusion thresholds, tracheostomy, endotracheal extubation, rehabilitation, cannulation configuration, or ventilator management.

Potential discontinuation of ECMO in the setting of perceived futility should be clearly discussed with patients and their surrogate decision-makers.

Rarely, children can require ECMO support for severe ARDS, myocarditis, or multisystem inflammatory disease in children; ECMO patient selection and management should follow conventional guidelines.

ECMO Program Organization[3]

International

- Centers providing ECMO that are not ELSO member centers are encouraged to join ELSO and contribute to COVID-19–related ECMO cases in the international registry.
- We also recommend participation in other key international efforts related to COVID-19 data collection, such as the EuroELSO survey[8] and COVID-19 Critical Care Consortium,[16,17] to enable a real-time understanding of COVID-19 ECMO practices and to help facilitate crucial research and quality assurance in this area.[15]

National/Regional

- Creating or utilizing existing national and regional ECMO networks is encouraged to coordinate referrals within given geographic areas in which patient transport is possible.[18–21]
- If a patient is referred to an ECMO center that lacks capacity, efforts should be made to redirect the referral to another ECMO center in the region with available capacity, with consideration of availability of mobile ECMO if indicated.
- Before ECMO capacity becomes saturated within a given region, we recommend these ECMO networks adapt unified patient exclusion criteria (see below: Patient Selection) at a regional level to promote equitable access to ECMO and to avoid the need for transferring centers to make referrals to multiple ECMO centers.
- Mobile ECMO has been safely used to retrieve patients with COVID-19 from referring centers.[22–27]
- Adult and pediatric ECMO centers within a region[28] should consider pooling resources, whenever feasible, such as pumps, disposables, or staff, to optimize ECMO capacity from existing resources.

- When ECMO equipment resources are constrained, ECMO centers may use ELSO's Supply Exchange (supplies.elso.org) to improve access to ECMO services when there is a supply disruption, either due to increased demand or an unforeseen limitation in supplies.
- ECMO centers and referring centers may use ELSO's ECMO Availability Map (elso.org) for the purposes of regional coordination of ECMO capacity. This tool is publicly available and updated by ELSO member centers.
- Educational webinars and conferences hosted by ELSO and other scientific societies, as well as regional ECMO networks, should be utilized to rapidly disseminate new data to ECMO practitioners as they emerge.

Institutional

- In select cases, where regional resources exist to support the creation of new ECMO centers, and it is felt essential to meet increased demand due to the pandemic, this should be undertaken utilizing guidance from ELSO and in close collaboration with other experienced centers to optimize patient outcomes.[29,30] Telemedicine could be utilized to facilitate this.[31]
- Tracking of available staffing, equipment, and beds should be performed to determine ECMO capacity on a regular basis. Capacity determination should take into consideration other related services that utilize the same resources as ECMO (cardiothoracic surgery, cardiac critical care, medical critical care, transplant, *etc.*).[32,33]
- Bedside staffing ratios may be altered under contingency and crisis capacity[34] to allow a bedside specialist to care for more patients than usual. This may be facilitated using methods for remote monitoring and co-locating patients who are receiving ECMO (including both COVID-19 and non-COVID-19 ECMO patients, as appropriate for the individual hospital).
- If surgical procedures involving cardiopulmonary bypass are suspended, perfusionists may be deployed to the bedside to relieve ECMO specialists for other duties, where applicable.

Patient Selection

ECMO is a finite resource and requires the utilization of other finite resources, such as intensive care unit (ICU) beds and staffing. Patient selection must be judicious and equitable and should become more stringent as capacity diminishes.[32,35,36]

Indications

- Indications for ECMO initiation should remain unchanged during a pandemic, and we refer to ELSO guidelines and established literature outlining these indications.[1,2,4,15,37–40]
- Conventional therapies for ARDS should be applied according to the standard algorithm, leading to the use of ECMO after other measures have been attempted, especially prone positioning, unless contraindicated (Figure 1).[41] It should be emphasized that low-pressure and low-volume ventilation should be adhered to, with consideration of ECMO if unable to safely mechanically ventilate the patient, even if oxygenation is relatively intact.
- While it may be tempting to stretch the use of conventional therapy to avoid placing patients on ECMO due to resource constraints, there is no evidence to support delaying ECMO initiation when it is indicated. We recommend ECMO patient selection as in Figure 1. Outcomes with delayed ECMO initiation may be worse and run duration may be longer, offsetting any potential benefit from attempted conservation of resources.[42–44]
- Patients who are deteriorating in non-ECMO centers should be referred early for ECMO consideration to allow for safe transport or time to organize mobile ECMO rescue in appropriate patients.[22]
- Survival with V-V ECMO for COVID-19–related pneumonia and ARDS[6–8] is similar to historical survival data for other causes of acute severe respiratory failure meeting V-V indications in the ELSO Registry.[9] This suggests that COVID-19 could be considered similarly to other causes of reversible infectious pulmonary disease, with awareness that COVID-19 patients may require longer run times.[6–8,45–47] However, mortality in this population may be increasing over time and updated data should be considered in decision-making (elso.org).
- It is currently unknown if COVID-19 patients requiring V-A ECMO have similar survival compared with historical data.

Contraindications

- We recommend that ECMO centers establish descriptions for levels of diminishing ECMO capacity,[34] and capacity should be tightly linked to exclusion criteria, that is, when capacity diminishes, exclusion criteria become more stringent based on characteristics associated with increased mortality (Figure 2),[7,15,32,44,48,49] and longer run duration.[50,51] Of note, there is survival and run-time variability depending on the indication for ECMO and individual patient characteristics, and thus each ECMO referral should be considered on a case-by-case basis.
- Mortality increases with prolonged exposure to mechanical ventilation before ECMO[44]; the additional impact of prolonged exposure to high-flow nasal cannula or noninvasive positive-pressure ventilation before mechanical ventilation is currently unknown.
- COVID-19 patients receiving ECMO may consume more resources to meet personal protective equipment (PPE) requirements, and this may be a factor in patient selection by necessity when PPE is limited.
- Risks and benefits of providing ECPR for patients who have COVID-19 or whose status is unknown, for example, out-of-hospital cardiac arrest, should be carefully considered given the increased potential for PPE breach and lower historical survival with ECPR compared with most other uses of ECMO.[49] However, ECPR outcomes also vary considerably according to patient population based on factors that include witnessed or unwitnessed arrest, in-hospital *versus* out-of-hospital arrest, duration, and etiology of arrest. Thus, context matters in the decision of whether or not to proceed with ECPR, and centers should a priori determine whether or not they will provide ECPR for patients with COVID-19 and patients with unknown COVID-19 status.

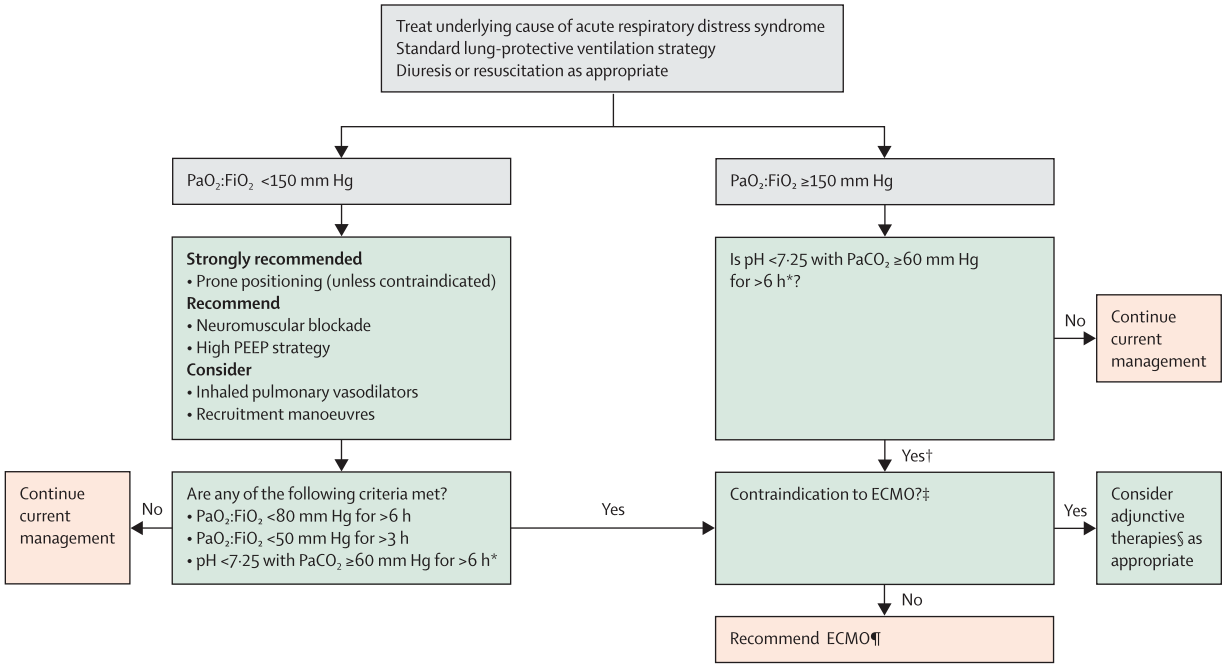

Figure 1. Algorithm for management of acute respiratory distress syndrome, including indications for ECMO. *With respiratory rate increased to 35 breaths per minute and mechanical ventilation settings adjusted to keep a plateau airway pressure of <32 cm H_2O. †Consider neuromuscular blockade. ‡There are no absolute contraindications that are agreed upon except end-stage respiratory failure when lung transplantation will not be considered; exclusion used in the EOLIA trial can be taken as a conservative approach to ECMO contraindications. ∫For example, neuromuscular blockade, high PEEP strategy, inhaled pulmonary vasodilators, recruitment maneuvers, and high-frequency oscillatory ventilation. ¶Recommend early ECMO as per EOLIA trial criteria; salvage ECMO, which involves deferral of ECMO initiation until further decompensation (as in the crossovers to ECMO in the EOLIA control group), is not supported by the evidence but might be preferable to not initiating ECMO at all in such patients. Credit: Abrams *et al*.[39]. ECMO, extracorporeal membrane oxygenation; EOLIA, Extracorporeal Membrane Oxygenation to Rescue Lung Injury in Severe Acute Respiratory Distress Syndrome; $PaCO_2$, partial pressure of carbon dioxide in arterial blood; PaO_2:FiO_2, ratio of partial pressure of oxygen in arterial blood to the fractional concentration of oxygen in inspired air; PEEP, positive end-expiratory pressure.

- Systems should be prepared to rapidly identify changes in capacity and communicate resultant changes in exclusion criteria to their ECMO teams and regional networks to continually optimize the benefit-to-resource utilization ratio.

Cannulation Strategies

- Conventional two-site (V-A and V-V) and multisite, e.g., veno-arteriovenous (V-AV), cannulation strategies, as well as V-V dual-lumen cannulas, as needed to address the underlying problems, are appropriate for use in patients with COVID-19.
- There may be a role for the use of dual-lumen single cannula right ventricular assist device (right atrium to pulmonary artery) in patients with COVID-19 pneumonia; however, the evidence is limited.[46,47]

Ongoing Care During ECMO

Routine management of the patient receiving ECMO is outside the scope of this guideline, and we refer to previously published guidelines[2] and reviews[37,52,53] Recommendations on disease modifying agents are also outside of the scope of this guideline, and we refer to published national and international guidelines.[54–56] A concise list of COVID-19 ECMO-specific recommendations is provided in Figure 3.

Pulmonary

- There are no data to suggest deviation from commonly performed ventilator management (very low-pressure, low-volume ventilation) for patients receiving V-V ECMO with COVID-19.[2,57]
- Percutaneous tracheostomy appears to be safe and feasible for patients with COVID-19.[58–60]
- Prone positioning during ECMO is feasible[61] and 81% of COVID-19 patients in one study were placed in the prone position.[6] Preliminary data demonstrate a potential association of prone positioning on ECMO with lower mortality.[15,62,63] However, a recommendation cannot be offered at this time.
- An early extubation strategy with awake ECMO may be feasible for patients with COVID-19.[46,47] However, there is currently no data to support this strategy over one in which the patient remains endotracheally intubated during ECMO.

Hematologic and Hemodynamic Monitoring

- COVID-19–induced coagulopathy appears to include both thrombotic and bleeding events.[64–66] Specific ramifications for ECMO include circuit clotting,[67,68] higher than previously reported rates of pulmonary embolism,[6] and intracranial hemorrhage.[69–72] However, when normalized

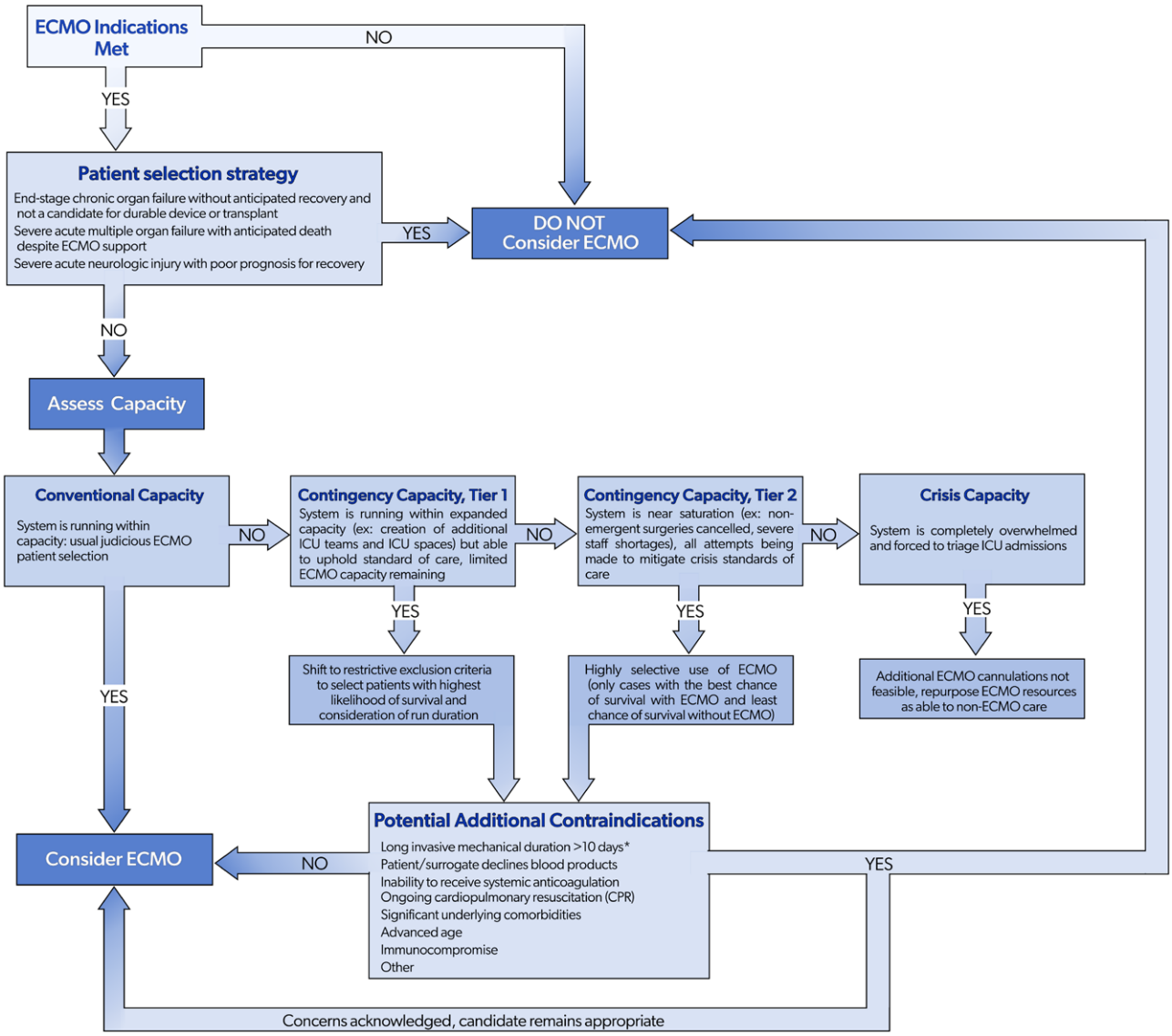

Figure 2. Contraindications algorithm for V-A and V-V ECMO use (COVID-19 and non-COVID-19) during a pandemic based on system capacity. *The impact of duration on high-flow nasal cannula and/or noninvasive mechanical ventilation in addition to invasive mechanical ventilation is unknown. COVID-19, coronavirus disease 2019; CPR, cardiopulmonary resuscitation; ECMO, extracorporeal membrane oxygenation; ICU, intensive care unit; $PaCO_2$, partial pressure of carbon dioxide in arterial blood; PaO_2:FiO_2, ratio of partial pressure of oxygen in arterial blood to the fractional concentration of oxygen in inspired air; PEEP, positive end-expiratory pressure; V-A, venoarterial; V-V, venovenous.

to ECMO run duration, rates of bleeding, and circuit clotting in patients with COVID-19 are similar to historical data, in one observational study.[7] Balancing hematologic derangements with ECMO anticoagulation is complex. Many centers have increased their anticoagulation targets but bleeding remains a concern, and there are insufficient data to suggest deviation from usual anticoagulation practices[2] for patients with COVID-19 receiving ECMO.

- There are insufficient data to recommend routine surveillance for deep venous thrombosis for patients with COVID-19[73]; however, we recommend a low threshold to pursue imaging for suspected deep venous thrombosis, including after decannulation, given that there may be a propensity for clotting in COVID-19 patients during ECMO.[74,75]
- While elevated cytokine profiles have been observed in patients with COVID-19, these seem to be lower than in non-COVID-19–related ARDS and sepsis and much lower than chimeric antigen receptor (CAR) T-cell-mediated cytokine release syndrome,[76] although evidence is needed to provide further insights. Therefore, extracorporeal hemadsorption or elimination therapies can only be recommended within the context of clinical trials.[77]
- There is no evidence to deviate from usual institutional practices for blood transfusion thresholds during ECMO.[78]
- We recommend remaining vigilant for acute hemodynamic deterioration during V-V ECMO. This may occur due to cardiac complications of COVID-19, for example, myocarditis, stress cardiomyopathy, acute right

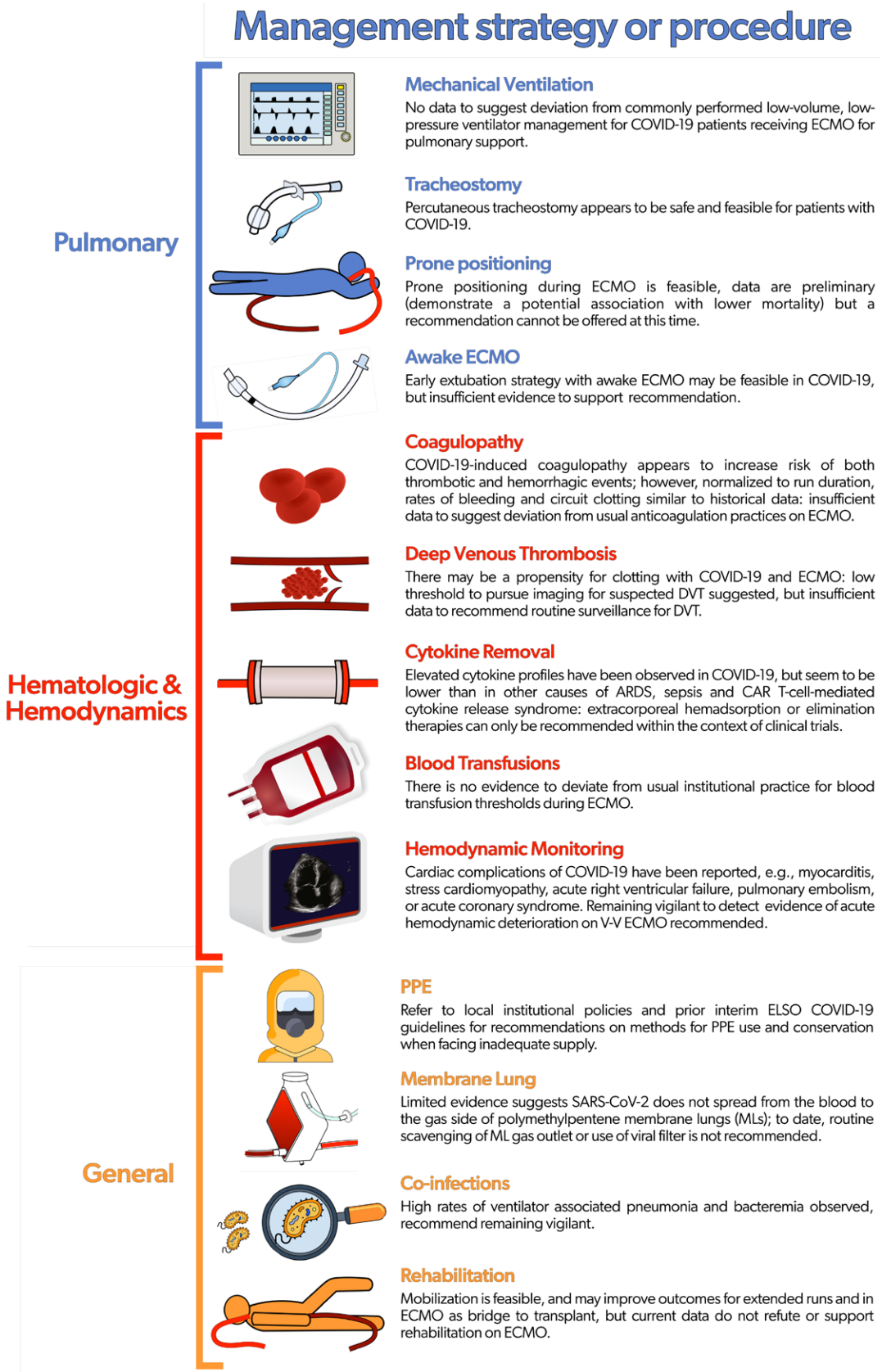

Figure 3. Recommendations for ongoing care for patients with COVID-19 receiving ECMO. ARDS, acute respiratory distress syndrome; CAR, chimeric antigen receptor; COVID-19, coronavirus disease 2019; DVT, deep venous thrombosis; ECMO, extracorporeal membrane oxygenation; ELSO, Extracorporeal Life Support Organization; ML, membrane lung; PPE, personal protective equipment; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2; V-V, venovenous.

ventricular failure,[79,80] pulmonary embolism, or acute coronary syndrome.

General

- We refer the reader to local institutional policies and prior interim ELSO COVID-19 guidelines for recommendations on PPE use and conservation methods when facing inadequate supply.[3,4]
- There is no evidence to suggest that virions can travel out of the exhaust of a polymethylpentene membrane lung, and thus routine scavenging is not recommended, although the current evidence is limited.[81]
- Remain vigilant for bacterial coinfection and superinfection given high observed rates of ventilator-associated pneumonia and bacteremia in some studies.[6,82–85]
- Mobilization of patients is feasible while undergoing ECMO[46,86–88] and may be necessary to achieve favorable outcomes for patients with extended ECMO runs and those bridging to transplant. However, there are currently insufficient data to refute or support mobilization specifically for patients receiving ECMO for acute COVID-19.
- Intra-hospital transport can be safely performed, and thus traveling within the hospital should be pursued when indicated, for example, radiology, unit relocation, *etc*.[89]

Weaning and Discontinuation of ECMO

- Centers should determine a priori whether they plan to offer lung or heart transplant or durable ventricular assist devices to patients with COVID-19 who are unable to wean from ECMO, as this will have implications for decision making surrounding continuation or discontinuation of ECMO in patients who are not recovering. Regional referral can be considered if transplant or durable device placement is not locally available.
- If patients are bridging to recovery, the consent process should include a discussion outlining criteria with family for when ECMO support will be stopped once it is determined to be unlikely to provide further benefit to the patient. In this case, the patient will be returned to conventional therapy or consideration given for withdrawal of life-sustaining therapies (futility and principle of proportionate therapy).[35]
- It is challenging to determine futility in the patient receiving V-V ECMO with single-organ failure awaiting pulmonary recovery. It is important to note that prolonged hospitalization in this cohort may not portend a higher mortality rate: patients hospitalized at 40 days had an estimated 90 day mortality of 14% in the ELSO Registry study.[7]
- Duration on ECMO (>90% V-V) for COVID-19 from three large observational studies was median 13.9 days (interquartile range [IQR], 7.8–23.3 days),[7] median 20 days (IQR, 10–40 days),[6] and mean 18 days.[8] It is important to note that successful native lung recovery has been reported after prolonged (>28 days) V-V ECMO support.[90]
- The role of chest imaging in determining futility while on V-V ECMO is unknown.
- Lung transplantation has been successfully pursued for some COVID-19 patients who were receiving ECMO, with single-organ failure, but without recovery of adequate lung function. The timing for when this should be considered, and for when further attempts at awaiting native pulmonary recovery should be abandoned, remain unclear.[91–93]

ECMO in Children with COVID-19

Acute infection with severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in children is most commonly either asymptomatic or associated with only mild respiratory disease. Occasionally, however, this can lead to life-threatening hypoxemic respiratory failure with ARDS due to severe COVID-19 or, rarely, acute heart failure and cardiogenic shock secondary to myocarditis. Furthermore, a minority can develop multisystem inflammatory syndrome in children (MIS-C) within 4 weeks of exposure to the virus, presenting with clinical and laboratory evidence of systemic inflammation, which can rapidly progress to shock.[94] Most children who require intensive care with acute COVID-19 or MIS-C receive targeted therapy, recover and are discharged home.[95,96] Rarely, children with severe disease ultimately require ECMO.[97–99] While the basic principles of ECMO for COVID-19 in children do not significantly differ from ECMO use for other diseases, there are some special nuances that a pandemic presents that should be considered in the decision-making process.

Candidacy

- We recommend applying similar principles currently published in ELSO guidelines[2] for patient selection of pediatric COVID-19–associated respiratory failure and MIS-C.

Cannulation

- Standard cannulation strategies appropriate for any pediatric ECMO patient should be used. There is no evidence to support alteration of cannulation strategy for patients with COVID-19.
- Appropriately sized dual-lumen or two-site cannulation approach is commonly employed for V-V support of pediatric respiratory failure patients without circulatory collapse.
- V-A support is indicated for cardiac compromise associated with COVID-19–related myocarditis and MIS-C and for patients with severe respiratory disease where adequately sized V-V cannulation cannot be accomplished.

Management Principles

- We recommend the use of standard pediatric institutional ECMO protocols for the management of pediatric patients with COVID-19. There is no evidence to recommend changes in anticoagulation, sedation, or other protocols for patients with COVID-19.
- Management of the underlying COVID-19 and MIS-C diseases should follow institutional and national guidelines.[100]

Conclusions

Patients with COVID-19 initially exhibited similar mortality when supported with V-V ECMO as compared to historical data in patients with other causes of acute severe respiratory

failure. However, mortality may be increasing and is still being determined with ongoing data collection. Data are still limited regarding V-A ECMO support in COVID-19. That said, ECMO may be utilized for adult patients with COVID-19 and severe cardiopulmonary failure when resources permit. Children may require ECMO support for severe ARDS, myocarditis or MIS-C, and ECMO patient selection and management should follow conventional guidelines. ECMO centers should consider forming networks within geographic regions to pool resources and coordinate patient referrals for ECMO. Submission of patient data is essential for ongoing research to enhance the care of patients receiving ECMO for COVID-19–related cardiopulmonary failure. When conventional capacity exists, indications and contraindications for ECMO should remain unchanged; however, as hospital system capacity diminishes, contraindications for ECMO use should become more stringent based on characteristics associated with increased mortality and longer run duration. There are no data to recommend deviation from conventional ECMO management for COVID-19 patients during their ECMO run, for example, anticoagulation, blood product transfusion thresholds, tracheostomy, endotracheal extubation, mobility, cannulation configuration, or ventilator management. The criteria surrounding ECMO discontinuation for perceived futility should be clearly discussed with patients and families.

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Management of Adult Patients Supported with Venovenous Extracorporeal Membrane Oxygenation (VV ECMO): Guideline from the Extracorporeal Life Support Organization (ELSO)

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Disclaimer: **The use of venovenous extracorporeal membrane oxygenation (VV ECMO) in adults has rapidly increased worldwide. This ELSO guideline is intended to be a practical guide to patient selection, initiation, cannulation, management, and weaning of VV ECMO for adult respiratory failure. This is a consensus document which has been updated from the previous version to provide guidance to the clinician.**

Key Words: venovenous ECMO, extracorporeal life support, ventilatory management, mechanical ventilation, circuit management, fluid management, cannulation/decannulation

INTRODUCTION

The use of venovenous extracorporeal membrane oxygenation (VV ECMO) among adults is rapidly increasing worldwide. By 2020, the Extracorporeal Life Support Organization (ELSO) Registry had recorded >24,000 cases of adult respiratory ECMO use among 282 centers internationally. Venovenous extracorporeal membrane oxygenation is a therapy in the management of respiratory failure in multiple guidelines. Extracorporeal Life Support Organization provides guidelines to inform and guide the initiation, use, management, and weaning of VV ECMO for adult patients with respiratory failure.

In this statement, we provide recommendations for the clinical management of adult patients supported with VV ECMO. Although these recommendations were not developed using a formal, reproducible methodology, we have reviewed English-language publications in PubMed, where available, in developing the guidance provided herein. As this is the fifth revision of these adult respiratory VV ECMO guidelines, we expect that it will be revised at regular intervals as new information, devices, treatments, and techniques become available. As with all guidelines, this statement should not replace the medical judgment and the multidisciplinary decision to establish and manage a patient's ECMO support strategy. A number of important management principles and recommendations are made in other ELSO guidelines, including: circuit components, patient selection, patient and circuit management, patient sedation, and nutrition. This document contains numerous additional literature references, organized by topic, found in Supplemental Digital Content 1, http://links.lww.com/ASAIO/A626.

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J.E.T. had full access to all the sections in the guideline and takes responsibility for the integrity of the submission as a whole, from inception to published article. J.E.T., D.A., and E.F. conceived guideline design; all authors drafted the work; all authors revised the article for important intellectual content, had final approval of the work to be published, and agree to be accountable to for all aspects of the work.

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PATIENT SELECTION

When assessing adults with acute severe respiratory failure for ECMO, it is important to establish that the cause of respiratory failure is potentially reversible, refractory to conventional treatments, and without formal contraindications for the initiation of this support. In the case of irreversible disease (*e.g.*, end-stage pulmonary disease), the patients may be suitable candidates for ECMO, if it is as a bridge to lung transplant.

INDICATIONS AND CONTRAINDICATIONS

Venovenous extracorporeal membrane oxygenation should be considered in patients with severe, acute, reversible respiratory failure that are refractory to optimal medical management. The physiologic rationale for use of VV ECMO includes: 1) increasing systemic oxygenation and CO_2 removal (ventilation) and 2) avoiding the need for injurious mechanical ventilation. In response to the most recent data and ECMO trials, at minimum, we now recommend patients with severe acute respiratory distress syndrome (ARDS) and refractory hypoxemia (PaO_2/FiO_2 < 80 mm of mercury [mm Hg]), or severe hypercapnic respiratory failure (pH < 7.25 with a $PaCO_2$ ≥ 60 mm Hg), should be considered for ECMO after optimal conventional management (including, in the absence of contraindications, a trial of prone positioning); a more complete list of indications is found in **Table 1**. As it is also known that increasing duration of mechanical ventilation before extracorporeal life support (ECMO) is associated with worsening mortality after ECMO, optimal medical management should be rapidly and maximally implemented, not delaying ECMO when indicated.

Currently, the only absolute contraindication for the start of ECMO is anticipated nonrecovery without a plan for viable decannulation (**Table 1**). This situation could be due to the disease process itself or to multiorgan failure, within the context of no options for organ transplantation. Sometimes it is unknown whether the patient is a transplant candidate at the point when a decision to initiate ECMO needs to be made; in these situations, ECMO can be initiated under the indication of "bridge to decision." Importantly, we advise that this *only* occur in the context of an ongoing multidisciplinary discussion regarding "ECMO decannulation" options, and with a clear discussion regarding the duration of ECMO support being offered.

Transfer for Extracorporeal Membrane Oxygenation

At centers not capable of initiating ECMO, intentional planning for early transfer should occur in patients in whom the provider feels ECMO may be of benefit. In this assessment, the RESP and Murray Scores are useful. The RESP score provides predicted survival once on ECMO. The Murray Score provides estimated mortality without. If ECMO is to be a consideration, and transfer would be necessary, it should be done early.

MODE OF SUPPORT

Indications/Rationale

Oxygen Delivery. It is fundamental to understand that ECMO provides a variable quantity of oxygen delivery to the body. This quantity of oxygen is equal to the product of ECMO circuit flow (in liters per minute [LPM]) and outlet minus inlet oxygen content of the blood (CaO_2 = [hemoglobin (in g/L)] × 1.39 × [SaO_2] + (0.0034 × [PaO_2 (in mm Hg)]). After cannulation for ECMO, this quantity of oxygen is added to total body circulation as oxygen supplied from the circuit. The amount required for total support at rest is 120 ml/m^2/minute.

Systemic oxygen delivery is the arterial O2 content times flow. The normal systemic oxygen delivery is 600 ml/m^2/minute. Systemic oxygen delivery as low as 300 ml/m^2/minute is sufficient to maintain metabolism at rest. In VV ECMO, the circuit should be designed to provide at least 240 ml/m^2/

Table 1. Indications/Contraindications for Adult VV ECMO

Common indications for venovenous extracorporeal membrane oxygenation
One or more of the following:
1) Hypoxemic respiratory failure (PaO_2/FiO_2 < 80 mm Hg)*, after optimal medical management, including, in the absence of contraindications, a trial of prone positioning.
2) Hypercapnic respiratory failure (pH < 7.25), despite optimal conventional mechanical ventilation (respiratory rate 35 bpm and plateau pressure [P_{plat}] ≤ 30 cm H_2O).
3) Ventilatory support as a bridge to lung transplantation or primary graft dysfunction following lung transplant.

Specific clinical conditions:
- Acute respiratory distress syndrome (*e.g.*, viral/bacterial pneumonia and aspiration)
- Acute eosinophilic pneumonia
- Diffuse alveolar hemorrhage or pulmonary hemorrhage
- Severe asthma
- Thoracic trauma (*e.g.*, traumatic lung injury and severe pulmonary contusion)
- Severe inhalational injury
- Large bronchopleural fistula
- Peri-lung transplant (*e.g.*, primary lung graft dysfunction and bridge to transplant)

Relative contraindications for venovenous extracorporeal membrane oxygenation
- Central nervous system hemorrhage
- Significant central nervous system injury
- Irreversible and incapacitating central nervous system pathology
- Systemic bleeding
- Contraindications to anticoagulation
- Immunosuppression
- Older age (increasing risk of death with increasing age, but no threshold is established)
- Mechanical ventilation for more than 7 days with P_{plat} > 30 cm H_2O and F_iO_2 > 90%

*Clinical trials have utilized several cutoff points for the indication of the start of VV ECMO: PaO_2/FiO_2 < 80 mm Hg [EOLIA Trial[1]], Murray Score >3 [CESAR Trial[2]], without strong data indicating the superiority of any one.

minute of oxygen supply and 300 ml/m²/minute of systemic oxygen delivery. Based on these equations, blood flow rates and hemoglobin should be managed to achieve these oxygen delivery goals. As an example, an 80 kg adult with a hemoglobin level of 12 g/dl would require an ECMO flow of about 4 L/minute to reach those goals. The ECMO flow is adjusted down when the native lung is recovering, and increased when the metabolic rate increases in the absence of native lung function.

In VV ECMO, only a portion of the venous return is directed to the circuit, oxygenated to a saturation of 100% and returned to the right atrium. The remainder of the venous return, with a typical saturation of 60–80%, continues through the RV without further oxygenation. These flows mix in the right atrium and ventricle and proceed through the lungs into the systemic circulation. The resultant saturation of the patient's arterial blood is the result of mixing these flows and oxygen contents.[3] Given this setting, the arterial saturation will always be less than 100%, and is typically 80–90%. This physiologic principle becomes relevant during VV ECMO because the ECMO flow must be adjusted relative to the total venous return (the cardiac output) to achieve the desired arterial content and, therefore, the systemic oxygen delivery. In clinical practice, an ECMO flow that is less than 60% of total CO is frequently associated with a SaO_2 <90% in the context of ARDS.[4] A comprehensive discussion of oxygenation is presented in Chapter 4 ("The Physiology of Extracorporeal Life Support") in the fifth Edition of the *ELSO Red Book*.

Recirculation. Recirculation refers to post oxygenator blood returning to the prepump drainage cannula. Recirculation decreases the amount of oxygenated blood being delivered to the patient and is more common with single lumen dual cannulation in the femoral and IJ positions. It is identified by increased venous saturation or brightening of the color of the drainage cannula blood, indicating oxygenation. Recirculation should be treated if this is noticed and should be ruled out in cases of insufficient systemic oxygen delivery. Recirculation should also be suspected with a paradoxical decrease in systemic saturation with increasing VV ECMO flow. In this case, although the total flow may have increased, the recirculation fraction has also increased, leading to a net decrease the amount of oxygenated blood returning to the body from the ECMO circuit.

Hypoxemia. Hypoxemia on ECMO can have many causes. Increased metabolic demand will increase oxygen utilization and decrease systemic saturation. Common causes of elevated oxygen utilization (VO_2), including sepsis, fever, agitation, movement, and shivering should be considered. Hypoxemia can also be caused by recirculation (see *Recirculation*). After all other causes of hypoxemia and their therapies have been tried, mild hypothermia can be employed to decrease oxygen utilization; finally, beta-blockade has been used to decrease the amount of blood flow bypassing the ECMO circuit through the native circulation, but also decreases oxygen delivery with the overall effect being difficult to predict for an individual patient (see *Fluid Management*).[5]

Incorporating recirculation, the body's saturation (which results from the ratio of ECMO flow to total body cardiac output) is calculated as ([total ECMO flow] – [recirculation flow])/CO. The ratio of ECMO flow to patient cardiac output will impact the overall systemic saturation. Other relevant factors in the estimation of adequate oxygenation are the ratio of oxygen delivery to oxygen utilization (DO_2/VO_2). As the oxygen delivered by VV ECMO is directly proportional to circuit flow returning to the body, in cases of inadequate tissue oxygen delivery, VV ECMO flows can be increased in an attempt to achieve a normal DO_2/VO_2 ratio of 5:1, but certainly above the critical threshold of supply dependence which occurs near a ratio of 2:1.

CO_2 Removal. Gas exchange *via* the oxygenator accomplishes CO_2 removal from the blood and is controlled by the "sweep gas" inflow rate to the oxygenator, for a given oxygenator membrane size; CO_2 removal increases with increasing sweep gas flow. Sweep gas typically ranges from 1 to 9+ LPM, and for VV is typically 100% O_2. Sweep gas very effectively lowers P_aCO_2. Upon initiation of ECMO, it is reasonable to start sweep at 2 LPM, and blood flow at 2 LPM, and titrate frequently to ensure a controlled slow modulation of P_aCO_2 and pH. A rapid decrease in CO_2 is associated with neurologic injury.

Cannulation

General Principles. Venovenous extracorporeal membrane oxygenation flows are typically limited by cannula size to 5–6 LPM. In patients with concomitant high cardiac output, ECMO drainage will not be able to keep up with the native cardiac output. As flow limitation is often because of insufficient uptake of venous blood into the ECMO circuit, this may improve with the use of multistage (multihole) drainage cannula or with placement of additional venous drainage cannula.[6]

Basic Configuration. Cannulation for VV ECMO involves removal of blood from the venous system of the patient (termed a *drainage cannula*), passing that blood through a centrifugal pump then through a membrane oxygenator for gas exchange, followed by return of the blood to the venous system (termed a *return cannula*). This *in series* cannulation strategy (as opposed to the *in parallel* strategy of VA ECMO) underlies some fundamental characteristics of VV ECMO compared with VA ECMO that should be understood. For VV ECMO:

1) Gas flow to the oxygenator can be completely turned off without creating a venous to arterial shunt in the patient.
2) Increasing circuit flow will *not* improve patient blood pressure.
3) Increasing circuit flow will increase the ratio of [blood entering the circuit: total cardiac output], and therefore total oxygen content in the patient, assuming no recirculation.

Although uncommon, VV ECMO can additionally be accomplished through hybrid configurations, such as VVA, which are discussed elsewhere.

Cannula Size. To select the correct cannula size, first priority should be given to titrating to estimated patient cardiac output needs. For example, in a 180 cm tall male, a 25F drainage cannula will often be sufficient, although in cases of severe respiratory failure, a larger (~29F) cannula will provide better flow and therefore oxygenation. Within a given cannula, increasing pump speed results in increasing flow, although at higher pressure. Assuming adequate filling, larger cannulas have greater flow at lower pump speed. An appropriately sized cannula will allow sufficient ECMO flow at a below-maximum speed for the given pump. The venous drainage cannula (or bicaval dual lumen cannula) should be maximized according to the

Table 2. Three Major Cannulation Strategies Which Dictate Cannula Selection for Venovenous Extracorporeal Membrane Oxygenation

Type	Return Location	Drainage Location(s)	Advantages	Disadvantages
Single-lumen dual cannula	Right atrium *via* internal jugular vein	Inferior vena cava *via* femoral vein		Limited patient mobility
Bicaval dual-lumen single cannula	Tricuspid valve *via* the right internal jugular vein.	superior vena cava; cannula extends across the right atrium and drains from within the inferior vena cava	Potentially facilitates patient mobility	Insertion more difficult, cannula movement, cerebral venous congestion, air embolism upon removal, possibly higher ICH with larger diameter catheters,[7] may be more difficult to achieve higher flows
Bifemoral venous cannulation	Right atrium *via* femoral vein	Inferior vena cava *via* femoral vein		Limited patient mobility

ICH, intracranial hemorrhage.

potential physiologic needs of the patient due to the fact that future patient physiology will change throughout the ECMO run. Importantly, oversized cannulas can result in venous congestion, vessel injury and deep vein thrombosis, the latter occurring even with appropriately sized cannula. Cannula peak flow and flow curves are provided in the manufacturer's instructions for use. Standardized cannula sizes within an institution/program allow rapid deployment in urgent clinical scenarios.

Cannulation Approach. For VV ECMO, there are three major cannulation strategies which dictate cannula selection (**Table 2**).

Until the advent of the dual-lumen single cannula (DLSC) for venovenous ECMO support, traditional cannulation involved placement of two single-lumen cannulas, typically in the femoral (drainage) and IJ (return) positions. Although the DLSC has clear advantages discussed below, single-lumen double cannulation retains the advantage of being able to be placed with surface vascular ultrasound.

The benefit of a DLSC strategy for VV ECMO is the potential for easier patient mobilization, which is feasible in this population.[8–11] Mobility with femoral cannulation has been described, although is not yet widely adopted.[12] Although there is limited outcome data, in non-ECMO patients, mobility during critical illness has been inconsistently associated with a variety of patient relevant improved outcomes.[13–15] As cannulas placed with modified Seldinger technique, they can be placed by appropriately trained surgeon and nonsurgeon operators.

Imaging. Imaging for cannula placement typically involves either fluoroscopic or echocardiographic (TEE) guidance, or both, depending on the cannula. Each has advantages and disadvantages. For single-lumen cannula placement, surface ultrasound for vascular access is preferred and has been demonstrated to be safest compared with blind placement. Depth of cannula placement can be estimated before placement, and then confirmed with radiography or echocardiography. For dual-lumen cannula placement, the DLSC traverses the right atrium into the inferior vena cava (IVC). Accordingly, live fluoroscopic or echocardiographic imaging is *required* to avoid misplacement, which can be fatal.[16,17]

Fluoroscopic Guidance. Fluoroscopic guidance enables visualization of the wire traversing the right atrium and into the IVC. This is important, as blind advancement of a wire from the internal jugular (IJ) often travels into the tricuspid valve and right ventricle (RV). Unrecognized ventricular wire position and advancement of the dilators and cannula into the RV can easily result in perforation, which is often fatal. Disadvantages of fluoroscopic guidance include the need for transport to a fluoroscopy laboratory, which may not be feasible in some patients, or the need for portable fluoroscopy and a trained operator.

Echocardiographic guidance. TTE and TEE have most commonly been described for use in combination with fluoroscopic guidance for cannula positioning,[18,19] although has also been described alone.[17,20] Although the outflow port of the DLSC can often be visualized at the level of the right atrium using fluoroscopy alone, echocardiographic guidance allows for visualization of the outflow jet directed toward the tricuspid valve, and has been described.[16] Echocardiographic guidance alone has the benefit that, with skilled operators, patients do not need to be transported.

PATIENT MANAGEMENT DURING VV ECMO

Hemodynamics

The consequences of hypoxemia and hypercarbia, before VV ECMO support, are significant. They can each lead to increases in pulmonary vascular resistance, elevated pulmonary arterial pressures, right heart strain or failure. The consequences of this situation are two-fold:

1) The VV ECMO circuit provides no direct hemodynamic support; the clinician must be prepared to medically manage significant hemodynamic changes that can arise during the initiation and maintenance phase of a patient on VV ECMO.
2) Although not providing direct support, the extracorporeal circuit will provide indirect hemodynamic support through optimization of pH, P_aCO_2 and P_aO_2. This often improves pulmonary arterial pressures and therefore RV dysfunction as well as coronary oxygenation and left ventricular function.[21]

With initiation of VV ECMO, an accompanying decrease in ventilatory settings will decrease intrathoracic pressure, which may increase cardiac filling and output.

Central venous access and invasive arterial blood pressure monitoring are recommended. Echocardiography continues to be an excellent tool to assess hemodynamic function and guide management during VV ECMO. Pulmonary artery catheterization may be considered in patients with complex hemodynamic compromise or right ventricular failure, although thermodilution cardiac output measurements are not reliable during ECMO. Inotropic and vasopressor support are often required to achieve standard circulatory goals (*e.g.*, mean arterial pressure ≥ 65 mm Hg, cardiac index > 2.2 L/minute/m^2, normal lactate).

Table 3. Recommended Mechanical Ventilation Settings During Adult VV ECMO

Parameter	Acceptable Range	Recommendation	Comments
Inspiratory plateau pressure (P_{plat})	≤30 cm H_2O	<25 cm H_2O	Further reductions in P_{plat} below 20 cm H_2O may be associated with less VILI and improved patient outcomes[24–26]
PEEP	10–24 cm H_2O	≥10 cm H_2O	Reductions in P_{plat} and tidal volume may lead to atelectasis without sufficient PEEP; PEEP can be set according to various evidence-based methods (*e.g.*, ARDSNet PEEP-F_IO_2 table or Express trial strategy) while maintaining the P_{plat} limit[27]
RR	4–30 breaths/min	4–15 breaths/min (set RR) or spontaneous breathing	CO_2 elimination is being provided primarily by VV ECMO, reducing the need for high minute ventilation (which may be associated with more VILI)
FiO_2	30–50%	As low as possible to maintain saturations	Oxygenation is being provided primarily by VV ECMO, reducing the need for high F_IO_2 from the ventilator unless required to maintain adequate oxygenation

ARDS, acute respiratory distress syndrome; PEEP, positive end-expiratory pressure; RR, respiratory rate; VILI, ventilator-induced lung injury.

The initiation of VV ECMO can lead to a number of abrupt hemodynamic changes. A gradual increase in ECMO flow during initiation can help reduce the risk of this complication. Hypotension and impaired circuit flow can occur as a result of significant vasoplegia because of a systemic inflammatory response after exposure to the extracorporeal circuit or hypovolemia related to unrecognized hemorrhage caused by complications during cannulation. Decisions regarding volume resuscitation with intravenous crystalloid, colloid, or blood transfusion should be patient-specific.

After stabilization on VV ECMO, vasoactive support can often be titrated down significantly. Hemodynamic goals should be reviewed daily and adjusted if necessary. In general, a fluid restrictive approach to volume resuscitation is promoted after the acute phase of critical illness to avoid excessive capillary leak and improve pulmonary function. A restrictive transfusion practice may also be considered. Some practitioners target a hemoglobin threshold >7 g/dl, whereas others recommend hemoglobin of 12 g/dl to optimize oxygen delivery.

Ventilator Management

A key principle of lung protection during VV ECMO is that gas exchange is primarily supported by the extracorporeal circuit, not the native lungs, and thus ventilator settings should be chosen to limit ventilator-induced lung injury. However, the optimal ventilatory strategy in patients with severe ARDS undergoing ECMO is not well defined.[22] Historically, typical ventilator settings during VV ECMO are the pressure controlled ventilation (PCV) mode, with an FiO_2 0.3, plateau pressure of 20 cm H_2O, positive end expiratory pressure (PEEP) of 10 cm H_2O, respiratory rate (RR) of 10 breaths per minute, and an inspiratory to expiratory ratio of 1:1. In the CESAR trial, ventilator settings were gradually reduced to allow so-called lung rest, using PCV to limit the inspiratory pressure to 20–25 cm H_2O, with a PEEP of 10 cm H_2O, an RR of 10 breaths/minute, and an FiO_2 0.3.[2] In the recent and largest ECMO trial to date (EOLIA), settings were similar with plateau pressure of ≤24 cm H_2O, PEEP of ≥10 cm H_2O, RR of 10–30 breaths/minute, and an FiO_2 0.3–0.5.[1]

Ventilator settings are adjusted as conditions change (decreasing rate as CO_2 is cleared by the circuit, *e.g.*), but should not exceed the rest settings you have chosen. At a minimum, rest ventilator settings should target values established in these two trials[1,2] (*i.e.*, plateau pressure ≤ 25 cm H_2O) or inspiratory pressure ≤15 cm, with a PEEP of ≥10 cm H_2O.[23] Ventilatory settings for patients supported with VV ECMO may fall into the following ranges (**Table 3**). The ventilatory strategy employed in recent clinical trials provides some examples (**Table 4**). Finally, although some experts endorse a higher PEEP strategy (>10 cm H_2O) to keep the lung open and prevent atelectasis,[28] some endorse a strategy that includes no external PEEP (*i.e.*, patient extubated).[29–31] Regardless of choice of specific rest settings, during VV ECMO when oxygenation and CO2 goals are not being met, return to our key principle—the management should be *via* adjustments in the ECMO circuit and not by increasing ventilator settings.

Some well-selected patients may tolerate extubation, but others may have profound tachypnea, which itself may be injurious. The balance between injury prevent from reduced ventilator pressures and injury caused from tachypnea in patients with ARDS on ECMO is not known, and the effect of spontaneous breathing on transpulmonary forces during lung injury is an area of ongoing research. Based on published studies to date, ventilator settings that minimize RR and ventilatory pressures are recommended.[32–34] In general, any mode (*e.g.*, volume/assist-control, pressure/assist-control, airway pressure release ventilation) that can achieve this lung-protective ventilation during

Table 4. Ventilatory Strategies From Recent Clinical Trials for Adult VV ECMO

	CESAR[2]	EOLIA[1]	
Ventilatory mode	PCV	V-AC	APRV
Set parameter	10 cm H_2O above PEEP	V_T for P_{plat} ≤ 24 cm H_2O	P_{high} ≤ 24 cm H_2O
PEEP (cm H_2O)	10	≥10	≥10
Respiratory rate (breaths/min)	10	10–30	Spontaneous
FiO_2	0.30	0.30–0.50	0.30–0.50

APRV, airway pressure release ventilation; FiO_2, fraction of inspired oxygen; PCV, pressure controlled ventilation; PEEP, positive end-expiratory pressure; V_T, tidal volume; V-AC, volume-assist control ventilation.

VV ECMO would represent a reasonable ventilatory strategy. Chapter 40, "Medical Management of the Adult with respiratory Failure on extracorporeallife support (ECLS)" in the fifth Edition of the *ELSO Red Book*, provides additional detailed discussion of choice of rest ventilator settings, extubation during VV ECMO, as well as the management of ventilatory support during ECMO.

Initial Fluid Management. The ability of the ECMO circuit to provide gas exchange is dependent on sufficient blood flow through the oxygenator. Ignoring recirculation for a moment, increasing blood flow during VV ECMO to achieve rated flow of the oxygenator predictably increases systemic oxygen delivery. It follows that the goal of fluid management during ECMO therapy is initially to ensure adequate vascular volume to enable ECMO flow commensurate with desired gas exchange. Practically, this means that many patients need fluid resuscitation after the initiation of VV ECMO.

Effect of Fluid Administration on Tidal Volumes. It is important to recognize that this initial need for fluid administration, plus any decreases in mean airway pressure that accompany ventilatory rest settings, may together result in an increase in pulmonary edema. During this resuscitative phase, lung compliance decreases; at stable inspiratory pressures, tidal volumes rapidly and predictably fall. The evidence to date suggests that changes should not be made to increase tidal volume, assuming adequate systemic oxygen delivery.[24,35]

Chatter and Suck-Down. Over the course of an ECMO run, the patient's condition and treatment will affect intravascular volume. Additionally, it is important to remember that the IVC will often exhibit rhythmic collapse during respiration, periods of coughing or valsalva. Unless there is venous engorgement such that the cannula does not contact the venous walls, there will be some element of *partial* dynamic cannula occlusion in many patients along the lateral fenestrations of the cannula. Although chattering should be prevented by careful administration of fluid or reduction of flow, if possible, excessive fluid administration must be avoided. Inadequate intravascular volume, or cannula misplacement, can result in suck-down, in which the ECMO flows acutely drop by more than 1–2 LPM from baseline. This can result in flows of <1 LPM at full pump speed and is dangerous, as it can result in hemolysis, and, at worse, cavitation of air within the pump and air embolization. Suck-down should be treated by rapidly decreasing motor speed, adjusting the ventilator as necessary for oxygenation, and then slowly ramping back up while changing patient position to increase venous filling, and by giving fluid as needed.

Subsequent Fluid Management and Diuresis. After initiation of ECMO, increases in blood flow and oxygen delivery often lead to improvement in organ function, and in cases of preserved renal function, an autodiuresis. A conservative fluid management strategy has shown benefit in patients with ARDS without ECMO[36,37]; in the absence of other data, we assume the same holds true for critically ill patients managed with ECMO after initial fluid resuscitation. Multiple studies now indicate that a negative fluid balance is associated with improved outcomes (Supplemental Digital Content 1, http://links.lww.com/ASAIO/A626). Thus, the best available data at this time suggest that after the initial resuscitative phase of VV ECMO, patients should achieve a negative fluid balance whenever hemodynamically possible, until achieving their dry weight.

Procedures on ECMO. Procedures from venipuncture to liver transplantation can be done with success during ECMO. When an operation is necessary, coagulation should be optimized (anticoagulation minimized) as described earlier. Even small operations like chest tube placement are done with an extensive use of electrocautery.

Tracheostomy is often done in ECMO patients, but the technique is different than standard tracheostomy. The trachea is exposed through a small incision, all with extensive electrocautery. The smallest opening in the trachea is made between rings, preferably with a needle, wire, and dilation technique. Do not incise a ring or create a flap. Because the patient is on ECMO support there is no urgency about gaining access or conversion from endotracheal tube to trach tube. The operative site (and trachea) should be bloodless after operation. Subsequent bleeding (common after a few days) should be managed by complete reexploration until bleeding stops.

Anticoagulation. Anticoagulation for ECMO is covered in a separate guideline.

Duration of Support. The expected duration of VV ECMO support is dependent on multiple factors, but among published studies, most patients are on ECMO for 9–14 days, although some may require 4 weeks or more.

Futility. Consideration should be given to discontinue ECMO if there is no reasonable hope for meaningful survival or bridge to organ replacement (*e.g.*, transplant, durable left ventricular assist device, etc.) through shared decision-making with the patient's surrogate/family, in accordance with local laws and practice. The possibility of stopping for futility should be explained to the family before ECMO is begun. The definition of irreversible heart or lung damage depends on the patient, the resources of the institution, and the region/country. In general, it is important to clearly set expectations early on during an ECMO course.

WEANING OFF VV ECMO

Assessing adequate gas exchange reserve before considering weaning from VV ECMO and subsequent steps to prepare for decannulation are discussed in the following. It is important to note that weaning may occur over several hours to days, based on clinical condition of the patient. Arterial blood gases should be obtained throughout the process when significant adjustments are made, as clinically indicated. A detailed discussion of this topic is included in Chapter 42, "Weaning and Decannulation of Adults with Respiratory Failure on ECLS" in the fifth Edition of the *ELSO Red Book*.

Recommendations

1. Assess readiness to be weaned from VV ECMO. This includes assessing for both ventilatory and oxygenation reserve. **Table 5** lists criteria for intubated and nonintubated patients on VV ECMO who can undergo a weaning trial, including radiographic criteria. To initially assess oxygenation ability, the ECMO flow can be decreased to 1–1.5 LPM to ensure the patient maintains adequate oxygenation. Alternatively, the ECMO flow can be maintained and fraction of delivered O_2 can be weaned. To assess ventilatory reserve, the patient should tolerate a low sweep gas flow (<2 LPM) with an acceptable P_aCO_2 and work of breathing/RR. As a last step, patients can be placed on 100% FiO_2 for 15 minutes and check an ABG

Table 5. Oxygenation, Ventilation, and Radiographic Conditions Sufficient for Initiating a Weaning Trial

	Intubated Patients	Nonintubated Patients
Oxygenation*	■ F_iO_2 consistently ≤ 60% ■ PEEP ≤ 10 cm H_2O ■ P_aO_2 ≥ 70 mm Hg	■ P_aO_2 ≥ 70 mm Hg on no more than a moderate amount of supplemental O_2 (example: ≤6 LPM NC or facemask, or ≤ 40 LPM with F_iO_2 ≤ 0.3 on high-flow nasal cannula)
Ventilation	■ Tidal volume ≤ 6 mL/kg PBW ■ Plateau pressure ≤ 28 cm H_2O ■ Respiratory rate ≤ 28 bpm ■ ABG demonstrates acceptable pH and P_aCO_2 based on the patient's clinical condition without excessive work of breathing	■ ABG demonstrates acceptable pH based on the patient's clinical condition without excessive work of breathing
Imaging	Chest radiograph demonstrates improvement in appearance	

ABG, arterial blood gas; LPM, liters per minute; PBW, predicted body weight; PEEP, positive end-expiratory pressure.

to assess P_aO_2 buffer. Finally, perform ventilator challenge in intubated patients (**Table 6**).

2. **Table 7** lists the steps and criteria for a trial off of VV ECMO. Weaning may occur over several hours to days based on clinical condition of the patient. Ensure oxygenator is cleared of condensation and blood flow is maintained at >1 L/minute per cannula to avoid thrombosis.

LIMITATIONS

Venovenous extracorporeal membrane oxygenation use in adults has rapidly increased worldwide. This document is intended to be a practical, consensus based guide to patient selection, initiation, cannulation, management, and weaning of VV ECMO for adult respiratory failure. This document is not comprehensive and cannot stand alone as a sole management guide for all of adult respiratory ECMO. As examples, additional guidance for essential topics not covered in this document are provided in **Table 8**. Additionally, these recommendations will be updated as new information becomes available, and the latest version of this document will be available at https://elso.org/Resources/Guidelines.aspx.

PRACTICE POINTS TO REMEMBER

Utilize evidence-based ARDS therapies before ECMO, including low tidal volume ventilation (4–6 ml/kg PBW) and, in the absence of contraindications, prone positioning. As recently as 2017, it was demonstrated that only 11% of ECMO patients at the US centers underwent prone positioning at any point during their course.[38] Available evidence at this time demonstrates a clear and strong mortality benefit from prone positioning for ARDS; ECMO should *not* be an alternative to proning; proning is a complement that should be performed

Table 6. Weaning Ventilator Challenge in Intubated Patients on VV ECMO

	Volume-Regulated Modes of Ventilation	Pressure-Regulated Modes of Ventilation
Respiratory Compliance	■ Liberalize tidal volume by 1 ml/kg increments up to 6 ml/kg ■ Plateau pressure at each increment remains ≤ 28 cm H_2O	■ Liberalize total pressure to no more than 28 cm H_2O ■ Ensure that tidal volumes increase to 6 ml/kg
Clinical Parameters	■ Monitor respiratory rate and minute ventilation ■ Avoid excessive work of breathing based on patient's physiologic status and underlying comorbidities	

Table 7. Suggested Approach to Weaning From Venovenous Extracorporeal Membrane Oxygenation *via* Reduction of Gas Flow with Preserved Higher Blood Flows

Step	Purpose	Process
1	Reduce FDO_2	■ Stepwise reduction in FDO_2 from 1.0 to 0.21 in decrements of approximately 20%. ■ Maintain acceptable SpO_2 > 92% or P_aO_2 of at least ≥ 70 mm Hg ■ ABG as clinically indicated
2	Reduce sweep gas	■ Stepwise reduction in sweep gas flow rate by 0.5–1 L/min to goal of 1 L/min ■ Check ABG with each decrement in sweep gas flow rate ■ Maintain acceptable pH based on the patient's clinical condition without excessive work of breathing
3	Off-sweep gas challenge	■ If patient able to tolerate discontinuation of ECMO, trial off sweep gas for 2–3 hours or longer. ■ Monitor SpO_2 ■ Check ABG off sweep gas after allotted time
4	Prepare for decannulation	■ Notify surgeon or whomever decannulates. ■ Confirm off-sweep gas ABG demonstrates PaO_2 ≥ 70 mm Hg and acceptable pH based on the patient's clinical condition without excessive work of breathing ■ *Nil per os/nothing by mouth* status ■ Active blood type (ABO) and antibody screen in the case of significant blood loss ■ Prepare to give sedation depending on patients' predecannulation sedation status. ■ Hold heparin for at least 1 hour before decannulation. ■ Trendelenburg position if jugular vein cannula ■ Close cannulation site with a suture, apply slight compression dressing and observe carefully ■ Check for deep vein thrombosis after 24 hours

ABG, arterial blood gas; FDO_2, fraction of delivered oxygen.

Table 8. Additional Guidance for Essential Topics

Topic	ELSO Guidelines	Fifth Edition Red Book Chapter
Anticoagulation	ELSO Anticoagulation Guideline 2014	7—"Anticoagulation and Disorders of Hemostasis"
Bridge to lung transplantation		58—"ECMO as a Bridge to Lung Transplantation"
Cannulation Strategies	ELSO Guidelines General v1.4—Section III, Ultrasound Guidance for VV ECMO	38—"ECLS Cannulation for Adults with Respiratory Failure"
Circuit design	ELSO Guidelines General v1.4—Section II,	5—"The circuit"
	ELSO Guidelines for Adult Respiratory Failure v1.4 – Section II	
Complication management		Chapters 40, 41, 43
ECMO team design	ELSO Guidelines for ECMO Centers v1.8,	65—"Implementing an ECLS program"
	ELSO Guidelines for Training and Continuing Education of ECMO Specialists	
Extubation during ECMO	Endotracheal Extubation in patients with respiratory failure receiving VV ECMO	Chapters 40, 41
Management of fluid balance/renal failure/ nutrition	ELSO Guidelines for Adult Respiratory Failure v1.4—Section IV	40—"Medical Management of the Adult with Respiratory Failure on ECLS"
Procedures during ECMO	ELSO Guidelines for Adult Respiratory Failure v1.4—Section VI	61—"Procedures during ECLS"
Sedation	ELSO Guidelines for Adult Respiratory Failure v1.4—Section IV	40—"Medical Management of the Adult with Respiratory Failure on ECLS"
Selective CO_2 removal ($ECCO_2R$)	ELSO Guidelines for Adult Respiratory Failure v1.4—Section VI	63—"Extracorporeal Carbon Dioxide Removal"
Transfusion management	ELSO Guidelines for Adult Respiratory Failure v1.4—Section IV	8—"Transfusion Management during Extracorporeal Support"
Unusual patient populations (pregnancy, immunosuppressed, *etc.*)	ELSO Guidelines for Adult Respiratory Failure v1.4—Section I	Section 7—Extracorporeal Life Support: Special Indications—Chapters 53, 54, 56, 58, 60

ECLS, extracorporeallife support; ELSO, extracorporeal life support organization; VV ECMO, venovenous extracorporeal membrane oxygenation.

before ECMO. On ECMO, continue to adhere to the principles of lung protection: reduce the intensity of mechanical ventilation and avoid high airway/driving pressure (**Table 3**).

Plan Ahead for Potential Venovenous Extracorporeal Membrane oxygenation Cases

Determine who has the skill and experience to cannulate, who the team will be, and what resources are needed, such as echocardiography or fluoroscopy. If patients are to be transferred for VV ECMO, make the referral call early enough to allow for worsening without extremis.

Ground Assessments of Adequate Oxygenation on Objective Measures of Tissue Perfusion, Rather Than on Percent Saturations of Arterial Blood

It is important to pay attention to hemoglobin, systemic vascular resistance, and cardiac output (in short, oxygen delivery). Although it is possible to have inadequate saturations *and* oxygen delivery on VV ECMO, it is critical to not confuse the two as often they are distinct.

PITFALLS TO AVOID

Overreacting to Low Saturations on Venovenous Extracorporeal Membrane Oxygenation and Increasing the Ventilator Settings to Compensate

The rationale to initiate VV ECMO includes augmentation of oxygenation and ventilation, but increasingly, also the implementation of ultralow settings and lung rest. Failing to decrease ventilatory settings once on VV ECMO obviates a major potential benefit of VV ECMO.

Waiting too Long for Cannulation

Cannulation for VV ECMO may involve transport to a fluoroscopically enabled area or to a center that can cannulate, or if the patient is already prone, supination of the patient. Any of these movements often result in temporary desaturation as consolidations redistribute and lung recruits. We advocate a combined use of the Murray Score (Lung Injury Score) and the RESP score to guide decisions regarding initiation of VV ECMO, utilizing initiation threshold criteria discussed earlier from the EOLIA trial. If ECMO is to be a consideration, and transfer would be necessary, it should be done early.

Initiation of Venoarterial Extracorporeal Membrane Oxygenation When Venovenous Extracorporeal Membrane Oxygenation Will Suffice

Although it is common to see elevated pulmonary pressures and right ventricular dysfunction in the setting of acute respiratory failure due to hypoxemia and hypercarbia, this is not to be confused with pre-existing heart failure. The former typically improves with oxygenation and ventilation and initiation of VA ECMO for a process that will improve with VV ECMO results in additional unnecessary and significant risk. Some patients with hypoxemia in the setting of sepsis can develop a concomitant severe cardiomyopathy that may benefit from VA ECMO.

Conversion of Venovenous Extracorporeal Membrane Oxygenation to Venoarterial Extracorporeal Membrane Oxygenation for Low Saturations

Extracorporeal membrane oxygenation provides a variable content of oxygen to the blood that is directly related to the hemoglobin × blood flow rate. Delivery of that oxygen content to the arterial system achieves little or no increase in systemic oxygen delivery over VV, with an increase in meaningful complications.[39] In the case of severe ARDS treated with VA ECMO, as the heart recovers, patients can have upper body (and cerebral) hypoxemia; this is known as Harlequin or North/South syndrome.

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Extracorporeal Life Support Organization Guideline for Transport and Retrieval of Adult and Pediatric Patients with ECMO Support

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Disclaimer: This extracorporeal life support organization guideline describes the preparation for and undertaking of transport and retrieval of patients on extracorporeal membrane oxygenation (ECMO). The guideline describes useful and safe practice put together by an international multidisciplinary team with extensive experience in the field of ECMO and ECMO transport. The guideline is not intended to define the delivery of care or substitute sound clinical judgment. The guideline is subject to regular revision as new scientific evidence becomes available.

Introduction

As the indications for extracorporeal membrane oxygenation (ECMO) exponentially expand, transportation of patients on ECMO support or the rescue of patients at outside facilities with ECMO implantation adds an additional degree of complexity to the already complicated task of transporting critically ill patients. Mobile ECMO requires a unique skill set focused on the care of a patient requiring ECMO. This guideline aims to provide ECMO centers with a practical reference for providing primary and secondary mobile ECMO services. The same principles apply to the transport of patients with other modes of extracorporeal life support for example, extracorporeal carbon dioxide removal.

Transport of ECMO patients requires coordination and careful considerations of potential risks and benefits of transport and is typically accomplished *via* ground or air. In most cases, the circuit and equipment utilized for mobile ECMO are the same as the components used for in-house ECMO support with adaptation for the unique aspects of mobile care. Regardless of transport mode or equipment, safety of the patient, transport team, and public is paramount during ECMO transport. There is little evidence guiding the transport of patients supported with ECMO; however, it is recommended that transport be performed by well-equipped teams acquainted with mobile transport.[1–3] Several case series describe safe transportation of patients supported with ECMO using different models and team structures.[4–13] This guideline is predominantly based on expert opinion.

Section I: Types of ECMO Transportation

There are several types of ECMO transportation defined by where the patient is retrieved from, transported to, and by which facility's ECMO team. This section contains common types with a description of defining criteria. This may be helpful in determining team responsibility, authority, and other policy and operational implications.

a. **Primary ECMO transportation**. A mobile ECMO team initiates ECMO at an outside facility and, after initial stabilization the patient is transferred to an ECMO center.
   1. Patient is a good ECMO candidate; determined by the referring and accepting ECMO team.
   2. Timely response is essential.
   3. Adequate preparedness is paramount to avoid delays and optimize patient outcomes.

b. **Secondary ECMO transportation.** A patient is currently supported with ECMO but must be transferred to another facility on ECMO support.
   1. Patient may require specialized management such as transplant or durable mechanical circulatory support.
   2. Patient may require another center's medical expertise.
   3. Family request.

c. **Tertiary ECMO transportation.** Hospital A has a patient with ECMO indication and a mobile ECMO team from Hospital B goes to Hospital A. The ECMO team from Hospital B puts the patient on ECMO and transports the patient to Hospital C with ECMO capacity.

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1. In periods of high demand there may be a Hospital C without mobile ECMO but with ECMO capacity.
2. A hospital with mobile ECMO team capabilities, but without the capacity to receive a patient, could carry out this transport.
3. Preparation and coordination between the three institutions is required.

d. **Intra-facility ECMO transfer.** A patient is currently supported with ECMO but must be moved within an institution.

1. Possible reasons for intra-facility transfer: patient may require a diagnostic test (*e.g.*, CT scan), may require a procedure, or be transferring to a different floor.

Section II: Mobile ECMO Specific Considerations

Transport preparation is critical. It is important to consider the type and urgency of ECMO transport being performed, the equipment required, and develop prespecified processes for communicating and documenting salient clinical information. Well-delineated processes can increase efficiency and minimize the risk of transport.

a. Communication and documentation.

1. Documentation of clinical information should be performed in an efficient and timely manner.

i. Consider the use of electronic medical record tools and standardized formats.
ii. Consider the use of a standardized referral form (see Figure 1, Supplemental Digital Content 1, http://links.lww.com/ASAIO/A775).
iii. Develop a standardized referral process utilizing a centralized transfer or care logistics center when available.
iv. Pretransport team huddle is recommended.

b. Equipment.

1. Mobile ECMO team should be self-sufficient in terms of medication, equipment, monitoring, and diagnostic devices. An equipment checklist should be completed by the mobile ECMO team before departure. (see Figure 2, Supplemental Digital Content 1, http://links.lww.com/ASAIO/A775).
2. Pre-prepared, stocked, and checked ECMO bag(s) are recommended for rapid team mobilization.

i. Equipment should be standardized and available for restock upon completion of the mission.

3. A standardized checklist should be sent to the referring hospital detailing equipment and supplies to have ready before the transport team's arrival.

i. Supplies should be standard and basic (central line kit, drapes, gowns, gloves, *etc.*).
ii. Medications available at bedside (heparin, fluids, pressors/inotropes, *etc.*).
iii. Blood products.

c. The mobile ECMO specific equipment should consist of the following components:

1. Blood pump (centrifugal is recommended) capable of providing sufficient blood flow2 with considerations listed below:

a. The enhanced performance of modern centrifugal pumps with a nonocclusive mechanism seems a safer choice than roller pumps for mobile ECMO.
b. Roller pumps have a higher potential for kinking.
c. Inadvertent compression of venous tubing can result in cavitation.

2. Membrane oxygenator.
3. Appropriate cannulas and tubing for connections.
4. Medical gas tanks and compatible hoses, pressure regulators, connectors, and flow meters for provision and adjustment of sweep gas.
5. Back-up console, back-up motor and/or hand crank (depending on console type).
6. Back-up circuit, circuit components, and priming fluids.
7. Appropriate clamps for circuit emergencies.
8. Point-of-care lab capabilities.

a. Anticoagulation (*i.e.*, ACT).
b. Blood gas analysis.
c. Hemoglobin/hematocrit.
d. Basic electrolytes.

9. Special considerations for pediatric patients.

a. May need to request blood for blood priming (2 units of packed red blood cells).
b. Consider regulating blood flow based on patient weight:

1. Consider bringing equipment for a bridge if one is expected.
2. Consider the use of a Hoffman clamp for flow regulation.

d. Additional ECMO equipment that can be considered includes the following:

1. Heater-cooler unit (if sufficient power for operation).
2. Medical air/portable air compressor.
3. Blender.
4. Pre-and post-pump pressure monitoring.
5. Bubble detector.

e. Additional critical care transport equipment recommended:

1. Transport ventilator appropriate for patient size and clinical needs.
2. Transport monitor for vitals including end-tidal CO_2 and invasive monitoring when able (arterial, central venous/pulmonary artery lines).
3. Portable Point-of-Care Ultrasound (POCUS) capable of vascular imaging and transthoracic echocardiography.
4. Infusion pumps for medication and fluid infusion.
5. Electrical adapters may be necessary because the plugs may be different at the destination. ECMO Transport team should check before leaving.

f. All equipment should be mounted, strapped, locked-in, housed, or otherwise secured for transport.

1. Stabilize against vibration, acceleration, deceleration, turbulence, rough roads, inclement weather, *etc.*, as unsecured equipment can become a projectile in the event of sudden acceleration/deceleration.
2. Account for forces in all directions.
3. Cannulas should be well secured to avoid movement during horizontal and vertical movements associated with emergency medical service (EMS) travel.
4. Circuit tubing length should be as short as possible to avoid the potential for snagging and inadvertent compression.
    i. Circuit tubing should be long enough to allow for safe loading and unloading of the patient.
    ii. Overly long circuit tubing may increase the risk of kinking or compression.
5. ECMO lines should be carefully traced before, after, and during movement to ensure the absence of kinks, compression, hazard for catching or pulling that could result in hemodynamic instability including cardiac arrest and death.
6. Allow for ready access to back-up systems in case of equipment or power failure.
7. The membrane oxygenator/pump should be secured at the level of the patient, if able.
    i. When below the patient, the oxygenator can accentuate ECMO flow fluctuation and G-forces due to the impact of gravity.
    ii. When higher than the patient, the oxygenator can increase the risk of air entrapment and pump stoppage.

g. Sufficient power and back-up power should be secured for all electrical equipment (ECMO console, infusion pumps, ventilator, defibrillator/monitor, *etc.*).
    1. Consider uninterruptable power source (UPS) use for sensitive powered equipment.
    2. Transport ECMO team must be familiar with electric specifications of all transport equipment particularly during international transfer.
h. Ensure sufficient medical gas for the transport.
    1. Availability of twice the anticipated medical gas requirements is recommended.
    2. Consider the use of oxygen concentration equipment.
i. Any equipment used during air transport should meet Civil Aviation Authority, Federal Aviation Administration, or equivalent airworthiness requirements as established by the relevant state, national, or international regulatory agencies.
    1. High emission of electromagnetic (EM) or radio-frequency interference may affect the performance of aircraft equipment.
    2. Mobile ECMO equipment modification with EM shielding may be required for flight safety.
    3. Such shielding adds weight and can affect equipment portability.
j. ECMO transport team preparedness planning includes:
    1. Conduct preplanning and simulation of mobile setup and layout.
    2. Establish communication and coordination regarding the optimal transportation method for both insertion and retrieval of the team (they may be different) with consideration of:
        i. Patient size and weight,
        ii. Crew size and weight,
        ii. Equipment weight, and
        iv. Modes of transportation available (ground, rotor wing, fixed wing, *etc.*).
    3. Ensure adequate patient restraint such as a 5-point harness or straps.
    4. Ensure adequate stretcher strength for both patient and equipment.
    5. Secure all equipment and pressurized tanks (O_2, air).
    6. Establish adequate pressure point protection for overweight patients.
    7. Ensure visualization and access to indwelling lines, tubes, and catheters.
    8. Ensure adequate power for all equipment.
    9. Plan for adequate attention and mitigation for managing patient temperature.
        i. Consider use of heater-cooler,
        ii. Consider use of blankets, and.
        iii. Consider use of thermal enclosure.

Section III: Mobile ECMO Team Structure and Responsibilities

The composition of teams is variable but should be composed of no less than: team lead; cannulating provider (for primary ECMO missions, can be the same person as 1) ECMO specialist; and medical transport team/EMS. Definitions for each team member are as follows:

a. Team lead.
    1. Responsible for overall planning, execution, and oversight of the mission.
    2. Often also performing one of the other team roles, in addition to team lead.
b. Cannulating provider (for primary ECMO missions).
    1. Should be an experienced cannulation expert.
    2. Should have comfort with POCUS (both vascular and echocardiographic).
    3. Responsible for safe and appropriate placement/connection of ECMO cannula(s).
    4. Often works in collaboration with an on-site medical team.
    5. Ensure appropriate environment for ECMO implant (bedside, move to OR, interventional lab, *etc.*).
c. ECMO provider.
    1. Can be the same as cannulating provider.
    2. Should be an experienced ECMO clinician.
    3. Should have comfort with POCUS (both vascular and echocardiographic).

4. Upon arrival to bedside, should assess/reassess the patient and pertinent data, confirm candidacy, and assist with medical stabilization.
    i. Patient's clinical status may have changed between acceptance and arrival.
    ii. Some patients may be transported without an ECMO implant.
    iii. Some patients may not be suitable for ECMO upon further review and be best left in the care of the local treating team.
5. Provide clinical update to the patient/family while establishing expectations of ECMO and ECMO process.
6. Obtain informed consent.
7. Assumes direct medical oversight of the patient once cannulated and throughout transport.

d. ECMO specialist.
    1. Can be a perfusionist, nurse, respiratory therapist, or medical provider.
    2. Should be an experienced ECMO practitioner.
    3. Responsible for set up and priming of ECMO circuit.
    4. Responsible for ECMO circuit management from implant to arrival at destination center.

e. Medical transport team.
    1. Paramedic or equivalent level of care to supplement the implant team.
    2. Can include nurse or respiratory therapists.
    3. Responsible for:
        i. Patient movement and handling,
        ii. Coordination and communication with command center/dispatch,
        iii. Patient loading and offloading from transport vehicles, and
        iv. Oversight and securing of mobile medical equipment.
    4. Cross-training is recommended (nurse/critical care paramedic, respiratory therapist/critical care paramedic, etc.).
    5. If the medical transport team is unable to perform critical duties such as ventilator management, supplementation of the team with appropriate medical staff to ensure safe transport is recommended.

f. ECMO transport and retrieval teams should have the skills and competencies to perform patient assessment, cannulation, initiation/maintenance of ECMO support, and safe transportation.

g. Team training with medical simulation in the following mobile-specific areas are recommended:
    1. Mock calls for testing the communication system.
    2. Team simulation in the common transport environments the team expects to utilize for transports (ground ambulance, rotor-wing air ambulance, fixed wing air ambulance); and.
    3. High fidelity simulation of common and high-risk low-frequency events, such as:
        i. Transfer of a patient from hospital stretcher to ambulance stretcher,
        ii. Suction events,
        iii. Bleeding,
        iv. Hypotension,
        v. Arrhythmia,
        vi. Catastrophic ECMO system failure/power failure,
        vii. Cannula dislodgement,
        viii. Ambulance malfunction, and
        ix. Air entrainment.

Section IV: Mobile Mission-Specific Guidelines

ECMO centers should collaborate with EMS and establish Standard Operation Procedures (SOPs) for the activation, prioritization, and mobilization of the mobile ECMO transport team. Specific phases of ECMO transport are identified below with appropriate considerations for each phase.

a. Activation and mobilization.
    1. Requesting ECMO.
        i. The use of a clinical information form (either electronic or paper based) that can be easily shared by the ECMO team is recommended for efficient transfer of critical information from requestor to the team.
        ii. Information that should be included in this form includes:
            1. Requisition center/provider demographics,
            2. Patient demographics,
            3. Identification of person making medical decisions (patient or family) and indication if patient/family is aware ECMO consideration,
            4. Basic clinical history,
            5. Current medication list,
            6. Recent vital signs and vent settings if currently intubated,
            7. Basic and relevant recent laboratory review,
            8. Review of relevant imaging studies, and
            9. Current lines and access.
    2. Communication among ECMO team members – a standard method of activating and communicating within the ECMO team should be established by the mobile ECMO center.
    3. A standard system of communicating relevant information back to the requesting center should be established. Documented information includes:
        i. Acceptance or deferral of ECMO team activation,
        ii. Names and credentials of the responding team,
        iii. Patient-specific recommendations,
        iv. Patient and staff preparation instructions for ECMO team arrival, and
        v. Estimated time of arrival.
    4. A centralized dispatch/communication center is preferred for documentation and time keeping purposes.

b. Mobilizing the ECMO team.

1. Utilizing the tools noted above, a multidisciplinary team briefing should occur for the identification and initiation of mission-specific items.

i. Identify and secure transportation, and
ii. Assembly location for both personnel and equipment should be identified.

2. Data tracking/Key Performance Indicators (KPIs) should be recorded and used for quality improvement.

i. A standardized registry repository of key data should be established and reposed for clinical research and quality improvement.
ii. KPIs should include both clinical (outcomes, morbidity, mortality, *etc*.) and performance (time from referral to ECMO team mobilization, time from assembly to patient contact, *etc*.) indicators.

3. Preparation.

i. The use of standardized and checked mobile bags is recommended.
ii. The use of a premission checklist is recommended to ensure accounting for all necessary equipment and supplies.

c. Post-cannulation.

1. Stabilization of the patient by the ECMO team post-implant should occur with consideration of the transportation needs.

i. Gradual and not sudden changes in clinical support (hemodynamic, ventilation, *etc*.) are recommended to avoid overcorrection, particularly during transport.
ii. Minimize nonessential medications.
iii. Ensure adequate hemodynamics for transport.
iv. Ensure adequate supply of medications for transport.
v. Ensure blood product availability as needed for transport.
vi. Optimize ECMO and ventilator settings as clinically appropriate.
vii. Awareness of clinical changes likely to occur during the transport is important with planning for needed interventions en route to destination center (point-of-care labs, *etc*.).

2. Transfer to the transport stretcher includes:

i. Secure patient,
ii. Secure equipment, and
iii. Ensure no equipment is left behind.

3. A standardized pretransport checklist should be completed before leaving the sending facility.

d. Transport mode selection: ideal mode of transport should be evaluated on a case-by-case basis.

1. General considerations:

i. Geographical factors and distance.
ii. Traffic conditions.
iii. Urgency.
iv. Weather condition.
v. Experience.
vi. Availability and cost.
vii. Weight of patient, crew, and equipment.

2. Patient-specific considerations.

i. Type of ECMO.
ii. Patient clinical status.
iii. Patient height and weight.

3. General/nonmode specific transport considerations:

i. Appropriate stretcher weight capacity for patient and equipment.
ii. A nonslip area for loading and unloading as available.
iii. Ability to load/unload at ambulance floor height (powered lift platform if available).
iv. Electrical inverter checked before each mission.
v. Adequate oxygen.
vi. Adequate lighting.
vii. Adequate temperature regulation.
viii. Communication method for critical information to receiving center; we require two communication methods to avoid issues, which is why we recommend redundancy and planning for transport.

4. Mode specific considerations:

i. Ground (Figure 1a, b, and c).

1. Most common and available.
2. Multiple sizes – larger patient care areas (preferentially with 360-degree access to the patient) are preferred when available.
3. Can accommodate larger teams.

ii. Air transportation, in general:

1. Pilot flying time must be considered, as time is often regulated and may impact transportation options.
2. Weather and aircraft will be coordinated with air travel regulatory agencies which may impact timing.

iii. Rotor wing (helicopter) (Figure 2).

1. Smaller cabin space has limited crew capacity.
2. More weather-dependent than ground units.
3. Flexible landing and take-off locations with vertical assent capability.
4. Helipads are available at many medical centers.
5. Not affected by road traffic.
6. Need to consider altitude within the treatment plan.
7. Often use liquid oxygen which can have variable flow at different temperatures.
8. Should factor in vibration and noise mitigation for patient, crew, and equipment. Alarms can be hard to hear.
9. In-flight communication system to allow communication with flight crew and pilot is recommended.

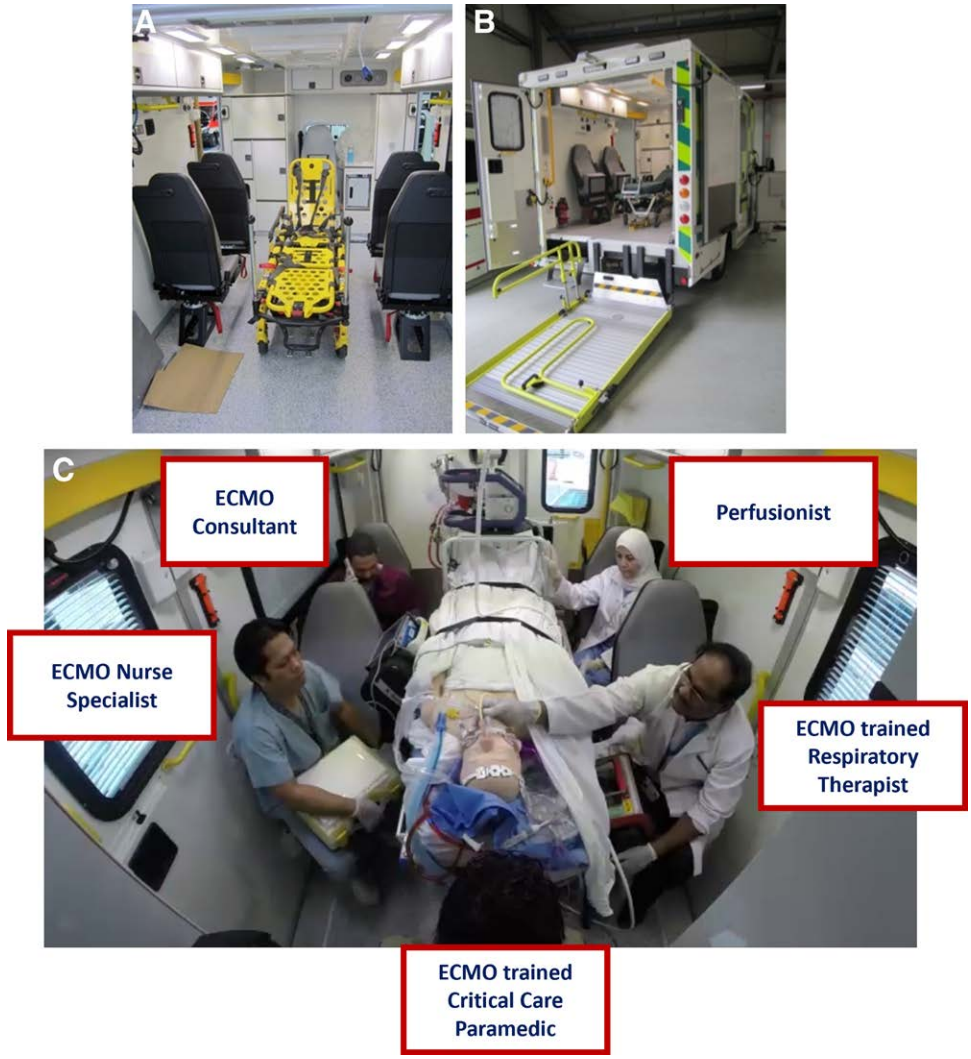

Figure 1. (A, B, and C). Spacious ICU ambulance with 360° access to patient. Seating for 5 medical personnel. Note sealed cabinet and floor for easy cleaning and infection control.

iv. Fixed wing (airplane) (Figure 3a, b, and c).

1. Capable of long transport distances.
2. Requires multiple transfers of the patient:
   a. Hospital bed to transport stretcher,
   b. Transport stretcher to aircraft stretcher,
   c. Aircraft stretcher to transport stretcher, and
   d. Transport stretcher to the hospital bed.
3. Consider altitude within the treatment plan.
   a. High altitude provides for shorter flight, less turbulence, and less fuel consumption.
   b. At low barometric pressure (higher altitudes), extra care must be taken to avoid hyper-oxygenation of the circuit as oxygen can bubble out of solution at lower pO_2 (rare in pressurized cabins).
   c. Effect of barometric pressure on endotracheal tube cuff.
4. Liquid oxygen which can have variable flow at different temperatures.
5. UPS systems for power where available.
6. Should factor in vibration and noise mitigation for patient, crew, and equipment. Alarms can be hard to hear.
7. In-flight communication system should allow communication with flight crew and pilot.
8. Ensure all equipment is approved for aircraft use by the appropriate governing body.
9. Consider the appropriate position of infants/neonates to reduce intracranial pressure during take-off and landing, if possible.

e. Considerations for transport of patients with transmittable diseases:[14–15].

1. Follow local and international recommendations.
2. Must adhere to infection control guidelines and use of personal protective equipment.
3. Avoid aerosol-generating procedures where possible.
4. Use of high efficiency particulate absorbing filters can be added to the expiratory limb of the ventilator.

Figure 2. Helicopter lay out. Note limited space and access to patient and equipment.

5. Vehicle decontamination is required before returning to in-service status.
6. Essential diagnostic and therapeutic interventions warrant careful planning and coordination to protect other patients, medical personnel, and the public.

f. Post-transport considerations:

1. Formal endorsement and handoff to receiving team should occur.
2. Patient transferred to the hospital bed.
3. Equipment should be cleaned and restocked for immediate use.
4. Team debriefing should occur for each case; high-volume transport centers may create more narrow debrief criteria.
5. Regular educational sessions incorporating significant events and critical incident stress debriefing should occur.

Section V: Clinical Governance and Risk Management

Providers should establish governance to ensure local and national standards for the Transport and Retrieval of ECMO-supported patients are maintained. Governance should include the use of audit, incident reporting, and feedback from patients and relatives regarding their experience.

a. Quality improvement process should be standard.

1. Use predetermined KPIs as quality metrics (*e.g.*, cardiac arrest, air embolism, bleeding).
2. Track process metrics (*e.g.*, compliance with checklists, timelines, and equipment failure/malfunction).
3. Review any critical incident comprehensively, noting opportunities for improvement, if any, with actionable items. Reviews should include:

i. Accidents or incidents affecting transport team,
ii. Blood product utilization or waste during transfer, and

Figure 3. (A, B, and C). An example of air ambulance. Note the special mechanism for lifting patient and difficult access.

iii. Educational opportunities for inappropriate or preventable referrals.

4. Critical incident stress debriefing is available for crews.

b. Training and competency development includes:[16–20]

1. Formal training in transport medicine and mobile ECMO for all team members.

i. Course should include formal education specific to transport of ECMO patients (both primary and secondary); and
ii. If able, simulation should be incorporated into the course for team training.

2. High and low fidelity simulation should be utilized for facilitation and maintenance of technical and practical competency.
3. Regularly scheduled clinical validation process is recommended.

c. Licensure and indemnity should be determined before mobilization of the ECMO transport team.

1. Emergency credentialing is recommended for primary ECMO transport.

i. Local, regional, and national governance should consider the need for emergency privileging to allow universal access to ECMO therapy.
ii. Each system should develop a standard workflow to obtain emergency privileging for the primary ECMO team.
iii. The team leader is responsible for ensuring credentialing is in place for the mobile ECMO team at the requesting hospital.
iv. When interacting with staff at a requesting hospital, the ECMO team should utilize the expertise at the referring hospital to best understand how to obtain emergency privileges.

2. Safety and well-being of the ECMO transport and retrieval team is top priority. Organizations should ensure appropriate indemnity and insurance to the mobile ECMO team.

i. A priori discussions with the administration, risk management, and, as required, insurance coverage to ensure appropriate coverage for the mobile ECMO team.

3. For teams that are flying, appropriate considerations should be taken for the implications of air travel for insurance, *etc*.

d. Finance:

1. Close collaboration is necessary regarding documentation, coding, and billing teams to ensure adequate and comprehensive documentation from the medical and fiscal perspectives.
2. Review of mobile cases by a multidisciplinary team to ensure appropriate coding and documentation is recommended for optimization of billing practices.
3. While fiduciary responsibilities are important, they should not influence the candidacy of a patient for ECMO therapy.

Summary

Primary and secondary transport of patients on ECMO support is both challenging and rewarding and should be undertaken by a specialized and well-trained multidisciplinary team of experienced ECMO practitioners. The team should be self-sufficient and readily available. Mobile ECMO can be undertaken by regional or high-volume centers as this is associated with improved patient outcomes and cost reduction.[2,3] Checklists, regular practice including high fidelity simulation, and effective coordination of team roles are key elements of providing safe and efficient ECMO transport.

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Extracorporeal Life Support Organization (ELSO)

General Guidelines for all ECLS Cases
August, 2017

Introduction

This guideline describes prolonged extracorporeal life support (ECLS, ECMO), applicable to **patients of any age with cardiac or respiratory failure**. Related guidelines with more specific discussion for categories of patients follow the same outline.

These guidelines describe useful and safe practice, prepared by ELSO and based on extensive experience. The guidelines are approved by the ELSO Steering Committee and are considered consensus guidelines. The guidelines are referenced to the ELSO Red Book which includes evidence based guidelines where available. These guidelines are not intended to define standard of care, and are revised at regular intervals as new information, devices, medications, and techniques become available.

The background, rationale, and references for these guidelines are found in "Extracorporeal Life Support: The ELSO Red Book, 5th Edition, 2017" published by ELSO. These guidelines address technology and patient management during ECLS. Equally important issues such as personnel, training, credentialing, resources, follow up, reporting, and quality assurance are addressed in other ELSO documents or are center-specific.

The reference is:

ELSO Guidelines for Cardiopulmonary Extracorporeal Life Support
Extracorporeal Life Support Organization, Version 1.4 August 2017
Ann Arbor, MI, USA
www.elso.org

Contents

I. Patient Condition (Chapters 11, 19, 29, 37, 44) 4
A. Indications 4
B. Contraindications 4
C. Specific patient considerations 4
II. Extracorporeal Circuit (Chapters 4, 5) 4
A. Criteria for selecting circuit components 4
1. Blood flow for cardiac support 4
2. Blood flow and gas exchange for respiratory failure (VA or VV) 5
B. Circuit components 5
C. Pump 5
1. Inlet (suction) pressure 5
2. Outlet pressure 5
3. Power failure 6
4. Hemolysis 6
D. Membrane lung (often called the Oxygenator) (Chapters 4, 5) 6
E. Sweep gas 7
F. Priming the circuit 7
G. Heat exchanger 8
H. Monitors 8
I. Alarms 9
J. Blood tubing 9
K. Elective vs. emergency circuits 9
III. Vascular Access (Chapters 4, 12, 20, 30, 38, 47) 9
A. The modes of vascular access are 10
B. Cannulas 10
C. Cannulation 10
1. Methods 10
2. Cannulation technique 10
3. Management of the distal vessels 11

4. Adding or changing cannulas....12
IV. Management during ECLS (Chapters 4, 5, 14, 22, 32, 40, 49)....12
A. Circuit related....12
1. Blood flow....12
2. Oxygenation....12
3. CO_2 clearance....13
4. Anticoagulation (Chapters 6, 7, 8)....13
5. Circuit monitors, alarms, and safety (Chapters 4, 5)....15
6. Component and circuit changes....17
7. Traveling (Chapter 66)....17
B. Patient related management (Chapters 4, 5, 14, 22, 32, 40, 49)....18
1 Hemodynamics....18
2. Ventilation....18
3. Sedation....20
4. Blood volume, fluid balance and hematocrit (Chapters 8, 41, 62)....21
5. Temperature....21
6. Renal and nutrition management (Chapters 4, 41, 62)....22
7. Infection and antibiotics....22
8. Positioning....22
9. Bleeding (Chapter 7)....22
10. Procedures (Chapter 6)....24
V. Weaning, Trials off, Discontinuing ECLS for Futility....25
(Chapters 4, 16, 24, 34, 42, 51)....25
A. Weaning....25
B. Trial off....25
C. Decannulation....26
D. Stopping support for futility....26
VI. Patient and Disease Specific Protocols....26
VII. Expected Results (per patient and disease category)....26

ECLS is the use of mechanical devices to temporarily (days to months) support heart or lung function (partially or totally) during cardiopulmonary failure, leading to organ recovery or replacement. Supporting literature, evidence, and rationale for these guidelines is in the ELSO Red Book. In this document references to specific chapters in the 5th Edition Red Book are identified " Chapter x."

I. Patient Condition (Chapters 11, 19, 29, 37, 44)

A. Indications

The primary indication for ECLS is acute severe heart or lung failure with high mortality risk despite optimal conventional therapy. ECLS is considered at 50% mortality risk, ECLS is indicated in most circumstances at 80% mortality risk. Severity of illness and mortality risk is measured as precisely as possible using measurements for the appropriate age group and organ failure. See patient- specific protocols for details.

Other elective indications are to support heart and or lung function during temporary nonfunction, such as extensive bronchoalveolar lavage, operations on the trachea or mediastinum, or coronary artery occlusion during procedures.

B. Contraindications

Most contraindications are relative, balancing the risks of the procedure (including the risk of using valuable resources which could be used for others) vs. the potential benefits. The relative contraindications are: 1) conditions incompatible with normal life if the patient recovers; 2) preexisting conditions which affect the quality of life (CNS status, end stage malignancy, risk of systemic bleeding with anticoagulation); 3) age and size of patient; 4) futility: patients who are too sick, have been on conventional therapy too long, or have a fatal diagnosis. See patient-specific protocols for details.

C. Specific patient considerations

See patient-specific protocols

II. Extracorporeal Circuit (Chapters 4, 5)

A. Criteria for selecting circuit components

The circuit is planned to be capable of total support for the patient involved, unless the intent is specifically partial support (i.e. CO_2 removal for asthma)

1. Blood flow for cardiac support

Access is always venoarterial. The circuit components are selected to support blood flow 3 L/m^2/min (neonates 100 cc/kg/min; pediatrics 80 cc/kg/min; adults 60

cc/kg/min.) The best measure of adequate systemic perfusion is venous saturation greater than 70%. Achieving a desired flow is determined by vascular access, drainage tubing resistance, and pump properties.

2. Blood flow and gas exchange for respiratory failure (VA or VV)

The membrane lung and blood flow should be capable of oxygen delivery and CO_2 removal at least equal to the normal metabolism of the patient (i.e. an oxygen delivery of 6 cc/kg/min for neonates; children 4-5 cc/kg/min; adults 3 cc/kg/min), This will usually equate to VV blood flows of 120 ml/kg/min for neonates down to 60-80 ml/kg/min for adults. Oxygen delivery capability is determined by blood flow, hemoglobin concentration, inlet hemoglobin saturation, and membrane lung properties. Carbon dioxide removal always exceeds oxygen delivery when the circuit is planned for full support.

If the circuit is planned for CO_2 removal only, access can be venoarterial, venovenous, or arteriovenous. Typical blood flow is approximately 10-25% of cardiac output, which is sufficient to remove the CO_2 produced by metabolism (3-6 cc/Kg/min). CO_2 removal is determined by the blood flow and the sweep gas rate, the inlet PCO_2 and the membrane lung properties.

B. Circuit components

The basic circuit includes a blood pump, a membrane lung, and conduit tubing. Depending on the application, additional components may include a heat exchanger, monitors, and alarms.

C. Pump

The pump should be able to provide full blood flow for the patient, as defined above. Any pump which meets the specifications can be used (modified roller with inlet pressure control; centrifugal or axial rotary pump with inlet pressure control; peristaltic pump).

1. Inlet (suction) pressure

With the inlet line occluded the suction pressure should not exceed minus 300 mmHg. The inlet pressure can be very low (minus 300 mmHg) when the venous drainage is occluded (chattering) which causes hemolysis. Inlet pressure in excess of minus 300 mmHg can be avoided by inherent pump design or through a servocontrolled pressure sensor on the pump inlet side.

2. Outlet pressure

With the outlet line occluded the outlet pressure should not exceed 400 mm/Hg (inherent in the pump design or by a servocontrolled system).

3. Power failure

The pump should have a battery capable of at least one-hour operation, and a system to hand crank the pump in the event of power failure.

The pump and circuit should have a mechanism to alarm for or **prevent reverse flow** (arterial to venous in the VA mode) if the power fails.

4. Hemolysis

The plasma hemoglobin should be less than 10 mg/dl under most conditions. If the plasma hemoglobin exceeds 50 mg /dl, the cause should be investigated.

D. Membrane lung (often called the Oxygenator) (Chapters 4, 5)

The gas exchange material in membrane lungs may be solid silicone rubber, a microporous hollow-fibre (polypropylene for example), or a solid hollow-fibre membrane (PMP, polymethyl pentene for example). Membrane surface area and mixing in the blood path determine the maximum oxygenation capacity (the rated flow).

When used for total support, the membrane lung should provide full O_2 and CO_2 exchange for the patient as defined in II.A. The gas exchange capability of a specific membrane lung is described as “rated flow” or “maximal oxygen delivery.” These are two ways of describing the amount of desaturated (75%) blood that can be nearly fully saturated (95%) per minute

Rated flow is the flow rate at which venous blood (saturation 75%, Hb 12 mg%) will be fully saturated (95%) at the outlet of the membrane lung. **Maximal O_2 delivery** is the amount of oxygen delivered per minute when running at rated flow. This is calculated as outlet minus inlet O_2 content (typically 4-5 cc/dL, same as the normal lung) times blood flow. For example, a specific device has a rated flow of 2 L/min, (max O_2 100 ccO_2/min). If the blood flow required for total support of a patient is 1 L/min (O_2 about 50 cc/min) this membrane lung will be adequate. If the blood flow required for total support is 4 L/min, this membrane lung is not adequate and the circuit will need two of these membrane lungs in parallel, or a larger membrane lung rated at 4 L/min.

In venovenous mode, recirculation of infused blood may occur, raising the inlet saturation well above 75%. In this situation, the outlet-inlet O_2 difference per unit of blood flow is decreased, and higher blood flow, cannula repositioning, increased patient volume or higher hematocrit is/are required to provide the desired amount of O_2 delivery.

E. Sweep gas

For most applications, the sweep gas will be 100% oxygen or carbogen (5% CO_2, 95% O_2) at a flow rate equal to the blood flow rate (1:1). Increasing the sweep flow will increase CO_2 clearance but will not affect oxygenation. Water vapor can condense in the membrane lung resulting in poor CO_2 clearance, and may be cleared by intermittently increasing sweep gas flow to a higher flow.

For CO_2 clearance only, blood flow can be as low as 0.5 L/min/m^2. The membrane lung can be smaller than that required for full support, and the sweep gas flow is typically oxygen at 10:1 (gas:blood).

Avoiding air embolism via the membrane lung. Air or oxygen bubbles can pass through the membrane into the blood if the sweep gas pressure exceeds the blood pressure, or if the blood pressure is subatmospheric (this occurs when there is no blood flow or blood pressure, and blood drains from the membrane lung into the tubing by gravity, entraining air through the membrane lung). This is a specific problem with microporous hollow fiber devices but can also occur with silicone or polymethyl-pentene lungs due to very small holes in the membrane which can allow air entrainment. Prevention is achieved by maintaining the blood side pressure higher than the gas side pressure. This is accomplished by including a pressure popoff valve or pressure servo regulation control in the sweep gas supply, and by keeping the membrane lung below the level of the patient, so that if the pump stops the risk of entraining air from the room will be minimized. Even with silicone and PMP lungs it is safest to maintain the membrane lung below the level of the patient

F. Priming the circuit

The assembled circuit is primed under sterile conditions with an isotonic electrolyte solution resembling normal extracellular fluid including 4-5 MEq/L potassium. The prime is circulated through a reservoir bag until all bubbles are removed. This can be expedited by filling the circuit with 100% CO_2 before adding the prime. Microporous membrane lungs are quick to prime because gas in the circuit can be purged through the micropores. The circuit can be primed at the time of use, or days before. It is not recommended to use a primed circuit after 30 days.

Before attaching the circuit to the patient, the water bath is turned on to warm the fluid. ECLS is usually instituted with crystalloid prime. Many centers add human albumin (12.5 gm) to “coat” the surfaces before blood exposure. For infants, packed RBCs are added to bring the hematocrit to 30-40. When blood is added to the prime, heparin is added to maintain anticoagulation (1 unit per cc prime) then calcium is added to replace the calcium bound by the citrate in the bank blood. If time allows, it is helpful to verify the electrolyte composition and ionized calcium before starting flow. For emergency cannulation, the prime can be crystalloid with dilutional effects treated after initiating flow.

G. Heat exchanger

A heat exchanger is needed if it is necessary to control the blood and the patient temperature at a specific level. Heat exchangers require an external water bath which circulates heated (or cooled) water through the heat exchange device. In general, the temperature of the water bath is maintained <40º Celsius, and usually at 37º. Contact between the circulating water and the circulating blood is very rare, but should be considered if small amounts of blood or protein are present in the circulating water, or if unexplained hemolysis occurs. The water in the water bath is not sterile and may become contaminated. The water bath should be cleaned and treated with a liquid antiseptic from time to time.

H. Monitors

Monitors are designed to measure circuit function and to alarm the operator of abnormal conditions. Most circuits will include:

1. Blood flow is commonly monitored by direct measurement of blood flow using an ultrasonic detector, or can be calculated based on pump capacity and revolutions per minute for a roller pump using standardized tubing.

2. Pre and post membrane lung blood pressure measurements can include maximum pressure servo regulation control to avoid over pressuring.

3. Pre pump venous drainage line pressure (to avoid excessive negative suction pressure by the pump) can be used as a servo regulation system to prevent excessive suction.

4. Pre and post membrane lung oxyhemoglobin saturation measurements: The venous oxyhemoglobin saturation is a valuable parameter for managing and monitoring both circuit and patient factors related to oxygen delivery and consumption. The post membrane lung saturation monitor will determine if the membrane lung is working at rated flow, and if function is deteriorating. Blood gases are measured from pre oxygenator and post oxygenator sites either by continuous on line monitoring or batch sampling. The primary purpose of measuring blood gases (as opposed to online saturation) is to determine the inlet and outlet PCO_2 to evaluate membrane lung function, and blood pH to determine metabolic status.

5. Circuit access for monitors, blood sampling, and infusions. Luer connectors and stopcocks provide access to the blood in the circuit. The number of access sites should be minimized, but at least two are necessary (pre and post membrane lung). Blood access sites should be avoided between the patient and the inlet of the pump because of the risk of entraining air. It is acceptable to use the circuit for all blood sampling and infusions, although some centers prefer to give infusions directly to IV lines in the patient.

I. Alarms

Pre and post membrane lung pressure and alarms. These measurements will determine the transmembrane lung pressure gradient. Clotting in the oxygenator is represented by increasing membrane lung pressure gradient.

Many centers use a bubble detector on the blood return line. Pressure and bubble detector alarms can be used to clamp lines and turn the pump on or off to automate these safety factors.

J. Blood tubing

Tubing length and diameter will determine the resistance to blood flow. Tubing is chosen to allow free venous drainage, and avoid high resistance pressure drop on the blood return side. The blood flow through 1 meter of tubing at 100 mmHg pressure gradient for common internal diameter in inches is: 3/16:1.2 L/min; ¼:2.5 L/min; 3/8:5 L/min; ½:10 L/min

A "bridge" between the arterial and venous lines close to the patient is a useful circuit component, particularly for periods off bypass during VA access., during weaning, or during an emergency. However, when clamped the bridge it is a stagnant area which can contribute to thrombosis and possibly infection. In general, if a bridge is used, it should be maintained closed during most of the ECLS run, with a system for purging the bridge of stagnant blood when it is not in use

K. Elective vs. emergency circuits

The characteristics of individual components are listed above. Emergency circuits should be available within minutes of the call to a patient, and should be fully primed with crystalloid and ready to attach as soon as the patient is cannulated. They should also include safety factors to prevent high negative pressure on the inlet side and high positive pressure on the outlet side to avoid errors during emergent cannulation and attachment. The emergency circuit may include a microporous membrane lung (easy to prime), and a centrifugal pump (high-pressure limited, does not require monitors or alarms during initial set up).

III. Vascular Access (Chapters 4, 12, 20, 30, 38, 47)

Vascular access is usually achieved by cannulation of large vessels in the neck or the groin. The blood flow resistance of the venous drainage cannula will determine the amount of total blood flow that can be delivered by the circuit. The resistance of the blood return cannula will determine the pressure in the post membrane lung blood return line, related to blood flow. Variations can be used for specific patient conditions (see patient protocols).

A. The modes of vascular access are

1. **Venoarterial** (required for cardiac support, appropriate for respiratory support)

2. **Venovenous** (no hemodynamic support, preferred for respiratory support because it avoids using a major artery and avoids potential systemic embolism)

3. **AV-arteriovenous** (limited to low blood flow, specifically for CO_2 removal)

B. Cannulas

The term "cannula" refers to the catheter that goes directly into the vessel for ECLS, to differentiate that device from all other catheters. The blood flow resistance of vascular access cannulas is directly proportional to the length and inversely proportional to the radius to the fourth power. Therefore, the internal diameter of the catheter is the most important factor controlling blood flow resistance. Other factors such as side holes and tapering sections also affect resistance, and the resistance increases at higher flows, so the characteristics of each cannula must be known before cannulation. Blood flow at 100 mmHg gradient for commonly used cannulas is described in the patient -specific protocols. Cannulas are chosen to provide the desired blood flow (section II A) above.

C. Cannulation

1. Methods

Cannulas can be placed via: 1) cut down, 2) percutaneously by a vessel puncture, guidewire placement, and serial dilation (Seldinger technique), 3) by a combination of cut down exposure and Seldinger cannulation, or 4) by direct cannulation of the right atrium and aorta via thoracotomy. **Cut down exposure** of the neck vessels is usually necessary in neonates and small children. **Percutaneous cannulation** is commonly used for VV-ECMO in children over two and in adults. Direct **cardiac cannulation** is usually used for patients who cannot come off CPB in the OR, using the CPB cannulas.

VV access can be gained with a double lumen cannula, or two separate venous cannulas.

2. Cannulation technique

A bolus of heparin (typically 50-100 units per kilogram) is given just before cannula placement, even if the patient is coagulopathic and bleeding.

Direct cut down cannulation. Cannulation is usually done in the ICU with full sterile preparation and OR team. Deep sedation/anesthesia with muscle relaxation is essential to prevent spontaneous breathing which can cause air embolus. Local anesthesia is used for the skin. Dissection exposes the vessels. Direct handling of the vessels is minimized as much as possible to avoid spasm. Topical lidocaine or papaverine is helpful to avoid spasm. Ligatures are passed around the vessels above and below the cannulation site. Heparin is given IV (50-100 units per kilogram) and the distal vessels are ligated. The proximal vessel is occluded with a vascular clamp, the vessel opened, and the cannula placed. If the vessels are very small, if there is difficulty with cannulation, or if spasm occurs, fine stay sutures in the proximal edge of the vessel are very helpful. The vessel is ligated around the cannula, often over a plastic "boot" to facilitate later cannula removal. In the femoral artery a non-ligation technique can be used (see semi-Seldinger technique below) which may ensure sufficient flow past the cannula to ensure distal perfusion

Percutaneous cannulation. Cannulation is done in the ICU, OR, or cath lab with full sterile preparation. The OR team is not essential but there should be a plan for direct cutdown access if there are complications with percutaneous placement. The safest technique is to place small conventional intravascular catheters first. The position of these preliminary catheters is verified by blood sampling or measuring the blood pressure. After full sterile preparation a guidewire is passed into the small catheter and the small catheter is removed followed by serial dilators. The final large dilator acts as an obturator for the cannula itself. With current equipment, two people are necessary to do percutaneous access: one to load of the dilators on the wire and pass the dilators, and one to occlude the vessel between dilators to avoid bleeding. When using the Seldinger technique with a large dilator and cannulas, it important to check the wire after each dilator. If the wire is kinked or bent, it must be removed and replaced with a new wire. The use of the ultrasound or fluoroscopy can help with cannula positioning. The heparin bolus can be given any time after the main wire is placed.

Semi-Seldinger technique. Performed in the ICU, OR, or cath lab under anaesthesia with aseptic precautions. The vessel is exposed by cut down but not dissected. A small (20G) IV catheter is passed into the vessel through the skin distal to the incision. Correct placement can be confirmed by aspiration and then heparin is administered. This catheter is then used to place the large guidewire. Dilator exchanges lead to placement of the ECMO cannula. The wound is then closed over the cannula, which is then treated like a standard percutaneous cannula. The advantages of this technique over a pure percutaneous approach are speed, accurate assessment of vessel size, and flexibility of approach.

3. Management of the distal vessels

If the neck cutdown access is used, the vein and artery are ligated distally, relying on collateral circulation to and from the head. Some centers routinely place cephalad venous cannulae but this is an institutional preference and is not mandatory. If the access is via the femoral vessels the venous collateral is adequate but the femoral

artery is often significantly occluded. If distal arterial flow to the leg is inadequate a separate perfusion line is placed in the distal superficial femoral artery by direct cutdown, or in the posterior tibial artery for retrograde perfusion.

4. Adding or changing cannulas

If venous drainage is inadequate and limited by the blood flow resistance of the drainage cannula, the first step is to add another venous drainage cannula through a different vein. It may be possible to change the cannula to a larger size, but removing and replacing cannulas can be difficult. If a vascular access cannula is punctured, kinked, damaged, or clotted, the cannula must be changed. If the cannula was placed by direct cutdown, the incision is opened, the vessel exposed, and the cannula replaced, usually with the aid of stay sutures on the vessel. If the cannula was placed by percutaneous access, a Seldinger wire is placed through the cannula to facilitate cannula change.

IV. Management during ECLS (Chapters 4, 5, 14, 22, 32, 40, 49)

A. Circuit related

Circuit components are selected based on patient size (II.A)

1. Blood flow

After cannulation blood flow is gradually increased to mix the circulating blood with the prime; then, blood flow is increased until maximum flow is achieved. This is done to determine the maximum flow possible based on the patient and the cannula resistance. After determining maximum possible flow, the blood flow is decreased to the lowest level that will provide adequate support. Ideally for VA access, the pump flow is decreased until the arterial pulse pressure is at least 10 mmHg (to assure continuous flow through the heart and lungs during ECLS), but this is often not possible when the heart function is very poor. For VV access, adequate support is defined as arterial saturation greater than 80%. For VV access, flow is decreased from maximal until the arterial saturation is at the desired level (greater than 80%).The physiologic goals (mean arterial pressure, arterial and venous saturation) are set and blood flow is regulated to meet the goals.

2. Oxygenation

As long as the blood flow is below rated flow for that membrane lung (and the inlet saturation is 70% or higher) the oxyhemoglobin saturation at the outlet of the membrane lung should be greater than 95%. Usually the outlet saturation will be 100% and the PO_2 will be over 300. If the sweep is 100% O_2 or if the outlet saturation at or below the rated flow is less than 95%, the membrane lung is not working at full

efficiency (due to irregular flow, clotting). It may be necessary to change the membrane lung.

Oxygen delivery from the circuit should be adequate for full support (systemic saturation greater than 95% (VA) or over 80% (VV) at low ventilator settings and FiO_2). Venous saturation should be 20-30% saturation less than arterial saturation. This indicates that systemic oxygen delivery is 3-5 times oxygen consumption. Maintaining the hematocrit over 40% will optimize oxygen delivery while allowing the lowest reasonable blood flow.

3. CO_2 clearance

CO_2 transfer across the membrane lung will exceed oxygen transfer. CO_2 clearance is controlled by the sweep gas flow rate. Initially the gas to blood flow ratio is set at 1:1 and titrated to maintain the PCO_2 in the desired range. An alternative is to use carbogen (5% CO_2/95% O_2) as the sweep gas which will maintain outlet PCO_2 around 40 mmHg without titration. If CO_2 clearance is decreased but oxygenation is adequate, the cause is usually water accumulation in the gas phase. If the initial $PaCO_2$ is greater than 70, the $PaCO_2$ should be normalized over several hours rather than immediately in order to avoid swings of cerebral perfusion related to CO_2 and pH.

4. Anticoagulation (Chapters 6, 7, 8)

4a: Heparin (regular or "unfractionated "heparin, not low molecular weight heparin) is given as a bolus (50-100 units per kilogram) at the time of cannulation, and by continuous infusion during ECLS

4a1: Measuring heparin effect. Heparin infusion is regulated to keep the **whole blood** activated clotting time (ACT) at a designated level (usually 1.5 times normal for the ACT measurement system). ACT is the time (in seconds) in which whole blood clots in response to a fibrin activating reagent. Each ACT device has a specific upper limit with normal blood (120 to 140 seconds for most systems). ACT is measured hourly and more frequently if the ACT is changing. ACT is measured at the bedside (not sent to the laboratory) because heparin dosing decisions are often required immediately.

Partial thromboplastin time (PTT) is the time (in seconds) in which calcium-free **plasma** clots in response to a fibrin activating reagent combined with calcium. PTT is more convenient than ACT because it can be measured in the laboratory. However, it is less reliable than whole blood ACT as a measure of the time to clotting because it is measured in plasma and platelets, and blood cells can affect the activity of heparin. For a normal person, 10 units of heparin per kilogram per hour will result in ACT approximately 1.5 times normal. However, ECLS patients are not normal and there is no standard dose of heparin, and no standard concentration of heparin in the blood during ECLS. If the patient has a high platelet or white cell count, or is

"hypercoagulable," a large amount of heparin may be required to maintain the target ACT. If the patient is thrombocytopenic, in renal failure, or has circulating fibrin split products, a small amount of heparin may be required.

Heparin concentration can be measured indirectly as "**anti-Xa**." This provides a measure of heparin blood concentration, so can be used to titrate the dose to achieve a desired level of heparin concentration (typically 0.5 units/ml). When using anti-Xa to titrate heparin it is important to realize that factors other than heparin also affect blood clotting.

Thromboelastography (TEG) uses a device to record the time and density of clot formation in response to a stimulus (typically kaolin). The measurement is in whole blood so the time to clotting is the ACT. The density of the clot is affected by clotting factors, platelets, and fibrinolysis, so TEG provides more information than ACT. TEG can be done with and without an agent which inactivates heparin, so the anticoagulant effect of heparin can be separated from other factors. TEG can be done at the bedside on fresh blood or in the laboratory in calcium-free blood (adding calcium to the activator).

4a2: Heparin acts by "activating" a plasma molecule called **antithrombin** (usually called AT3). If the AT3 concentration in plasma is low, clotting can occur even when large doses of heparin are given. AT3 levels should be maintained in the normal range (80-120% of control). Low AT3 can be treated by giving fresh frozen plasma, cryoprecipitate, or recombinant AT3. AT3 assay is not available in all hospital laboratories. If clotting occurs in the circuit despite a normal or high dose of heparin, and AT3 assay is not easily available, give fresh frozen plasma to replace AT3 (inexpensive) or give recombinant AT3 (very expensive) until clotting is controlled. Circuit clotting can progress to a consumptive syndrome similar to DIC. The treatment of circuit clotting is to change to a new circuit.

4a3 HITT. There is a rare condition called heparin induced thrombotic thrombocytopenia, characterized by multiple white arterial thrombi and platelet count less than 10,000. A simple assay for HITT is available, but it has a high false positive rate. ECLS patients are all on heparin and all are thrombocytopenic for many reasons. The HITT assay is often positive in these patients, although they do not have the rare disease of heparin induced thrombocytopenia. If an ECLS patient has true HITT, the platelet count will be consistently less than 10,000 despite platelet infusions. In such a case, if there are no other explanations for thrombocytopenia, it is reasonable to use a different anticoagulant than heparin. Direct thrombin inhibitor (argatroban or bivalirudin) is the alternative.

4a4 Reversing heparin. Heparin effect can be reversed by protamine. This is routinely done in cardiac surgery where the effect of heparin must be maximal during operation, but minimal after coming off bypass. During ECLS, protamine reversal is almost never indicated because precise protamine dosing is difficult and circuit clotting can occur if heparin is reversed to normal coagulation status.

4b. Direct thrombin inhibitors. DTIs are used in HITT patients, and many centers are using DTIs as the primary anticoagulant. DTI effect is measured by ACT, PTT, or TEG. DTI dose is titrated to clotting time 1.5 times normal, as with heparin. DTI does not depend on AT3, so AT3 monitoring or replacement is not necessary. There is no reversal medication but the half life is a few hours so overdose is not long lasting.

4c. Thrombocytopenia (platelet count less than 150,000) is common in ECLS patients. It may be a consequence of the primary disease, drugs, and other treatment, or caused by blood surface exposure. Circulating platelets adhere to the plastic surfaces, and undergo a "release reaction" which attracts other platelets. These aggregates of "effete" platelets circulate in the blood and are removed by the liver and spleen. If the platelet count is less than 20,000 spontaneous bleeding can occur. The usual practice is to transfuse platelets to keep the count greater than 80,000. Even though the platelet count is over 80,000, platelet function may be impaired. A kallikrein inhibitor (aprotinin or tranexamic acid*)* may improve platelet function if bleeding is a problem (see bleeding IVB).

4d. Fibrinogen. Even though fibrin formation is inhibited by anticoagulants, fibrinogen can become depleted during ECLS. Fibrinogen levels are measured daily and maintained within the normal range (250 to 300 mg/dl) by infusion of fresh frozen plasma or fibrinogen. The primary disease, or clots in the circuit, may cause fibrinolysis resulting in circulating fibrin split products. These molecules act as anticoagulants and can add to the risk of bleeding. If fibrin split products are detected and/or if bleeding is excessive, fibrinolysis can be inhibited with anti-fibrinolytics (see bleeding).

4e. Surface coatings. Extracorporeal circuits and devices are available with surface heparin coating or coating with other polymers intended to minimize blood surface interaction. These modified surfaces may decrease blood surface interaction somewhat, but systemic anticoagulation is still required when using the surface coatings currently on the market. It is possible to manage ECMO without systemic anticoagulation if bleeding cannot be controlled by other measures. During ECLS with no systemic anticoagulation blood flow should be maintained high, and a primed replacement circuit should be available if the circuit clots.

5. Circuit monitors, alarms, and safety (Chapters 4, 5)

5a. High pressure. The higher the perfusion pressure, the higher the risk of leak or blowout. 400 mmHg is typically the highest safe level. If the post pump pressure is greater than 300 mmHg at the desired flow rate, the cause might be high systemic blood pressure in the patient (in VA mode), high resistance in the blood return access cannula, high resistance in the conduit tubing from the membrane lung to the cannula, or high resistance in the membrane lung. If the pressure suddenly increases setting off the high-pressure alarm, the cause is usually temporary occlusion of the infusion tubing or

cannula. If this occurs stop the pump, then gradually return flow while determining the cause of the sudden increase in resistance

5b. Air in the circuit might be seen directly or detected by a bubble detector. If air is detected in the circuit stop the pump, clamp the lines near the patient, and put the patient on support settings. Because the patient is often totally dependent on ECLS, it is necessary to find and repair the cause of air in the circuit very quickly. The most common cause is aspiration of air into the venous drainage line at the site of cannulation or through a connector or open stopcock. Another common cause is air bubbles in the intravenous infusion lines going into the patient. When air is entrained on the drainage side it is usually as small bubbles, and usually is caught in the membrane lung or bubble trap before getting into the patient. Air on the infusion side is a much more serious problem. The most common cause is air entrainment in the membrane lung. This can occur if the membrane lung is higher than the patient and if the blood side pressure drops below the gas side pressure.

5c. Clotting in the circuit is detected by careful examination, using a flashlight to go over all the extracorporeal circuit. Clots are seen as very dark nonmoving areas on the surfaces. Every circuit will have some small clots at the site of connectors, infusion lines, or in areas of low flow in the pre-pump bladder or the membrane lung. These clots are in the range of 1 to 5 mm, do not require circuit changes, and are simply observed. Clots larger than 5 mm or enlarging clots on the infusion side of the circuit (post membrane lung) should be removed by removing that section of the circuit or by changing the entire circuit if there are many such clots. Platelet/fibrin thrombi appear as white areas on the circuit at connectors and stagnant sections. These are clots which have not accumulated red cells, usually because they are in areas of very high flow. As with dark clots, no intervention is necessary unless the white thrombi are greater than 5 mm or growing.

5d. Electrical power failure. The circuit should be designed to automatically switch to battery operation if the main source of electricity is lost. An alarm should sound when the circuit switches to battery operation. The battery will operate the circuit for 30-60 minutes while the cause of the problem is being identified. The major power requirement is the water bath for the heat exchanger. When operating on battery power, it is wise to turn off the water bath. If the electrical circuit and the battery fails, the alarm will be a low flow alarm or alarms attached to the patient (saturation or blood pressure). In that case it will be necessary to crank the pump by hand.

5e. Decannulation is a life-threatening emergency identified by major bleeding at the cannulation site, air in the drainage circuit (if the drainage cannula is coming out) and loss of volume and perfusion pressure if the infusion cannula is lost. Decannulation is prevented by securing the cannulas to the skin in at least two locations, and checking the position of the cannulas and cannula fixation at frequent intervals and adequately sedating the patient. If decannulation occurs, come off bypass immediately by clamping the lines close to the patient, control bleeding by direct pressure, and reinsert the cannula as soon as possible.

5f. Hemolysis is suspected if the urine has a pink tinge (which could be due to bladder bleeding, not hemolysis) and verified by plasma Hb measurement. Normally plasma hemoglobin should be less than 10 mg/dl. Higher plasma hemoglobin can be caused by a condition primary to the patient, or by circuit components. The pump itself will not cause hemolysis unless inlet (suction) pressures are greater than minus 300 mmHg, which can happen if the pump suction exceeds the blood drainage. The pump can also cause hemolysis if there are clots in the pump chamber (which can occur in centrifugal pumps). Hemolysis can occur if blood is flowing at a high rate through a very small orifice. This can occur if the blood return cannula has a very high resistance, or if there is a high level of occlusion in the post pump circuit. Hemolysis can also occur if a hemofilter or plasmapheresis device is attached to the circuit and run at high flows. If hemolysis occurs, the source should be found and corrected.

5g. Emergency drills addressing all these problems should be conducted by the team at regular intervals

5h. Safety. ECMO is a technology dependent therapy utilized in critically ill patients. A successful outcome is highly dependent on repetitive safe practices by a diverse team (physicians, ECMO specialists, perfusionists, nurses, etc). Policies that support a safe ECMO program include: regular emergency skills lab sessions, team training, using a pre-procedure "time out" to verify key elements and post-ECMO debriefings.

6. Component and circuit changes

It may be necessary to stop ECLS (come off bypass) to remove and replace small components such as stopcocks and connectors, large components such as the pump chamber or membrane lung, or the entire circuit. If the patient is totally dependent on ECLS, this can be done in less than one minute as follows: Put the patient on maximal ventilator and drug support settings. Get at least one helper and assemble all the clamps and components. Clamp the lines near the patient, and clamp the lines above and below the component to be changed. With sterile technique, cut out the component and insert the new component, filling the tubing with saline and eliminating all bubbles. When changing or adding a membrane lung, the lung must be primed with crystalloid solution before attaching to the circuit.

7. Traveling (Chapter 66)

Traveling poses risks. Do procedures in the ICU whenever possible.

In hospital. It may be necessary to travel to radiology, the operating room, or the cath lab as follows. Be sure that the battery is fully charged and the hand crank is available for the pump. Turn off the water bath to save electricity. Use a small full tank of oxygen for the sweep gas. Switch the circuit to battery power and portable oxygen before moving the patient from the bed. Before moving the patient, switch the patient

monitors to a portable monitor for EKG, blood pressure, and $Sa0_2$. Minimize the number of intravenous infusions as much as possible. Bring an Ambu bag, separate oxygen tank, and emergency drugs. Plan the trip before leaving the ICU. Hold elevators, clear hallways, and be sure the receiving unit is ready. When moving the patient and the ECLS cart, one person is assigned to keep one hand on the gurney and the other on the cart to reduce tension on the tubing.

Hospital to hospital. In addition to all the details listed above, the transport team must be totally self-contained for hospital to hospital transfer. This includes spare parts for all components, a variety of cannulas and sizes, operating instruments, and medications. Arrange for hospital privileges in the referral hospital. Send instructions to the referral hospital regarding family, consent, and blood, platelets, and plasma preparation, OR team if necessary, etc.

B. Patient related management (Chapters 4, 5, 14, 22, 32, 40, 49)

1 Hemodynamics

During **VV support** the patient is dependent on his own hemodynamic physiology. Appropriate medications and infusions are used to control cardiac output, blood pressure and resistance.

During **VA support** hemodynamics are controlled by the blood flow (pump flow plus native cardiac output), and vascular resistance. Because the pulse pressure is low the mean systemic arterial pressure will be somewhat lower than normal pressure (40 to 50 mmHg for a newborn, 50 to 70 mmHg for a child or adult). In addition, patients placed on ECLS for cardiac support are on high doses of pressors when ECLS is begun. As these drugs are titrated down, resistance falls and systemic pressure falls proportionately. If the systemic perfusion pressure is inadequate (low urine output, poor perfusion) pressure can be increased by adding blood or low doses of pressor drugs. Systemic vasodilatation requiring pressor drugs is common in patients in septic shock. Although the mean arterial pressure may be low, systemic perfusion may be completely adequate. Systemic perfusion is best measured by mixed venous blood saturation. Assuming SaO_2 is over 95% venous saturation greater than 70% indicates systemic oxygen delivery is adequate even though the pressure may be low. If systemic oxygen delivery is not adequate (venous saturation less than 70%) increase the pump flow until perfusion is adequate. If extra blood volume is required to gain extra flow, consider the relative advantages of blood and crystalloid solution.

2. Ventilation

2a. Mechanical ventilation. Whether the patient is on either VV. or VA mode, the ventilator should be managed at low settings to allow lung rest. For patients with respiratory failure, a common mistake is to try to recruit lung volume during the acute inflammatory stage early in ECLS. Typical rest settings include low rate with long

inspiratory time, low plateau inspiratory pressure (under 25 cm H_2O) low FiO_2 (under 30%). The end-expiratory pressure (PEEP) can be set at any level. In fact, the ventilator can be managed as APRV with continuous positive pressure and occasional pressure release, or CPAP with spontaneous breathing. Using high PEEP levels, however, will inhibit venous return and have the usual negative effect on hemodynamics when the patient is managed in the VV mode. PEEP is usually set between 5-15 cmH_2O

If there is a major pulmonary air leak or interstitial emphysema, the ventilator pressure can be reduced or turned off altogether for hours or days until the leak seals. This will lead to significant atelectasis in addition to the primary lung disease. If the patient develops a pneumothorax, placement of a chest tube is not an automatic response. Even placing a small tube may result in significant bleeding ultimately requiring thoracotomy. A small pneumothorax (less than 20%) with no hemodynamic compromise is best treated by waiting for absorption. An enlarging pneumothorax or a pneumothorax causing hemodynamic compromise requires external drainage. This is best done using the technique most familiar to the operator. This could be a small catheter placed by Seldinger technique, or a surgical thoracostomy with placement of a chest tube. (See procedures, section 9 below)

Lung recruitment maneuvers (prolonged inflation at 25 to 30 cm of water for one to two minutes) can be used when acute inflammation has subsided. When lung recovery begins, spontaneous breathing will enhance recovery. Adjusting the sedation drugs to allow spontaneous breathing, adjusting the sweep gas to maintain the infusion blood PCO_2 40-45 mmHg, and putting the ventilator in assist mode may speed lung recovery.

2b. Airway access. Initiating ECLS, all patients are intubated endotracheally. If the patient is on VA-ECLS for cardiac support, and lung function is adequate, the patient can be extubated and managed awake with spontaneous breathing.

If the patient has respiratory failure, the airway is managed by continuing endotracheal intubation at rest settings as above. Maintaining safe positive pressure can maintain existing lung inflation, and may improve lung function as lung recovery begins. Tracheostomy avoids the discomfort of intubation and decreases the risk of nosocomial pneumonia. However, tracheostomy has the risk of bleeding in anticoagulated patients, so the technique is important (see B10).

Since the gas exchange is totally supported with ECLS, patients can be extubated and managed without mechanical ventilation. This facilitates activity and ambulation and is often used for patients bridging to lung transplantation.

2c. Managing gas exchange with the ECLS circuit. Patient arterial blood **gases** are the result of infusion blood **mixing** with the native blood in the aorta (VA) or right atrium (VV). The infusion blood is typically PCO_2 40 mmHg, PO_2 500mmHg, saturation 100%, oxygen content 22 ccO_2/dL.

In **VV mode**, infusion blood mixes with systemic venous return blood. At typical blood flow, the ratio of infusion blood to deoxygenated right atrial blood is usually around 3:1. This results in PCO_2 41, PO_2 40, sat 80%, content 17ccO_2/dL in the pulmonary artery. If there is no native lung function, this will be the composition of gases in the arterial blood. It is important to realize that systemic arterial saturation around 80% is typical during VV support. As long as the hematocrit is over 40% and cardiac function is good, systemic oxygen delivery will be adequate at this level of hypoxemia. (Don't increase vent settings from rest settings because of hypoxemia.) Any native lung function will increase oxygenation over 80% sat.

In **VA mode** infusion blood mixes with blood in the aorta. The ratio of infusion to native aortic blood flow is typically 8:1 (near total bypass). If native lung function is normal (i.e. in cardiac support) and the FiO_2 is 0.2, this results in PCO_2 40, PO_2 200, sat 100%, content 21 ccO_2/dL.

If there is no native lung function this mixing results in PCO_2 40.5, PO_2 100, sat 98%, content 20 ccO_2/dL. NOTE: The forgoing is true if infusion blood goes to the aortic root (as in subclavian, carotid, or direct arch perfusion). If the infusion blood is going into the femoral artery and flow is retrograde, the mixing will occur somewhere in the mid aorta, the higher the flow rate, the higher the level of mixing. During severe respiratory failure, at typical VA flow rate (80% of full cardiac output) this can result in desaturated blood from the left ventricle perfusing the aortic arch and coronaries and fully saturated infusion blood perfusing the lower 2/3 of the body. This can occur in large children and adults. This can be managed by including SVC blood in the venous drainage, or by infusing some infusion blood into the right atrium (VVA). See patient specific protocols for further discussion.

3. Sedation

The patient should be thoroughly sedated to the point of light anesthesia during cannulation and management for the first 12 to 24 hours. The purpose is to avoid spontaneous breathing which might cause air embolism during cannulation, to minimize the metabolic rate, to avoid movement which might make cannulation difficult, and for patient comfort. It is rarely necessary to paralyze the patient, except to avoid spontaneous breathing during venous cannula placement.

After the patient is stable on ECLS, all sedation and narcotics should be stopped long enough to allow a thorough neurologic examination. Then sedation and analgesia may be resumed depending on patient's level of anxiety and discomfort. The primary reason for sedation during the VV-ECLS is to tolerate endotracheal intubation. Conversion to tracheostomy should be considered early in the course in patients over 5 years of age to allow decreasing sedation. Sedation should be minimal, but it is important to be sure the patient does not pull on cannulas and tubes running the risk of decannulation or occluding the perfusion line. If the venous blood drainage is limited for any reason, blood flow may not be adequate to support systemic perfusion or gas exchange. This is often the case if the patient is anxious, moving about, or coughing.

Sedation should be sufficient to avoid increasing the native metabolic rate, and systemic paralysis and cooling may be necessary if venous drainage cannot be achieved. Holding sedation and analgesia long enough to do a neurologic exam should be done daily (a daily drug holiday).

4. Blood volume, fluid balance and hematocrit (Chapters 8, 41, 62)

As with any critically ill patient, the ultimate goal of management is adequate hematocrit, normal body weight (no fluid overload), and normal blood volume. During ECLS the **blood volume** is increased by the volume of the extracorporeal circuit. Because the extracorporeal circuit is not compliant, this doubling or tripling of the blood volume has no hemodynamic effect; each milliliter of blood removed is immediately replaced by an identical volume. The extracorporeal circuit is primed with crystalloid solution (perhaps with red blood cells in infants) and the priming solution will equilibrate with the native blood volume during the first several minutes of ECLS. This will dilute blood cells, platelets, and proteins depending on the ratio between the native blood volume and the extracorporeal prime. This dilution is caused by an increase in the crystalloid component of the plasma which will equilibrate into the extracellular space causing edema.

The blood volume should be maintained at a level high enough to keep right atrial pressure in the range of 5-10 mmHg. This will assure adequate volume for venous drainage, as long as the resistance of the drainage cannula is appropriate

The goal of fluid management is to return the **extracellular fluid volume** to normal (dry weight) and maintain it there. The reason is that edema caused by critical illness or iatrogenic crystalloid fluid infusion causes lung and myocardial failure, adding to the primary problem. Achieving normal ECF status can be difficult in a patient who is septic and has active capillary leakage from the plasma into the extracellular space. During the acute inflammatory stage early in ECLS capillary leak will occur, and is exacerbated by excessive crystalloid infusion. When the patient is hemodynamically stable (typically 12 hours) diuretics are instituted and continued until dry weight is achieved. If the diuretic response is not sufficient to achieve negative fluid balance, or if the patient is in overt renal failure, continuous hemofiltration is added to the extracorporeal circuit to maintain fluid and electrolyte balance.

5. Temperature

Temperature can be maintained at any level by adjusting the temperature of the water bath. Temperature is usually maintained close to 37° C. If the patient was cannulated under conditions which could lead to hypoxic ischemic brain injury, it is reasonable to maintain mild hypothermia (32 to 34°) during the first 24 to 72 hours to minimize brain injury. Hypothermia will require sedation or paralysis to avoid shivering, and may exacerbate bleeding. Hyperthermia (from fever or inflammation) is controlled with the heat exchanger to avoid hypermetabolism.

6. Renal and nutrition management (Chapters 4, 41, 62)

As mentioned above spontaneous or pharmacologic diuresis should be instituted until patient is close to dry weight and edema has cleared. This will enhance recovery from heart or lung failure and decrease the time on ECLS. If renal failure occurs, it is related to the primary disease and is treated by continuous hemofiltration (CVVHD). As with all critically ill patients, full caloric and protein nutritional support is essential.

7. Infection and antibiotics

The cannula sites are cleaned frequently with antiseptic solution and may be covered with an antiseptic cream or ointment. Appropriate antibiotics should be given for documented infection. There is no standard policy regarding prophylactic antibiotics simply because the patient is on ECLS. Bacteremia during ECLS may be related to bacterial growth on a component of the circuit, but is usually related to another source in the patient. Unlike suspected "line sepsis" in the usual critically ill patient, it is usually not possible to change the access cannulas if contamination is suspected, and it may be dangerous to change the circuit. If all other sources of bacteremia have been ruled out, the entire circuit up to the cannulas can be changed expeditiously.

8. Positioning

Patient positioning should be as mobile and normal as possible depending on the primary condition. There is a tendency to allow the patient to be anesthetized and lay supine for days at a time. In older children and adults, this will lead to posterior lung compression and atelectasis and should be avoided. If the primary problem is respiratory failure, posterior consolidation can be prevented and even treated by prone positioning for several hours each day. An alternative is a sitting position, although it may be difficult to maintain ECLS flow in the sitting position. If the patient is on ECLS for cardiac support it is often possible to extubate and allow the patient to move about spontaneously in bed. Obviously this is not recommended for patients with trans-thoracic cannulation and an open chest.

9. Bleeding (Chapter 7)

Bleeding is the most common complication during ECL S because of systemic anticoagulation, thrombocytopenia, and thrombocytopathia. **Prevention** of bleeding is important throughout the ECLS course. Care providers may forget that simple venipuncture, fingersticks, endotracheal suctioning, passage of a catheter through the nose or urethra, can lead to uncontrollable bleeding. Because of ample blood access there is very rarely any need for needle punctures in ECLS patients. Suctioning and passage of catheters should be done with caution, and only after assuring that the anticoagulation status is optimal (low ACT, adequate platelet counts). If invasive procedures are necessary, appropriate preparation is essential. Management of anticoagulation is discussed in section IV.A.4 above. Particular attention should be paid to fibrinogen and AT3 level if the patient is on heparin.

Management of bleeding begins with **returning coagulation status to normal** as much as possible. This involves decreasing the anticoagulant infusion until the ACT or PTT is 1.4 to 1.5 times normal, transfusing platelets until the platelet count is greater than 100,000, and giving antifibrinolytics if fibrinolysis is documented or suspected (particularly after a recent major operation). Fresh frozen plasma or specific clotting factors may be indicated if deficiencies are demonstrated. Often these maneuvers will stop bleeding. If not, it is reasonable to turn the anticoagulant off altogether; however, this may result in major circuit clotting and should not be done until and unless **site specific** measures are completed. Using a thromboresistant coated circuit may allow withholding heparin for a longer period of time with less risk of clotting complications.

Cannulation site. This is the most common site of bleeding, particularly if access has been gained by direct cutdown. Bleeding can be minimized by doing the dissection without systemic heparin, then waiting a few minutes before cannulation if patient condition permits. Bleeding at the cannulation site may be an indication that the cannula is loose or pulling out. The possibility of decannulation should always be considered. Usually cannula site bleeding is slow oozing related to disruption of small vessels in the skin or subcutaneous tissue. Topical pressure will often control the bleeding, although care must be taken to avoid compressing the cannula. If bleeding persists after direct cutdown access the wound should be reexplored

Bleeding post chest tube placement: Bleeding is a common complication even if all appropriate steps are taken during tube placement. It may occur early or after days. Accumulated blood should be evacuated, even if this requires a lower, more posterior tube. Evacuating the blood quantifies the rate of bleeding and decreases the risk of a hemothorax and later organized clot. A CT scan is indicated to determine if the tube is in the parenchyma of the lung. If it is the tube should be removed, but thoracotomy will probably be need to control the bleeding and air leak. If not all the steps outlined above may stop the bleeding. If not thoracotomy is indicated (either via thoracoscopy or directly). Even if bleeding is controlled by operation it often recurs within days. Because of this, it is wise to pack the chest open which permits frequent bedside reexploration until the patients is off ECMO

Recent operation. The second most common site of bleeding is related to recent operations, particularly thoracotomy if the patient is on ECLS for postoperative cardiac failure. In this circumstance (particularly when going directly from CPB to ECLS) the first step is to place suction catheters in the operative site, seal the site with an occlusive plastic drape, and collect the blood to quantitate the rate of bleeding. Drainage blood can be collected with a “cell saver” for reinfusion. When going directly from CPB to ECLS in the OR, it is reasonable to wait until the ACT is normal or bleeding stops before starting anticoagulation. When the platelet count, ACT, and other medications are optimal, the operative site should be reexplored for active bleeding. When an operative site is explored for bleeding it is best to leave the site open with active drainage and a plastic seal closure, rather than surgical closure of the skin. (Cutdown

cannulation site is an exception.) Reexploration may be necessary many times before bleeding is controlled. There is a moderate risk of wound infection, but that risk is much lower than the risk of ongoing bleeding. See patient specific guidelines for post cardiotomy and other conditions.

Mucous membranes. Bleeding from the nasopharynx, mouth, trachea, rectum, or bladder commonly occurs with minor trauma associated with patient care. It is difficult to control bleeding in these areas by direct pressure but full nasal packing or traction on a Foley catheter with a large balloon in the bladder may stop major bleeding.

Uterus. Women in the childbearing years may experience a menstrual period during ECLS (although that is rare in critically ill patients). However, uterine bleeding is usually not severe and subsides spontaneously. When ECLS is used in a recent postpartum patient, uterine bleeding can be a significant problem. After ruling out retained products of conception, the bleeding may be controlled by oxytocin, or creating a balloon tamponade within the uterus. Very rarely hysterectomy may be necessary.

GI bleeding can occur from esophagitis, gastritis, duodenal ulcer, or other sources. It is important to determine the site of bleeding by endoscopy or angiography. If the site of bleeding can be reached by an endoscope or arterial catheter, local measures should be attempted. The decision to operate to control bleeding or excise the bleeding organ is the same as in any patient with GI bleeding and a systemic coagulopathy. The coagulopathy is corrected as much as possible, and then operation is indicated if uncontrolled bleeding persists. The same is true for spontaneous bleeding into other solid organs (liver, kidney, retroperitoneal tissue) or bleeding into the thorax or peritoneal space.

Bleeding into the head or brain parenchyma is the most serious ECLS complication. It is usually extensive and fatal. If it is possible to take the patient off ECLS on high ventilator and drug settings, it is reasonable to operate on the skull to drain the blood, if such a procedure is indicated

If bleeding persists despite all of these procedures and maneuvers, it is reasonable to **stop anticoagulation altogether** until the bleeding stops. The best way to do this is to come off bypass on high flow high ventilator/inotrope settings if the patient's condition will permit it. Often bleeding will stop once a patient is off ECLS for several hours. If the patient will not tolerate coming off bypass, it is reasonable to stop the anticoagulation altogether and allow the ACT to return to the normal range for hours. This may stop the bleeding but may also result in clotting in the circuit, so whenever anticoagulation is turned off a primed circuit should be immediately available.

10. Procedures (Chapter 6)

Procedures from venipuncture to liver transplantation can be done with success during ECLS. When an operation is necessary, coagulation should be optimized

(anticoagulation minimized) as described above. Even small operations like chest tube placement are done with extensive use of electrocautery. For the surgeon, the procedure is like operating on any coagulopathic patient.

Tracheostomy is often done in ECLS patients but the technique is different than standard tracheostomy. The trachea is exposed through a small incision, all with extensive electrocautery. The smallest opening in the trachea is made between rings, preferably with a needle, wire, and dilation technique. Do not incise a ring or create a flap. Because the patient is on ECLS support there is no urgency about gaining access or conversion from ET tube to trach tube. The operative site (and trachea) should be bloodless after operation. Subsequent bleeding (common after a few days) should be managed by complete reexploration until bleeding stops.

V. Weaning, Trials off, Discontinuing ECLS for Futility (Chapters 4, 16, 24, 34, 42, 51)

A. Weaning

When management is carried out as described in Section IV (using the lowest flow to provide adequate support at low ventilator settings and pressor doses), weaning is automatic. Extracorporeal support is decreased as native organ function improves. When ECC support is less than 30% of total, native heart or lung function may be adequate to allow coming off ECLS, and a trial off is indicated. Note: as long as ECC support is more than 30 to 50%, there is no indication to trial off, except in special circumstances such as uncontrolled bleeding.

B. Trial off

Trial off **during VV access** is very simple. Cardiac function is adequate and only native gas exchange is tested. Adjust ventilator to settings you would accept off ECLS (rate, plateau pressure, PEEP, FiO_2). Maintain blood flow and anticoagulation, stop the sweep gas, and cap off the oxygenator. Follow the patient SaO_2 and PCO_2. If lung function is adequate at acceptable ventilator settings for an hour or more the patient is ready for decannulation.

Trial off **during VA access** requires clamping of the drainage and infusion blood lines and circulating the circuit slowly through the AV bridge. Adjust the dose of inotropes and pressors, and the ventilator settings, to acceptable levels. Then clamp off the extracorporeal circuit and follow perfusion and gas exchange. Echocardiography is very helpful to assess cardiac function during a trial off. Anticoagulation is continued during the trial off, and the blood lines and access cannulas are unclamped periodically to avoid stagnation. If the trial off is successful, circuit lines can be cut and access cannulae “locked” with heparinized saline, awaiting decannulation. If the trial off is successful but the patient is precarious, the circuit can be cut away and access cannulas left in place in case the patient needs to be returned to ECLS support with a new circuit. In this circumstance the usual practice is to infuse low dose heparinized saline into the

cannulas and reassess frequently. Access cannulas can be left in place for 24 hour or more. If there is no uncertainty about the need for further ECLS, it is better to remove the cannulae after the trial off has finished successfully.

C. Decannulation

The cannulas can be removed whenever the patient is ready, but ideally after the heparin has been turned off for 30 to 60 minutes. Cannulas placed by direct cutdown are removed by direct cutdown. The cannulae are removed and the vessels simply ligated (or occasionally repaired). If the femoral artery has been cannulated by cutdown, vascular repair will be required. Venous and arterial cannulae placed by percutaneous access can be removed directly and bleeding controlled by topical pressure.

When removing a venous cannula, air can enter the venous blood through the side holes if the patient is breathing spontaneously. This is prevented by a Valsalva maneuver on the ventilator, or by short-term pharmacological paralysis when removing the venous cannula.

D. Stopping support for futility

ECLS should be discontinued promptly if there is no hope for healthy survival (severe brain damage, no heart or lung recovery, and no hope of organ replacement by VAD or transplant). The possibility of stopping for futility should be explained to the family before ECLS is begun. The definition of irreversible heart or lung damage depends on the patient and the resources of the institution. In each case, a reasonable deadline for organ recovery or replacement should be set early in the course. For cardiac failure, for example, three to five days of no cardiac function in a patient who is not a VAD or transplant candidate is considered futile in most centers. For lung failure, for example, two weeks of no lung function in a patient who is not a transplant candidate is considered futile in many centers, although there are cases of lung recovery after 50 days of ECLS. Fixed pulmonary hypertension in a patient with respiratory failure after several weeks of support on VV-ECMO may also be an indication of futility, or at least an indication to convert to VA access.

VI. Patient and Disease Specific Protocols

These guidelines are written to apply to all ECLS cases, but there are many circumstances where the guidelines are adapted, or additional guidelines are required for specific patients. Patient and disease specific guidelines are written for respiratory and cardiac support, for neonates, children, and adults. Additional guidelines will be written for special conditions such as asthma, pulmonary embolism, sepsis, ECPR, etc.

VII. Expected Results (per patient and disease category)

See patient specific guidelines. The outcome for ECLS patients is described in the semiannual report of the ELSO Registry.